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1 **Eustatic knickpoint dynamics in an uplifting sequence of coral reef**
2 **terraces, Sumba Island, Indonesia**

3

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13

14 **Keywords**

15

16 Eustatic knickpoint; coral reef terrace; alluvial erosion; ³⁶Cl cosmogenic denudation
17 rates.

18

19 **Abbreviations**

20

21 Coral Reef Terrace (CRT); Marine Isotopic Stage (MIS); Cosmogenic Nuclide ³⁶Cl
22 Concentration (CNC); Digital Elevation Model (DEM).

23

24 **Abstract**

25

26 An emerged coral reef terrace sequence flanks the northern coast of Sumba Island in
27 Indonesia. The sequence was created by the joint effects of uplift and Quaternary
28 sea level oscillations. Since its emergence, it undergoes chemical erosion, which is
29 facilitated by its carbonate lithology. The morphology is dissected by multiple catch-
30 ments drained by deep canyons, whose stream profiles display several knickpoints.
31 We applied a multi-methods approach using high-resolution topographic data (Pleia-
32 des imagery), geomorphological analysis and denudation rates derived from ^{36}Cl
33 cosmogenic nuclide concentrations to characterize the dynamics of these coastal
34 drainages. We specifically investigate (1) the channel response to eustatic forcing, by
35 analyzing knickpoint dynamics along a longitudinal river profile, and (2) the control of
36 internal and external forcing over the catchment-scale erosion. Firstly, knickpoints
37 form at the distal edge of the emergent reef at each regressive stage following a sea
38 level highstand. The knickpoint propagates and rotates upward by regressive ero-
39 sion. Knickpoint propagation rate decreases sharply over time until it becomes negli-
40 gible before the next sea-level rise, which implies a marked decline in knickpoint re-
41 treat rate before its resorption. We attribute the inability of the river at Cape Laundi to
42 fully propagate eustatic oscillations to its low stream discharge and low sediment
43 supply, related to its small drainage area, to the karstic nature of the coral reef ter-
44 races composing the sequence, and to the high frequency of eustatic forcing. Sec-
45 ondly, average denudation rates calculated from ^{36}Cl cosmogenic nuclide concentra-
46 tions of sands collected at the outlet of five catchments draining the sequence
47 amount to $69 \pm 16 \text{ mm.k}^{-1}$. We emphasize the role of canyon areas in driving the
48 denudation of the major catchments. However, no first-order correlation has been
49 observed between catchment metrics, uplift rates and denudation rates. Finally, our
50 correlations between catchment finite eroded volumes and uplift rates highlight the

51 tendency of catchments to widen with low uplift rate and to lengthen while incising the
52 sequence deeply with higher uplift rates.

53

54 **1. Introduction**

55

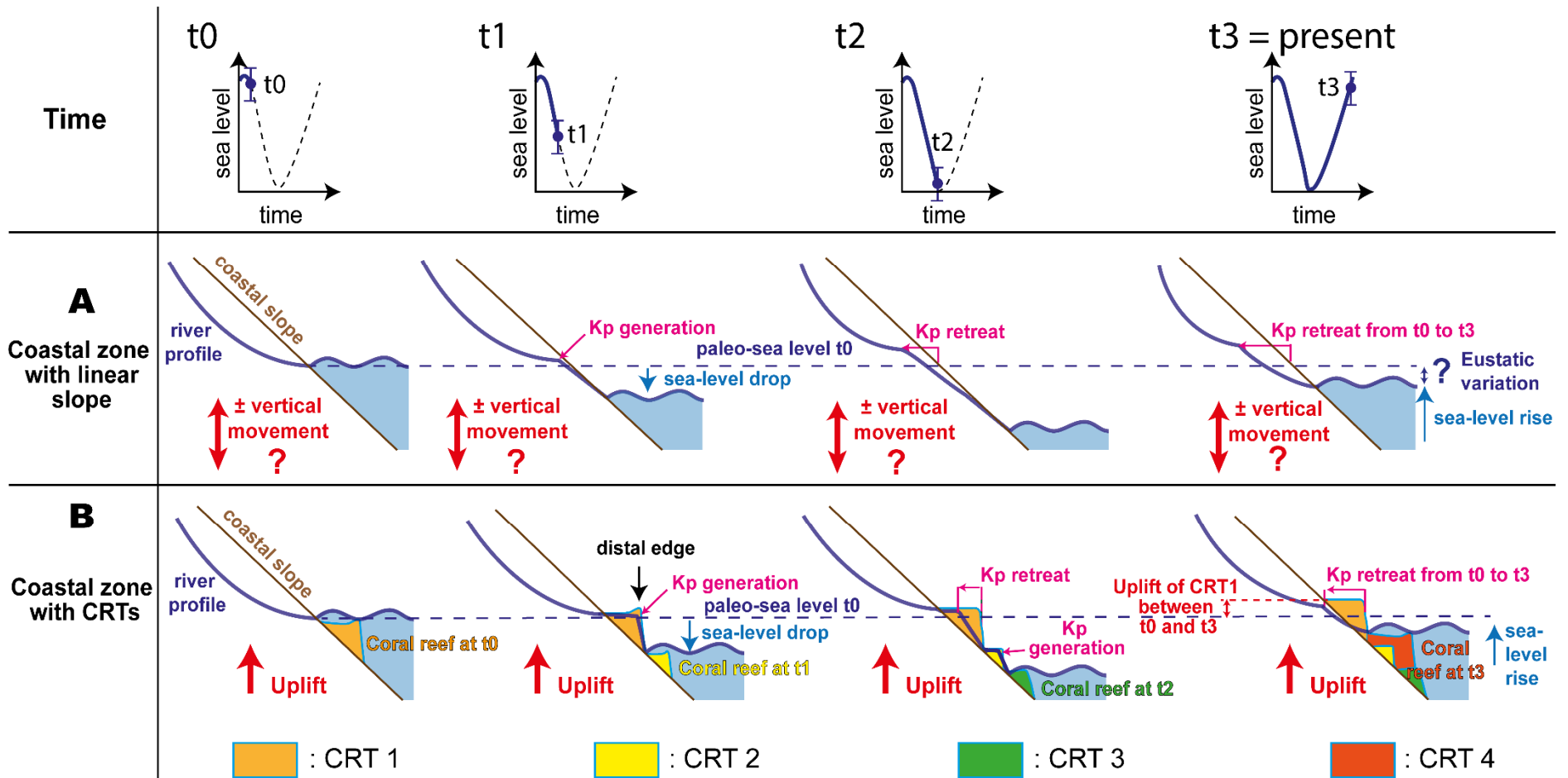
56 Rivers are relentlessly adapting to tectonic, climatic, eustatic, lithologic, and biologic
57 conditions by modulating their erosion or sedimentation dynamics. A river responds
58 to an extrinsic base-level drop by an upstream propagation of an incision wave (e.g.,
59 Whipple and Tucker, 1999; Montgomery and Brandon, 2002; Wobus et al., 2006; Kir-
60 by and Whipple; 2012). As the incision propagates upstream, it isolates the down-
61 stream region that is adjusted or adjusting to the new forcing conditions and the up-
62 stream relict region that retains topographic features adjusted to the initial or back-
63 ground forcing (Whipple and Tucker, 1999; Schoenbohm et al., 2004; Crosby and
64 Whipple, 2006; Reinhardt et al., 2007; Berlin and Anderson, 2007; Whittaker, 2012).
65 The river will be in a transient situation until the upstream relict region disappears.
66 The discrete and mobile boundary between the two regions is marked by upstream-
67 migrating steep reaches, called knickpoints, or more properly knickzones - the knick-
68 point being the upper break in slope from shallow to steep. Knickpoints can generate
69 large variations in denudation rates within the catchment (e.g., Willenbring et al.,
70 2013). Investigating the geometry of transient channels, coupled with quantified
71 stream incision rates allows for diagnosis of active fluvial processes and to better
72 characterize erosion laws and their controlling parameters (e.g., upstream drainage
73 area; local channel gradient; dimensional erosion efficiency factor; e.g., Whipple and
74 Tucker, 2002; Godard et al., 2019). In that respect, coastal areas are especially in-
75 teresting because they are exposed to eustatic base-level changes (Gardner, 1983;

76 Snyder et al., 2002; Loget and Van Den Driessche, 2009; Castillo et al., 2013; Ye et
77 al., 2013). According to the models of Snyder et al. (2002), sea-level drops may form
78 knickpoints if (1) the exposed seafloor (below current sea level) is steeper than the
79 upstream channel (above sea level), (2) the relative rate of base-level change ex-
80 ceeds wave and tide erosion, and (3) the rock-uplift rate remains uniform onshore
81 and offshore. In order to quantify knickpoint propagation rates, it is therefore neces-
82 sary to identify the initial base level from which the knickpoint started to retreat, which
83 is challenged by the uncertainties on eustasy and vertical motion (Fig. 1A; e.g., Pe-
84 doja et al., 2014). Paleo-sea level indicators such as marine terraces (e.g., Castillo et
85 al., 2013) help alleviating these uncertainties.

86

87 We focused on an uplifted coastal area characterized by a sequence of emerged
88 coral reef terraces (CRTs) in Sumba Island, Indonesia. CRTs are marine terraces in
89 the broadest sense of the term that thrive in the tropical coastal zones; they include a
90 slightly sloping area separated by steep slopes (Murray-Wallace and Woodroffe,
91 2014; Pedoja et al., 2018). When relative sea-level drops, the reef emerges, fossiliz-
92 es, and forms a CRT. The joint effects of sea-level oscillations and tectonic uplift re-
93 sult in the generation of CRT sequences whose staircase geometries are largely
94 structured by sea level highstands (e.g., Chappell, 1974; Pirazzoli, 2005). The CRTs
95 in Sumba Island are worldwide recognized (e.g., Murray-Wallace and Woodroffe,
96 2014) and associated with an active fringing reef. They are drained by a fluvial sys-
97 tem associated with deep canyons. The relative sea level due to Pleistocene glacio-
98 eustatic oscillations, coastal tectonic uplift and the dynamics of the incising channels
99 fingerprints the successive emergences of the coral reef terraces (Nexer et al., 2015,
100 Pedoja et al., 2011; 2014). The major rivers, embedded into the CRT sequence, dis-

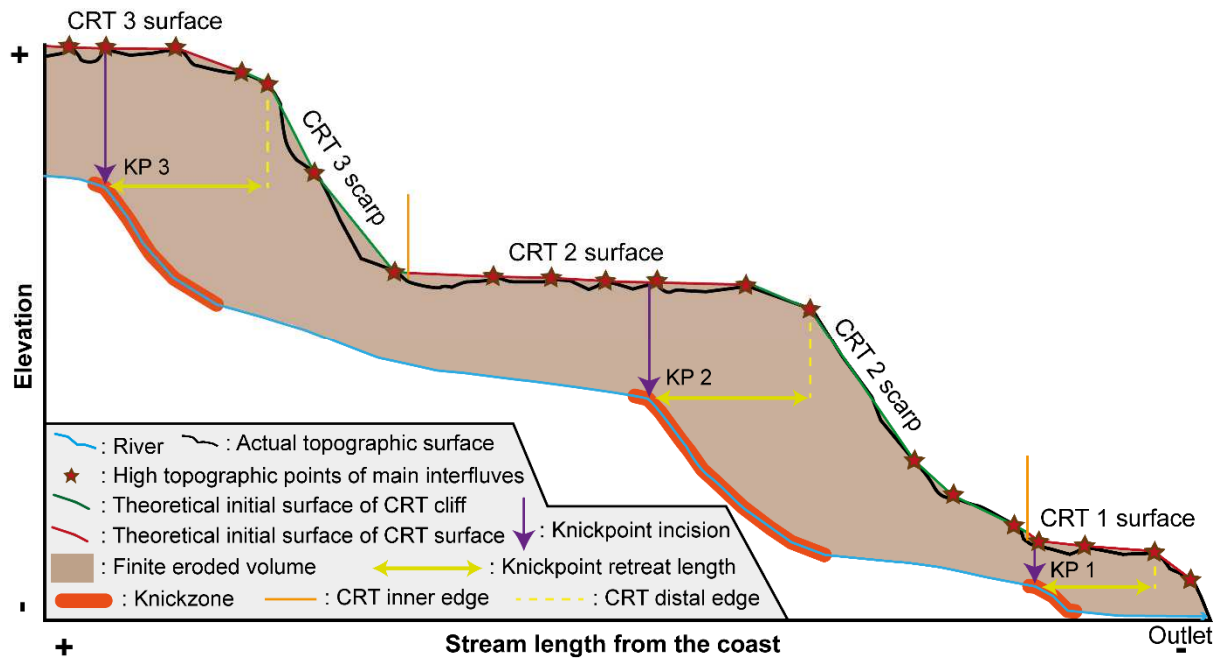
101 play pronounced knickpoints (Nexer et al., 2015). At a first order, the longitudinal pro-
102 file of the rivers mimic the profile of the CRT sequence: the amplitude of knickpoints
103 correlates with the amplitude of the CRT topographic steps.



104

105 **Fig. 1.** Eustatic-triggered knickpoint dynamics, in **A)** coastal environment with offshore linear ramp and **B)** coastal zone with
 106 emerged coral reef terraces (CRTs), and their association with the distal edge of CRTs.

107 We thus hypothesize that knickpoints are generated at the distal edge of the CRT,
108 along streams draining an emerged CRT sequence (Fig. 1B). These knickpoints are
109 better expressed than the knickpoints associated with marine terraces because they
110 initially adopt the downstream break in slope of the reef, which is more pronounced
111 than that of a rocky-shore platform from which marine terraces originate (e.g., Castillo
112 et al., 2013). The upstream migration of knickpoints associated with their erosion is
113 produced by the sediment load and the river flow that collectively allow the river to
114 rebalance itself. The distance of a knickpoint from the distal edge of the associated
115 CRT yields the upward retreat length knickpoint migration since the occurrence of the
116 eustatic drop (Figs. 1B; 2). In addition, the coral colonies from a CRT can be dated
117 (e.g., U/Th and ESR-dating; Pirazzoli et al., 1991; Bard et al., 1996), which allows
118 inference of the propagation rates of the knickpoints. Moreover, the propagation rates
119 of active knickpoints can be additionally measured by quantifying denudation rates
120 from terrestrial cosmogenic nuclides (e.g., ^{10}Be or ^{36}Cl) both upstream and down-
121 stream of the knickpoint (e.g., Brocard et al., 2016). Finally, the finite eroded volume
122 at the catchment scale can also be determined from the difference between the cur-
123 rent topography and the reconstructed surface of the original sequence (Fig. 2; e.g.,
124 Molliex et al., 2016). This finite eroded volume at a catchment scale can be com-
125 pared with denudation rates deduced from terrestrial cosmogenic nuclides measured
126 at the catchment outlet. We applied this multi-method approach with high resolution
127 topographic data (Pleiades imagery) to characterize the dynamics of coastal chan-
128 nels draining the CRT sequence of Sumba Island (Indonesia).



129 **Fig. 2.** 2D sketch of a theoretical river draining a CRT sequence, showing the princi-
 130 ple of the method of the finite eroded volume calculation (Sections 3.3. and 4.3).

131

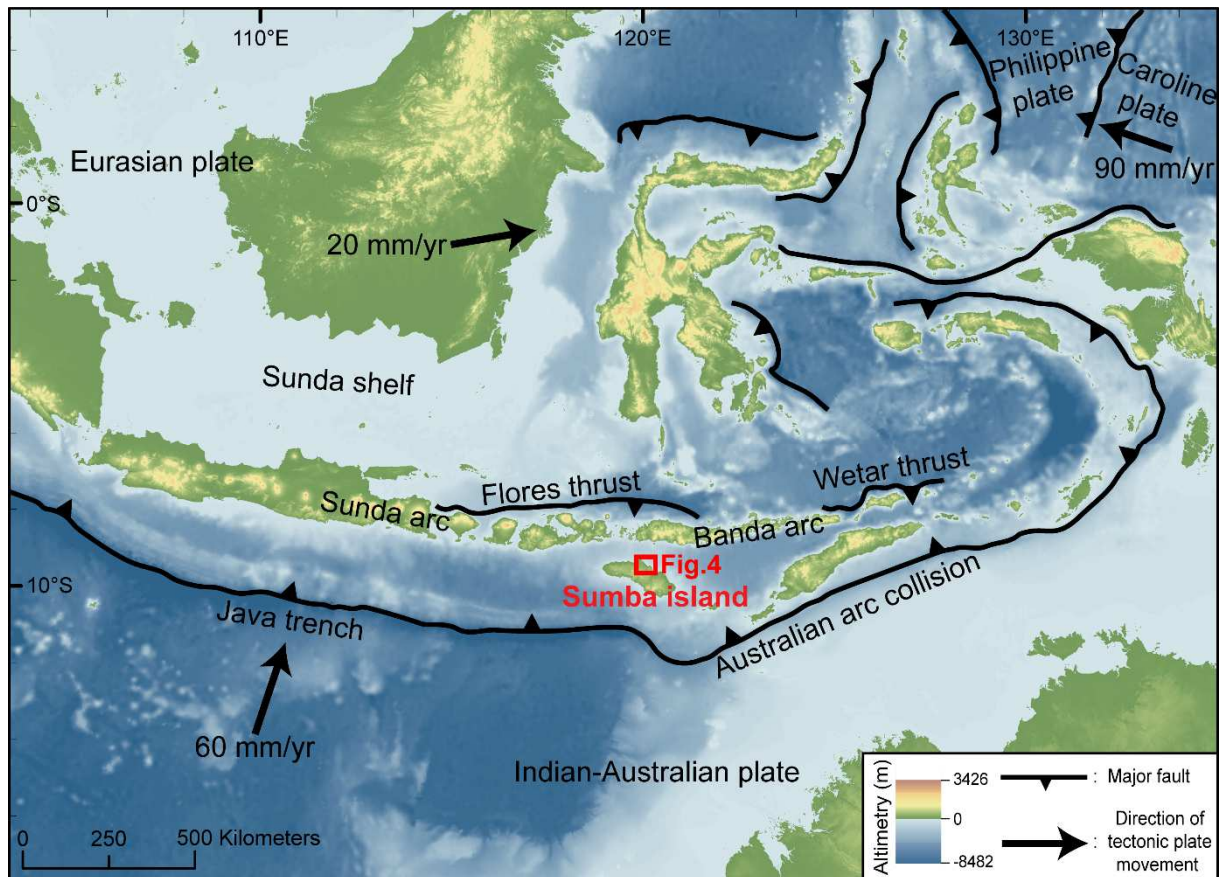
132 We selected a catchment draining the well-documented coastal sequence of CRTs at
 133 Cape Laundi. We detected knickpoints on the longitudinal profile of the main stream,
 134 the majority of which are associated with a CRT distal edge, and we calculated
 135 knickpoint retreat lengths, finite vertical incision and detrital cosmogenic nuclide ^{36}Cl
 136 denudation rates along the channel profile. These data constrain the eustatic knick-
 137 point dynamics at short (10^3 yr, inferred from ^{36}Cl denudation rate), medium (10^4 and
 138 10^5 yr, inferred from knickpoint retreat since a given MIS highstand) and long-term
 139 (10^6 yr, inferred from the finite eroded volume of the whole quaternary CRT se-
 140 quence). We complete the study of the dynamics of coastal transient landscapes by
 141 exploring the correlation between catchment-scale denudation rates, finite eroded
 142 volume, uplift rate, and catchment drainage area and mean slope. We analyzed the
 143 topography of five coastal catchments affected by various uplift rates and quantify
 144 ^{36}Cl -derived catchment-scale denudation rates.

145 **2. Settings**

146

147 Sumba Island is a 220 km-long and 65 km-wide island situated in the Sunda-Banda
148 fore-arc region (Fig. 3).

149

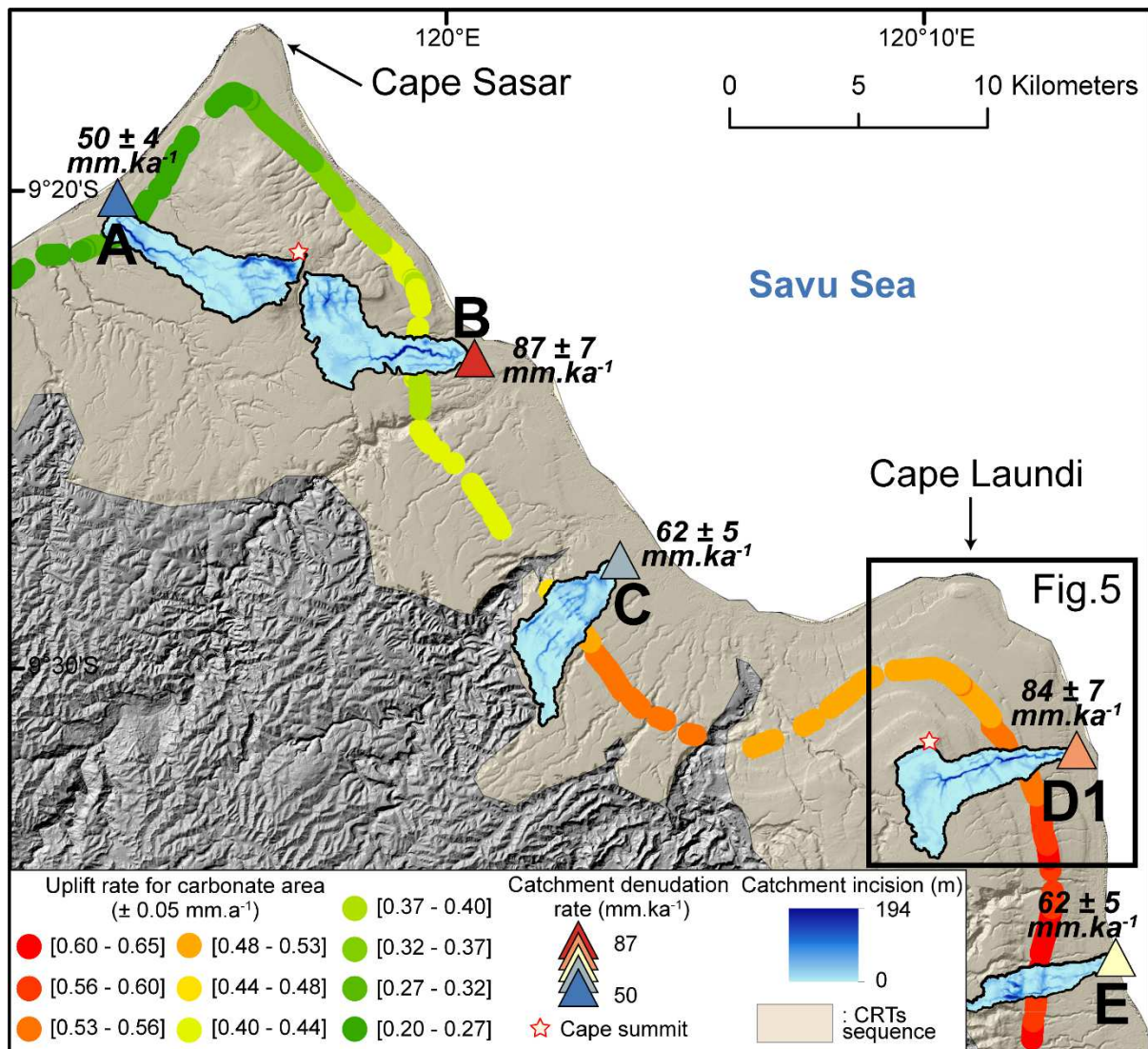


150 **Fig. 3.** Geodynamics of SE Asia and location of Sumba Island (Indonesia). Plate ve-
151 locities indicated with respect to Eurasia plate, from Nugroho et al. (2009), elevation
152 data from the Shuttle Radar Topography Mission (SRTM) and bathymetry data from
153 the General Bathymetric Chart of Oceans (GEBCO).

154

155 It lies at the convergent boundary between the Eurasian and Indian-Australian plates.
156 This places it near the transition from oceanic subduction to the West, along the Java
157 trench, to the collision of the Banda arc with the continental Indian-Australian plate to
158 the East (Hirschberger et al., 2005). Sumba Island is the emergent portion of the
159 Sumba Ridge, an isolated tectonic block of crystalline basement located halfway be-
160 tween the Sunda trench and the active volcanic arc (e.g., Fortuin et al., 1997). Sub-
161 duction of thick buoyant continental Australian crust under the Banda arc started dur-
162 ing the Late Miocene and induced uplift and emergence of the Sumba ridge (Harris,
163 1991; Fortuin et al., 1997; Hall and Smyth, 2008; Haig, 2012). The ensuing uplift is
164 responsible for (1) the diachronic emergence of Sumba starting ~3 Ma ago (Roep
165 and Fortuin, 1996) in the east, and ~1 Ma ago at Cape Laundi (Pirazzoli et al., 1991;
166 1993; Fig. 4), (2) the formation of an emerged CRT sequence along the northern,
167 western and eastern flanks of the island (Hantoro, 1992; Fleury et al., 2009; Nexer et
168 al., 2015), and (3) coeval south-verging collapse of the southern flank of the island
169 (Fleury et al., 2009). Sumba island consists of Late Cretaceous and Eocene–
170 Oligocene volcanic rocks largely covered by Miocene to Quaternary sediments (Ab-
171 dullah et al., 2000). The sedimentary cover is composed of the Waikabubak lime-
172 stones (Mio–Pliocene), Kannangar limestones and turbiditic sandstones (Mio–
173 Pliocene), and Quaternary reefal limestones (i.e. CRTs) that festoon two thirds of the
174 coastline (Rutherford et al., 2001). The CRT sequence in Cape Laundi develops over

175 the Mio-Pliocene limestones and is incised by linear streams embedded in canyons
176 of decametric depths. These valleys result from tectonic uplift and karstic processes
177 and only seldom reach the Mio/Pliocene basement.



178 **Fig. 4.** Map of catchments incision and uplift rates of the studied zone, near Cape
 179 Laundi, and location of the sampled catchments. The triangles correspond to the
 180 sampling location, and numbering (e.g., D1). Denudation rates, calculated for each
 181 catchment outlet, are in bold italics (Table 2).

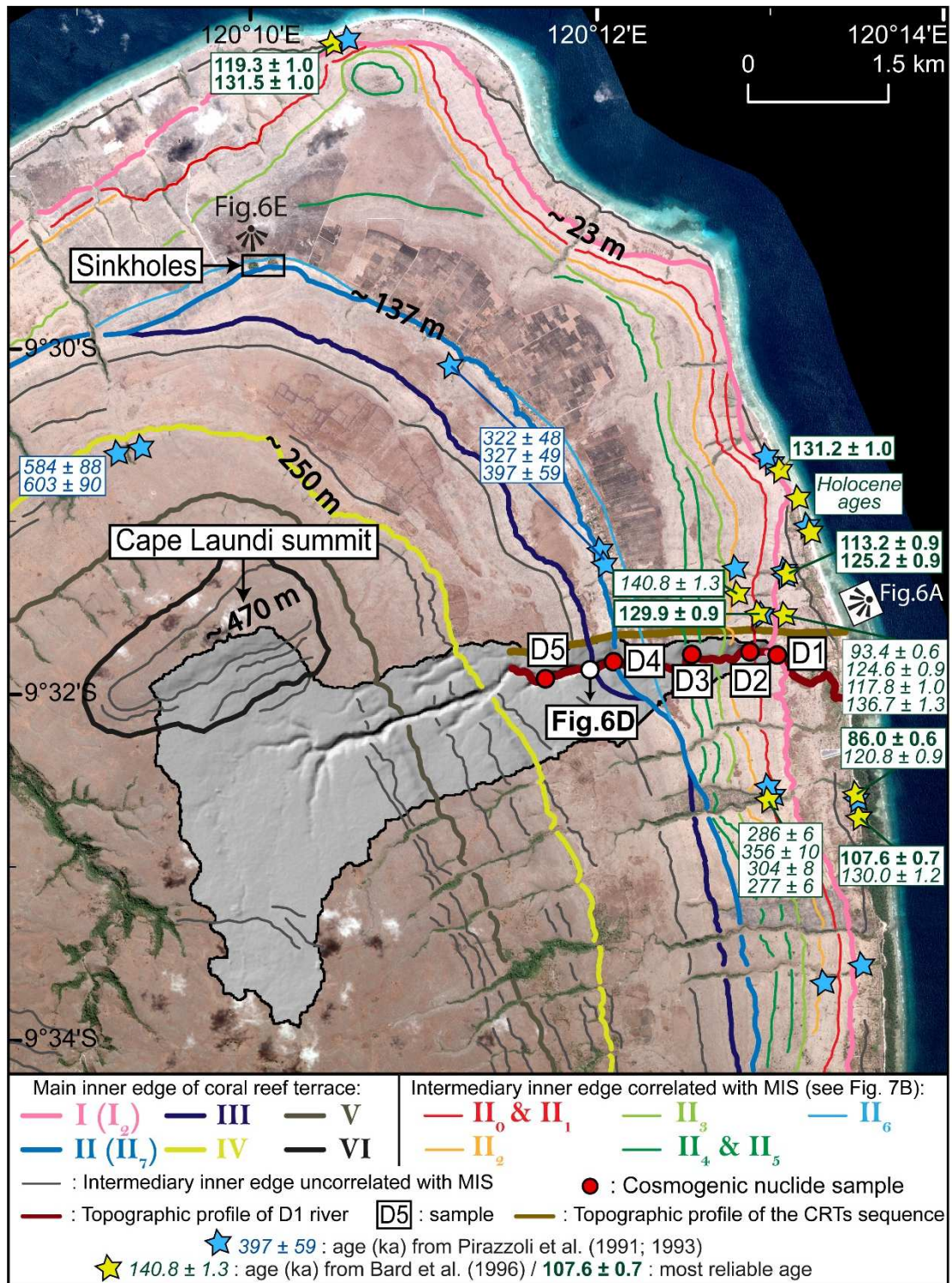
182

183 Detailed studies of the CRT sequences were carried out in our study area at Cape
 184 Laundi (Fig. 5). The sequence reaches ~ 470 m in elevation and has a staircase
 185 shape with six main CRTs separated by continuous high (>10 m) fossil sea cliffs (Pi-
 186 razzoli et al., 1993). Each main CRT includes several intermediate CRTs (Hantoro et
 187 al., 1989; Pirazzoli et al., 1993). Based on ~ 56 $^{230}\text{Th}/\text{U}$ -ages, the successive CRTs

188 were correlated to highstands associated with Marine Isotopic Stage (MIS) 1
189 (~Holocene) to MIS 29 (~1 Ma; Jouannic et al., 1988; Pirazzoli et al., 1991; 1993;
190 Hantoro, 1992; Bard et al., 1996; Chauveau et al., 2021). For the last 600 ka, steady
191 uplift rates are suggested, at $0.49 \pm 0.01 \text{ mm.a}^{-1}$ (Pirazzoli et al., 1991; 1993) and
192 from 0.20 to 0.50 mm.a^{-1} (Bard et al., 1996). The distal edge of the CRT associated
193 to MIS 11c (i.e. CRT III; Fig. 5), well-marked in the landscape and laterally continu-
194 ous on all the coastal stretch covered by the CRT sequence of Sumba Island, was
195 used as a morphological benchmark to calculate uplift rate all along the western,
196 eastern and northern coasts of Sumba Island (Nexer et al., 2015). The uplift rates
197 range from 0.02 to 0.06 mm.a^{-1} (Nexer et al., 2015).

198

199 Downstream, the active reef contains live coral colonies, which mostly develop on the
200 reef crest and fore reef, with micro-atolls of *Porites* and a few branching corals (Han-
201 toro, 1992). The back reef and reef flat comparatively bear a low density of living cor-
202 als (i.e. coral cover < 10%) and a coral-algal environment. Most species tolerate epi-
203 sodic emergence and water turbidity (e.g., *Goniastrea retiformis*, *Acropora digitifera*;
204 Bard et al., 1996).



205 **Fig. 5.** CRTs at Cape Laundi. The map is drawn on a Pleiades satellite imagery with
 206 a 1 m resolution. Location of samples (D2, D3, D4 and D5) and outlet sample (D1)
 207 and topographic profiles. Some data from Pirazzoli et al, (1991; 1993) are not located
 208 on the map because their coordinates were not provided.

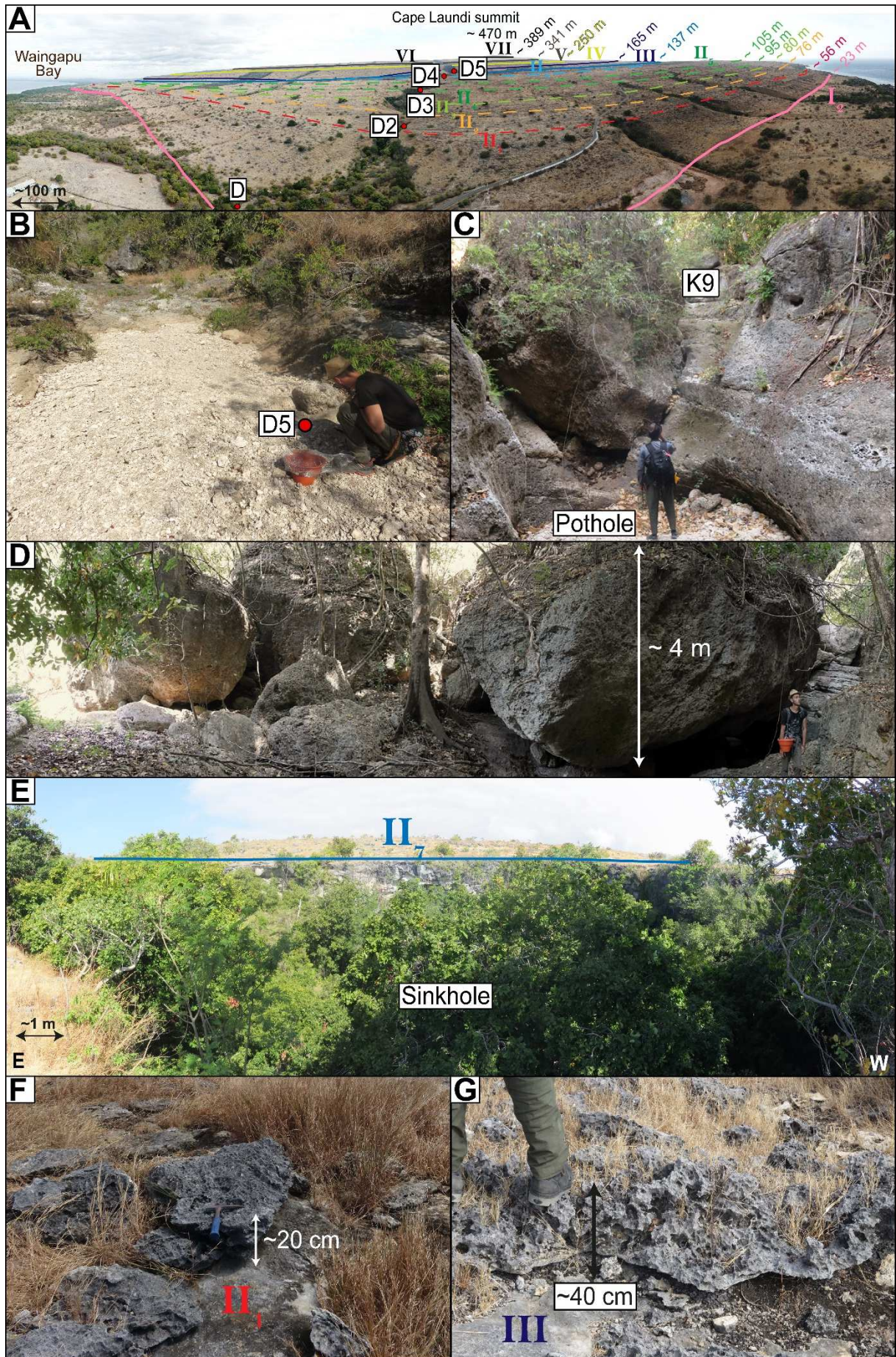
209

210 **3. Methods**

211 **3.1. Quantifications of knickpoint incisions**

212

213 We selected a coastal channel draining the well documented and dated sequence of
214 Cape Laundi (catchment D1; Figs. 4; 5; Jouannic et al., 1988; Hantoro, 1992; Piraz-
215 zoli et al., 1993; Bard et al., 1996; Chauveau et al., 2021) for which we assembled a
216 high-resolution digital elevation model from Pleiades satellite imagery. The stream is
217 embedded in a deep canyon ranging from 0 to 70 m depth. In addition to chemical
218 erosion affecting the CRTs, uplift allows characterizing this canyon as a tectonic
219 gorge. We walked upstream from the sea outlet, following the riverbed to D5 sam-
220 pling site (Figs. 5; 6A). Beyond this point, the vegetation in the riverbed is too dense
221 to continue. Downstream, the vegetation is concentrated in the lateral slopes of the
222 canyon (Fig. 6A). During our field campaign (July 2018; i.e. during the dry season),
223 the river was dry, which points to an intermittent seasonal cycle (i.e. an activity during
224 the rainy season from November to April; Prasetia et al., 2013; Figs. 6B; 6C; 6D).
225 Yet, the vegetation on the cliff slopes ensures constant humidity in the confined
226 space of the canyon and helps the formation and leaching of soil towards the riv-
227 erbed, thus supplying sediment load of the catchment. During the rainy season, large
228 blocks detach from the slopes to the riverbed, which increases the (carbonate) sedi-
229 ment load (Fig. 6D).



230 **Fig. 6.** Interpreted pictures of the Cap Laundi emerged CRT sequence and the can-
231 yon draining them (catchment D1). **A)** Aerial photo of Cape Laundi showing the stair-
232 case coastal landscape (location of capture on Fig. 5). **B)** Sampling site of sample
233 D5. **C)** Knickpoint K9 (see location on Fig. 7B). **D)** Collapsed blocks in the canyon
234 (location on Fig. 5). **E)** Sinkhole of Cape Laundi (location on Fig. 5). Epikarst on the
235 surface of CRT **F)** II₁ and **G)** III.

236

237 River D1 displays pronounced knickzones that are commonly located by waterfalls
238 that incise the CRTs, sometimes carving potholes (Fig. 6C). These river segments
239 are free of sediments. We mapped all the knickzones along the selected coastal
240 stream from field observations, GPS and DGPS data and satellite imagery (Pleia-
241 des). We identified each eustatic knickpoint that could be associated with the distal
242 edge of a CRT (Fig. 1B). To properly correlate a knickpoint to the CRT distal edge,
243 and therefore to the MIS responsible for the formation of the CRT, we considered that
244 the knickpoint must be 1) located upstream from the CRT distal edge, and 2) topo-
245 graphically lower than the distal edge of the CRT. Above and below the knickpoints,
246 the bedrock is homogeneous and partly covered by sediments (Fig. 6B). Carbonated
247 sands and gravels are abundant enough to allow sampling for ³⁶Cl cosmogenic nu-
248 clide analysis, on both sides of knickpoint, where the stream slope is lower (i.e. sam-
249 pling areas; Fig. 6B).

250

251 We calculated the steepness index for each 100-m-long river segment of D1 channel
252 (e.g., Wobus et al., 2006; Kirby and Whipple, 2012; Castillo et al., 2014). Under
253 steady state conditions, fluvial channels can be conveniently reconstructed using a
254 power-law relationship (Flint, 1974):

255

$$256 \quad S = k_s a^{-\theta}, \quad (1)$$

257 where k_s is the steepness index, S is the slope, a is the upstream catchment area,
258 and θ is the concavity index. Because concavity varies among rivers and that varia-
259 tion leads to large changes in k_s , the steepness index is often expressed in a normal-
260 ized form, k_{sn} , by using the same reference concavity, θ_{ref} , for all channels being ana-
261 lyzed (e.g., Snyder et al., 2000; Duvall et al., 2004; Kirby and Whipple, 2012), such
262 that:

263

$$264 \quad S = k_{sn} a^{-(\theta_{ref})}, \quad (2)$$

265 where $\theta_{ref} = 0.45$ is a standard value in the literature. k_{sn} values increase drastically
266 downstream knickpoints.

267

268 The mobility of knickpoints can be inferred from a slope-area relationship (Kirby and
269 Whipple, 2012). Vertical-step knickpoints are stationary and reveal discrete hetero-
270 geneities whereas knickpoints that represent a break in slope-area scaling typically
271 develop in response to a persistent change in forcing, either spatial or temporal (Kir-
272 by and Whipple, 2012).

273

274 **3.2. Denudation rate inferred from terrestrial Cosmogenic Nuclide ^{36}Cl Con-** 275 **centration (CNC)**

276

277 To examine the relationships between denudation rates, uplift rate and catchment
278 metrics, we selected five catchments in the same area along the central part of the
279 northern coast of Sumba. They collectively only drain the CRT sequence, but uplift at
280 variable rates (from 0.2 to 0.6 mm.a⁻¹; Fig. 4). We sampled sands at river outlets to

281 measure the ^{36}Cl cosmogenic nuclide concentration. To evaluate the spatial varia-
282 tions of denudation rate along a coastal channel due to its transient state, we sam-
283 pled at five sites separated from one another by knickpoints (catchment D1; Fig. 5).

284

285 Cosmogenic nuclide ^{36}Cl is appropriate for reefal limestones. Carbonate rocks accu-
286 mulate ^{36}Cl cosmogenic nuclides over the uppermost meters of soil because of the
287 interactions of Ca with secondary cosmic rays (e.g., Stone et al., 1994). After some
288 exposure, ^{36}Cl concentration will rise and plateau to value determined by the trade-off
289 between ^{36}Cl production rate and surface denudation rate (Bierman, 1994). ^{36}Cl con-
290 centration is inversely proportional to the surface denudation rate (e.g., Granger and
291 Riebe, 2014). ^{36}Cl concentrations of river sediments thus scale with average denuda-
292 tion rate over the catchment (Brown et al., 1995; Bierman and Steig, 1996; Granger
293 et al., 1996). The time scales over which denudation rates are averaged are inversely
294 proportional to denudation rate and is approximately equivalent to the time required
295 to remove ~ 60 cm of bedrock (von Blanckenburg, 2005).

296

297 We used a standard chlorine extraction technique with leaching to eliminate any po-
298 tential meteoric ^{36}Cl (Stone et al., 1996; Merchel et al., 2008; Schlagenhaut et al.,
299 2010). Each sample was washed and the fraction 250-1000 μm extracted. About
300 ~ 100 g of each sample is used for chemical analysis. Major oxides (SiO_2 , TiO_2 ,
301 Al_2O_3 , Fe_2O_3 , MnO , MgO , CaO , Na_2O , K_2O , P_2O_5) and trace elements (Li, Be, Mo,
302 Ba, Sm, Gd, Pb, Th, U, Sc, Cr, Cr, Co, Ni, Rb, Sr) have been measured on bulk
303 samples (i.e. the fraction finer than 250 μm collected after crushing), respectively by
304 an ICP AES - Ultima 2 - Jobin Yvon and a HR-ICP-MS Element XR, at the LGO (La-
305 boratoire Géosciences Océan, IUEM) in Brest (France). CO_2 concentration is deter-

306 mined by weighing the samples, dissolving them in a Gas Bench and measuring the
307 CO₂ produced (Pôle de Spectrométrie Océan, Plateforme Isotopes Stables, IUEM,
308 Brest, France). Cl isotopic ratio was measured by Accelerator Mass Spectrometry
309 (AMS) at CEREGE (Centre de Recherche et d'Enseignement de Géosciences de
310 l'Environnement) in Aix-en-Provence (France). Analytical uncertainties include uncer-
311 tainties associated with AMS counting statistics, chemical blank measurements, and
312 AMS internal error (0.5%). ³⁶Cl production and denudation rates were calculated fol-
313 lowing Schimmelpfennig et al. (2009) taking into account sea-level and high-latitude
314 production rates for rapid neutron spallation reactions in Ca (42.2 ± 2 atoms ³⁶Cl (g
315 Ca⁻¹ a⁻¹); Braucher et al., 2011; Schimmelpfennig et al., 2011; 2014), negative muons
316 (Heisinger et al, 2002), rate of epithermal neutron production from fast neutrons (Phil-
317 lips et al., 2001) and production from radiogenic neutrons (Fabryka-Martin, 1988;
318 Phillips and Plummer, 1996; more information related to ³⁶Cl production is detailed in
319 Appendix "A" of Schimmelpfennig et al., 2009). The effective fast neutron attenuation
320 coefficient is 177 ± 4 g.cm⁻² (Farber et al., 2008). Topographic shielding was calcu-
321 lated for each sample (i.e. average over the whole catchment) using the topographic
322 shielding add-in for ArcGIS software (Codilean, 2006). The scaling factors for nucle-
323 onic and muonic production are calculated with CosmoCalc 1.7 macro (Vermeesch,
324 2007; Dunai, 2010) and with the mean elevation, longitude and latitude of each
325 catchment.

326

327 The uncertainty on the extent of the actual catchment area contributing to stream
328 sediments adds to the uncertainty of the measured ³⁶Cl concentrations. The sub-
329 horizontal parts of the catchment area (i.e. the CRT surfaces) will mainly be affected
330 by chemical erosion, by means of sinkholes and epikarsts (Figs. 5; 6E; 6F; 6G; e.g.,

331 Authemayou et al., 2018; Chauveau et al., 2021). Consequently, it is difficult to quan-
332 tify dissolution inputs to karst surfaces and thus catchment parts that do not signifi-
333 cantly contribute to canyon inputs. To overcome this problem, we assume that the
334 overwhelming majority of the sediment supply comes from the canyon area itself, that
335 we define as a valley wherein slopes are systematically greater than $\sim 10^\circ$. To obtain
336 the maximum and minimum limits of the sediment supply area, we calculated the
337 denudation rates both for the whole drainage area extracted automatically with the
338 Digital Elevation Model (DEM), and for the canyon area only.

339

340 **3.3. Catchment metric and finite eroded volume of the emerged coral reef ter-** 341 **race sequence**

342

343 Morphometric parameters were computed for each catchment from the 12 m Tan-
344 DEM-X (the elevations are converted to orthometric heights; Boulton and Stokes,
345 2018) using Rivertools (<http://rivix.com/>) to determine if the catchment denudation
346 rate is a function of internal parameters. We extracted for each catchment the drain-
347 age area (catchment versus canyon), the finite eroded volume and the mean slope of
348 the canyon. In view of the particular morphology drained by the catchments, it is nec-
349 essary to also focus on the catchment metric parameters and finite eroded volume
350 restricted to the canyon areas that concentrate most of the mechanical erosion.

351

352 We calculated the uplift rates using the present-day elevation of the CRT III distal
353 edge (± 2 m at Cap Laundi, and ± 12 m on the rest of the island), correcting for eu-
354 stasy, during MIS 11c (-1.5 ± 11 APSL; Bowen, 2010), and assigning an age of $390 \pm$
355 20 ka to MIS 11c (Murray-Wallace and Woodroffe, 2014). We attribute a mean uplift

356 rate to each catchment with the uplift rate values calculated along the MIS 11 CRT
357 segment located on their drainage area.

358

359 To assess the lateral continuity of the CRT sequence, we also make use of stacked
360 swath profiles (Armijo et al., 2015; Fernández-Blanco et al., 2019). These are con-
361 structed using a large number of parallel swath profiles (here 600) to derive a 2.5-D
362 view of the landscape. Areas of the overall morphology with several lines stacked
363 together denote relatively flat surfaces separated by more or less steep slopes; in this
364 case, the CRTs of the sequence.

365

366 Long-term denudation estimates from finite eroded volume were obtained by sub-
367 tracting the actual topography (TanDEM-X and Pleiades imagery DEM) from a re-
368 constructed topography that attempts to compensate the effects of erosion. We com-
369 puted this theoretical uneroded surface from envelope of the highest points of the
370 sequence, after extraction of high points and main interfluves from the DEM, using
371 the “Topo to Raster” tool in “Spatial Analyst” extension of ArcGis software (e.g., Small
372 and Anderson, 1998; Molliex et al., 2016; Fig. 2). This tool interpolates the elevation
373 values of a raster by imposing constraints to ensure a drainage structure that is con-
374 nected and the correct representation of ridges and streams from the input isoline
375 data. The volume yielded by such an approach requires a subjective adjustment, for
376 it relies on the number of control points selected to reconstruct the purportedly pris-
377 tine topography (Lucazeau and Hurtrez, 1997; Champagnac et al., 2012). If such
378 points are too sparse, some reliefs may not be taken into account and the interpolat-
379 ed envelope can locally be lower in elevation than the actual topography. On the con-
380 trary, oversampling the topography yields an interpolated envelope that is close to

381 present-day topography. The difference between present-day topography elevation
382 and the reconstructed surface yields the minimum finite eroded volume by coastal
383 channels, since CRT distal edges experienced in-situ denudation (Chauveau et al.,
384 2021). In this study, because of the staircase morphology of the sequence, with a
385 fossil sea cliff separating successive CRTs, the finite eroded volumes are first calcu-
386 lated for the main surfaces of the CRT and then for the cliffs between two CRTs (Fig.
387 2). We assumed that the total finite eroded volume yielded by such a method globally
388 represents the finite eroded volume of coastal drainage since the beginning of the
389 incision following the emergence of the oldest CRT giving a mean long-term denuda-
390 tion rate of ~ 1 Ma at Cape Laundi (Pirazzoli et al., 1991). We also used this method
391 to calculate the maximum vertical incision of the knickpoint and the vertical incision
392 all along the stream profile of catchment D1 (Fig. 2).

393

394 **4. Results**

395 **4.1. Catchment D1: Morphological characteristics and knickpoints**

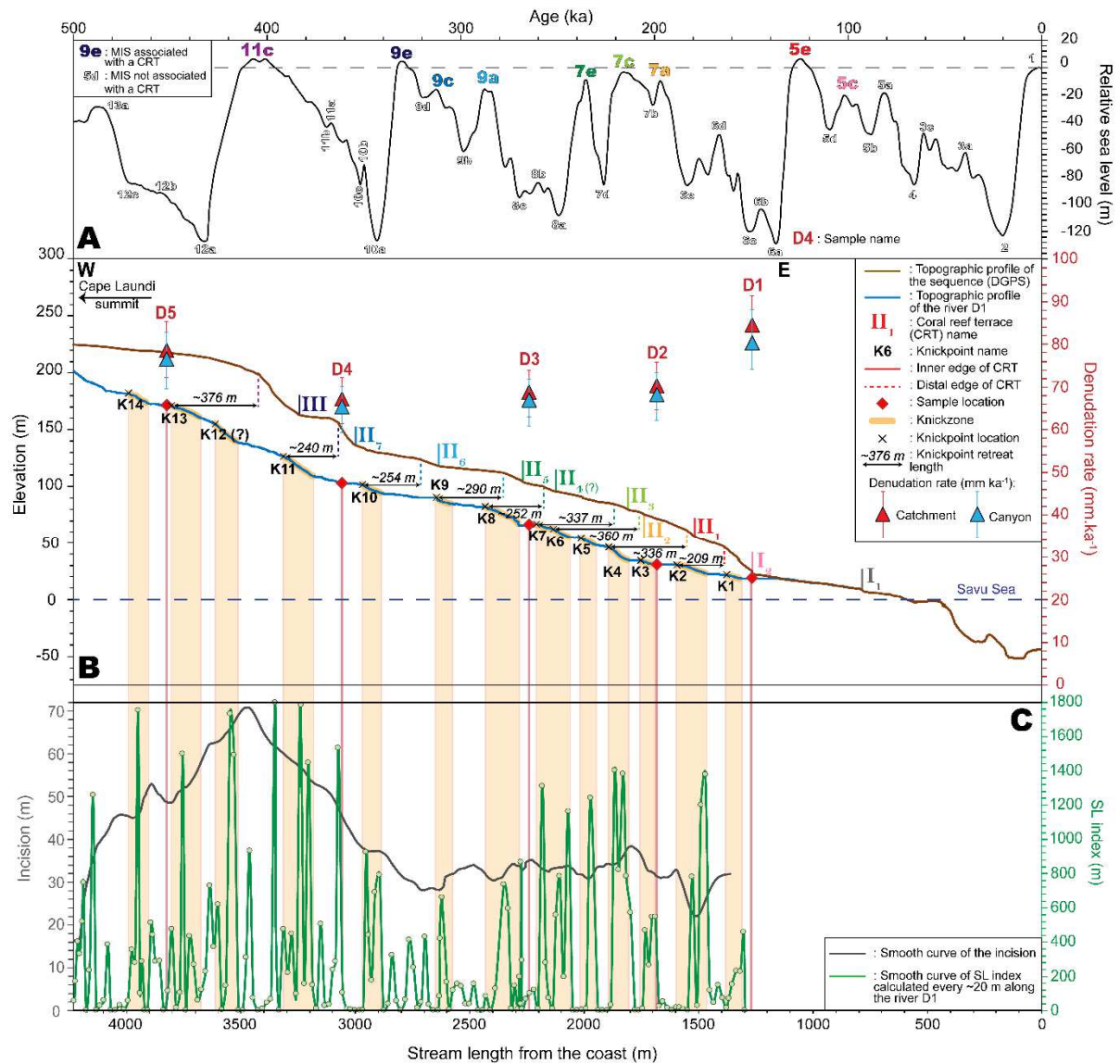
396

397 Catchment D1 is small (10.9 km^2 ; Table 1) and its main stream ($\sim 7.6 \text{ km}$) is almost
398 linear and deeply incises the CRT sequence in a canyon (Figs. 5; 6A; 7; 8A). Except
399 within the canyon, the staircase morphology of the CRT sequence is well preserved.
400 The drainage area restricted to the canyon is 1.2 km^2 (Table 1).

Catchment name	Mean elevation (m)	Catchment area (km ²)	Canyon area (km ²)	Uplift rate (mm a ⁻¹)	Mean slope of canyon area (°)	Finite eroded volume of catchment (km ³ ; $\pm 1.10^{-6}$)	Finite eroded volume of canyon area (km ³ ; $\pm 1.10^{-5}$)
A	196	11.8	1.5	0.27 \pm 0.03	15.3	0.0638	0.0271
B	220	12.2	3.9	0.39 \pm 0.03	12.3	0.0699	0.0505
C	216	9.5	1.7	0.45 \pm 0.04	10.6	0.0434	0.0199
D1	343	10.9	1.2	0.51 \pm 0.04	17.9	0.0434	0.0209
E	239	4.4	1.3	0.61 \pm 0.04	13.4	0.0264	0.0152

401 **Table 1.** Synthesis of metrics from studied catchments in Sumba Island.

402 We identified 14 knickpoints along the stream profile from the outlet up to 4 km up-
403 stream (Figs. 7; 8B; 8C). The majority of these knickpoints are also highlighted by
404 higher steepness index (i.e. k_{sn}) values downstream than upstream (Fig. 8C). Nine of
405 them have been correlated with distal edges of CRTs and assigned to sea level high-
406 stands (Figs. 7A; 7B; Pirazzoli et al., 1991; 1993; Bard et al., 1996). More specifically,
407 K2, K4, K6, K7/K8, K9, K10, K11, and K12 are respectively associated with regres-
408 sions following MIS 5e, MIS 7a, MIS 7c, MIS 7e, MIS 9a, MIS 9c, MIS 9e and MIS
409 11c highstands (Figs. 7A; 7B). Their retreat lengths range from 209 to 376 m (Figs.
410 7B). Five small knickpoints could not be correlated to any CRT (K1, K3, K5, K12 and
411 K14; Fig. 7B).



412 **Fig. 7.** The knickpoints of the Cape Laundi river. **A)** Relative sea level curve from
 413 Waelbroeck et al. (2002). **B)** Elevation profiles (derived from Pleiades DEM and GPS
 414 measurement) of the Cape Laundi main river (catchment D1) and associated profile
 415 of the emerged CRT sequence, in relation with the calculated cosmogenic ³⁶Cl denu-
 416 dation rates with catchment areas extracted from DEM (red triangles) and with can-
 417 yon areas (blue triangles), as well as the location of knickzones (orange areas), distal
 418 edge of CRT and knickpoint retreat length. **C)** Incision (black line) and SL index
 419 (green line and marks) along the stream profile.

420 **4.2. Denudation rates inferred from Cosmogenic Nuclide ^{36}Cl Concentration**
421 **(CNC)**

422

423 Catchment denudation rates calculated for the five selected catchments (Fig. 4)
424 range from $50 \pm 4 \text{ mm.ka}^{-1}$ (sample A) to $87 \pm 7 \text{ mm.ka}^{-1}$ (sample B) with an average
425 of $69 \pm 8 \text{ mm.ka}^{-1}$ ($n = 5$; Table 2). Catchment denudation rates calculated for the
426 canyon area range from $49 \pm 4 \text{ mm.ka}^{-1}$ (sample A) to $87 \pm 7 \text{ mm.ka}^{-1}$ (sample B)
427 with an average of $68 \pm 8 \text{ mm.ka}^{-1}$ ($n = 5$; Table 2). Along the river of catchment D1,
428 denudation rates range from $69 \pm 5 \text{ mm.ka}^{-1}$ (sample D4) to $78 \pm 7 \text{ mm.ka}^{-1}$ (sample
429 D1) with an average of $71 \pm 5 \text{ mm.ka}^{-1}$ ($n = 5$; Table 2; Fig. 7B). Samples D4, D3, D2
430 present comparable low values, whereas D5 and D1 have the highest denudation
431 rate values (Table 2; Fig. 7B). In this study, the calculated integration times of denu-
432 dation rates range from $6.9 \pm 0.5 \text{ ka}$ (highest denudation rates; sample B) to $12.0 \pm$
433 0.8 ka (lowest denudation rates; sample A), with an average of $8.8 \pm 1.6 \text{ ka}$ ($n = 5$;
434 Table 2).

435

Sample	Information	Longitude	Latitude	Elevation	N_{meas}	$\frac{S_{\text{el,s}}}{S_{\text{el,n}}}$	$S_{\text{el},\mu}$	P_s	P_{eth}	P_{th}	P_{μ}	P_r	Denudation rate of whole catchment	Denudation rate of canyon	Integration time
		(E)	(N)	(m)	(10^6 atom g^{-1} rock)	(\pm 0.04)	(\pm 0.03)	($\text{g}^{36}\text{Cl}^{-1}\text{yr}^{-1}$)	($\text{g}^{36}\text{Cl}^{-1}\text{yr}^{-1}$; ± 0.01)	($\text{g}^{36}\text{Cl}^{-1}\text{yr}^{-1}$; ± 0.02)	($\text{g}^{36}\text{Cl}^{-1}\text{yr}^{-1}$)	($\text{g}^{36}\text{Cl}^{-1}\text{yr}^{-1}$)	(mm ka^{-1})	(mm ka^{-1})	ka
A		119.88	-9.34	10.3	4.39 ± 0.10	0.68	0.65	19.60 ± 0.81	0.09	0.24	3.65 ± 0.91	0.0031	50.1 ± 4.2	49.4 ± 4.2	12.0 ± 0.8
B		120.01	-9.39	12.2	2.35 ± 0.05	0.70	0.65	18.58 ± 0.77	0.04	0.11	3.31 ± 0.83	0.0013	87.0 ± 7.2	86.8 ± 7.2	6.9 ± 0.5
C	drains only car- bonate surfaces	120.06	-9.45	12.5	3.72 ± 0.08	0.69	0.65	19.62 ± 0.81	0.07	0.19	3.81 ± 0.95	0.0020	61.5 ± 5.3	60.6 ± 5.2	9.8 ± 0.7
D1		120.01	-9.39	25.4	2.77 ± 0.06	0.76	0.69	19.02 ± 0.79	0.10	0.33	3.49 ± 0.87	0.0033	84.2 ± 7.0	81.3 ± 6.8	7.1 ± 0.5
E		120.23	-9.60	6.0	3.23 ± 0.07	0.71	0.66	18.69 ± 0.77	0.05	0.16	3.09 ± 0.77	0.0014	61.7 ± 5.0	62.4 ± 5.0	9.7 ± 0.7
D2		120.21	-9.53	30.6	2.91 ± 0.06	0.77	0.69	18.05 ± 0.75	0.08	0.25	2.97 ± 0.74	0.0030	70.3 ± 5.6	68.2 ± 5.4	8.5 ± 0.6
D3	Knicks points (catchment D)	120.21	-9.53	65.2	3.12 ± 0.07	0.77	0.70		0.09	0.28	3.09 ± 0.77	0.0036	68.8 ± 5.4	66.9 ± 5.3	8.7 ± 0.6
D4		120.20	-9.53	103.6	3.19 ± 0.07	0.78	0.70	18.10 ± 0.75	0.09	0.25	3.12 ± 0.78	0.0036	67.3 ± 5.4	65.4 ± 5.3	8.9 ± 0.6
D5		120.20	-9.53	200.3	3.07 ± 0.07	0.79	0.71	19.20 ± 0.79	0.06	0.17	3.62 ± 0.90	0.0024	78.4 ± 6.6	76.5 ± 6.4	7.7 ± 0.5

436

437 **Table 2.** ^{36}Cl concentrations in present-day river sands sampled at catchments outlets, the scaling factor for nucleonic ($S_{\text{el,s}}/S_{\text{el,n}}$)
438 and muonic ($S_{\text{el},\mu}$) production, ^{36}Cl production rate by spallation of target elements (P_s), capture of epithermal neutrons (P_{eth}), cap-
439 ture of thermal neutrons (P_{th}), capture of slow negative muons (P_{μ}), radiogenic ^{36}Cl production rate (P_r) and derived denudation
440 rates.

441 **4.3. Finite eroded volume and vertical incision**

442

443 The finite eroded volumes calculated for the five selected catchments range from
444 $\sim 0.026 \text{ km}^3$ (sample E) to ~ 0.070 (sample B) km^3 with an average of 0.049 ± 0.017
445 km^3 (Table 1). The finite eroded volumes values restricted to canyon range from
446 ~ 0.015 (sample E) to ~ 0.050 (sample B) km^3 with an average of $0.027 \pm 0.013 \text{ km}^3$
447 (Table 1). Therefore, canyons are responsible for $\sim 53 \%$ of the finite eroded volume
448 in average, ranging from $\sim 42 \%$ (catchment A) to $\sim 72 \%$ (catchment B).

449

450 Incision along stream D through the canyon is up to 70 m between knickpoints K14
451 and K10 through CRT older than MIS 9e (Fig. 7B). Maximum incision is found at the
452 distal edge of the CRT associated with the MIS 11c highstand (Fig. 7B). Down-
453 stream, incision values are comparable (~ 35 m) and decrease downstream of the
454 distal edge of the MIS 5e CRT to a few meters (Fig. 7B).

455

456 **4.4. Morphological and environmental parameters of catchments**

457

458 Morphometric parameters computed for the five catchments are summarized in Table
459 1. Uncertainties in the averages correspond to standard deviations. The drainage
460 areas of the catchments range from 4.40 km^2 (catchment E) to 12.23 km^2 (catchment
461 B), with an average of $9.75 \pm 1.60 \text{ km}^2$. The area of the canyon covers a minimum of
462 1.17 km^2 (catchment D1) and reaches a maximum of 3.85 km^2 (catchment B). The
463 mean slope of the catchment ranges from 5.54° (catchment C) to 8.26° (catchment
464 E), and averages to $6.59 \pm 1.05^\circ$. The mean slope restricted to canyons ranges from
465 10.58° (catchment C) to 17.92° (catchment D1), and averages to $13.90 \pm 1.41^\circ$. The
466 uplift rates range from $0.27 \pm 0.02 \text{ mm.a}^{-1}$ (catchment A; Cape Sasar) to 0.60 ± 0.03

467 mm.a⁻¹ (catchment E; North of Waingapu Bay), with an average of 0.45 ± 0.12 mm.a⁻¹
468 (Table 1; Nexer et al., 2015).

469

470 **5. Discussion**

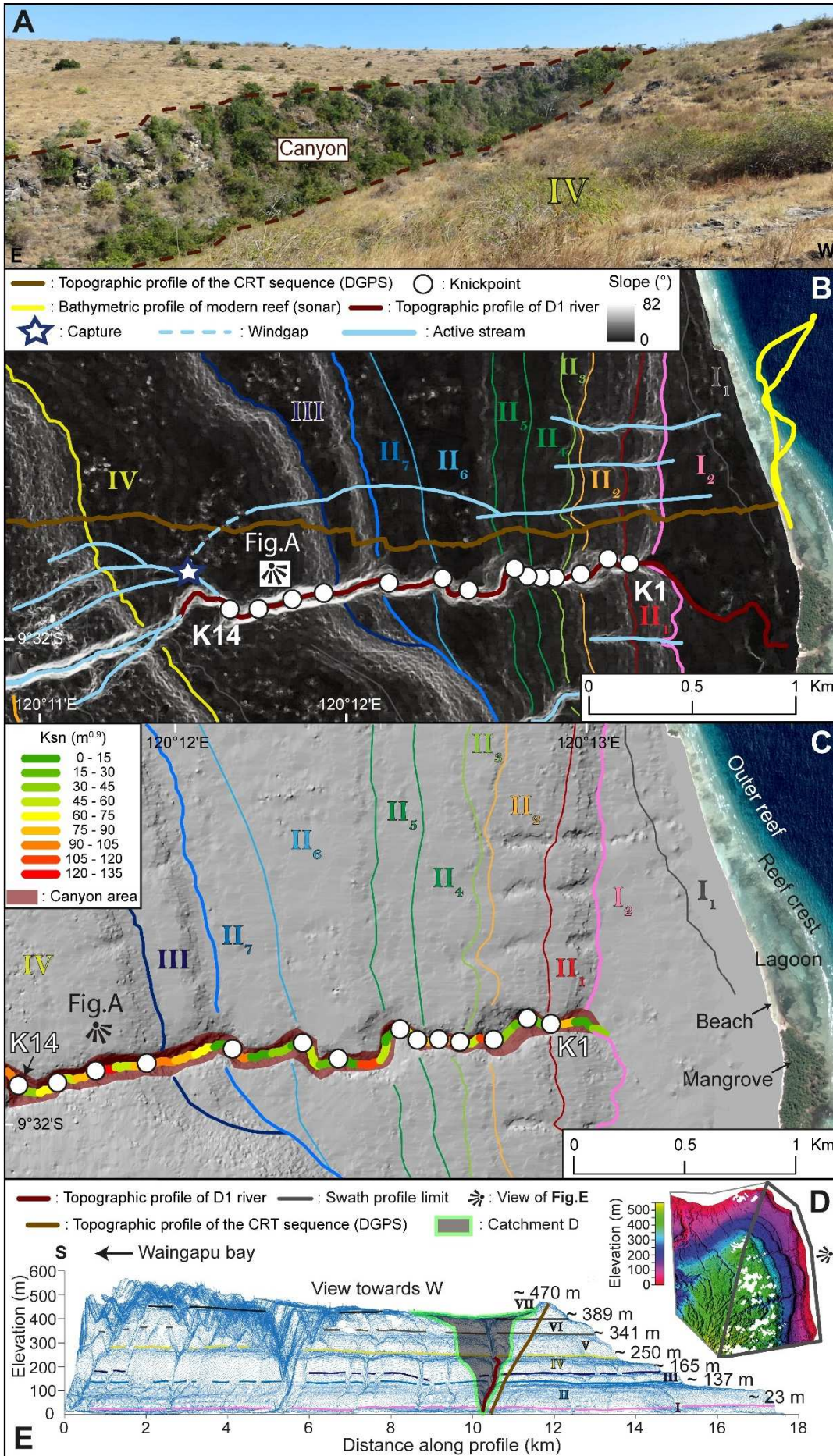
471 **5.1. Eustatic knickpoints on coral reef terraces sequence**

472 **5.1.1. Making the case for eustatic knickpoints**

473

474 Our findings indicate that the majority of the Cape Laundi knickpoints are transient
475 eustatic knickpoints (9 out of 14 knickpoints). First, the knickpoints are easily associated
476 with a CRT distal edge from the geomorphologic profiles, i.e. their point of origin dur-
477 ing the emergence of the CRT and the beginning of their subaerial incision can be
478 easily identified (Figs. 1B; 7B). Then, at the scale of catchment D1, the uplift rate is
479 spatially uniform (no lateral variability in the elevation of the inner edge of each CRT
480 in the catchment area; Fig. 8E) and temporally constant (Pirazzoli et al., 1991; 1993;
481 Nexer et al., 2015). There is no morphological evidence of active faulting (i.e. no line-
482 ar fault scarp was detected on the CRTs' surface), which may rule out the possibility
483 of tectonic knickpoints. The seismicity of the subduction zone on Sumba Island is
484 moderate (e.g., Jones et al., 2014), where no historical earthquakes have produced
485 coastal uplift on the island, and no co-seismic terraces have been observed at Cape
486 Laundi. Therefore, it is unlikely that knickpoints (K1, K3, K5, K12 and K14) are asso-
487 ciated with co-seismic terrace formation. Furthermore, over the studied area, the li-
488 thology is uniform, i.e. exclusively composed of reef limestones, ruling out lithological
489 knickpoints. Also, the catchments are too small to have a significant climatic gradient
490 within the catchment, excluding climatic influence on knickpoint development. Finally,
491 the three conditions that lead to the formation of eustatic knickpoint (following Snyder
492 et al., 2002) are reached: 1) eustatic knickpoints are caused by the emergence of the

493 fore-reef steeper than the upstream channel; 2) wave-base erosion has not balanced
494 the uplift rate otherwise the sequence could not be built; and 3) there are no spatial
495 variations in uplift rates onshore and offshore since the coast is normal to the region-
496 al tectonic tilting axis (Nexer et al., 2015).



498 **Fig. 8. A)** Canyon in catchment D1. **B)** Slope map of the south-east of Cape Laundi,
499 showing the different altimetric profiles (bathymetric and topographic), the location of
500 the knickpoints and the inner edge of the low CRTs. **C)** Hillshade map of the Digital
501 Elevation Model (2 m in resolution) based on Pleiades images southeast of Cape
502 Laundi, showing the canyon area, steepness index values (i.e. k_{sn}) along river D1,
503 knickpoint locations, inner edges of low CRTs, and current coastal morphology
504 (beach, mangrove, fringing reef). **D)** Hillshaded Digital Elevation Model (2 m in reso-
505 lution) from Pleiades images. The white spots inside the hillshade correspond to the
506 clouds in the Pleiades images. **E)** Stacked swath profiles (600 profiles, vertical exag-
507 geration x6, viewpoint location in panel D) and main inner edges of the CRT se-
508 quence at Cape Laundi.

509

510 Five knickpoints of lower amplitude (i.e. the height between the bottom and the top of
511 the knickzone) are not correlated to a CRT (K1, K3, K5, K12, K14). K1 is located just
512 downstream of K2, which was correlated to the post-MIS 5e regression. The CRT
513 associated with MIS 5c does not exhibit a clear distal edge that could be correlated
514 with K1 (Fig. 7B). This CRT was reworked by marine erosion during MIS 5a and Mid-
515 Holocene highstand (Chauveau et al., 2021). Consequently, the distal edge of the
516 MIS 5c CRT has been eroded, excluding a direct correlation of K1 to this CRT. Other
517 explanations can be proposed related to eustatic forcings for K5, K3 and K1. During
518 regression, when sea level reached a lower elevation than the distal part of the newly
519 emerged CRT, an acceleration of the base-level drop could generate a second
520 knickpoint (Cantelli and Muto, 2014). For instance, K5, K3 and K1 are located down-
521 stream of a large knickzone probably related to the onset of a major regression (Fig.
522 7B). Thus, they could have been produced during the sea-level drop. Cantelli and

523 Muto (2014) demonstrate that a single perturbation of base level (e.g., eustatic drop)
524 can generate multiple knickpoints. Therefore, it cannot be excluded that several
525 knickpoints are associated with the same regressive event. Knickpoints could also be
526 produced by a sudden sediment supply locally triggered by landslides on incised
527 stream sides, river captures, or confluences. Confluences may suddenly increase the
528 runoff and sediment supply of the main stream and could thus impact its longitudinal
529 profile (Hayakawa and Matsukura, 2003; Crosby and Whipple, 2006). The location of
530 K14 in the upstream part of the stream profile D at a confluence (Fig. 8B) could ex-
531 plain their formation. Yet, river capture cannot be excluded too, because an inactive
532 secondary pathway to the tributary located in the flat part of CRT IV, upstream of the
533 confluence (Fig. 8B).

534

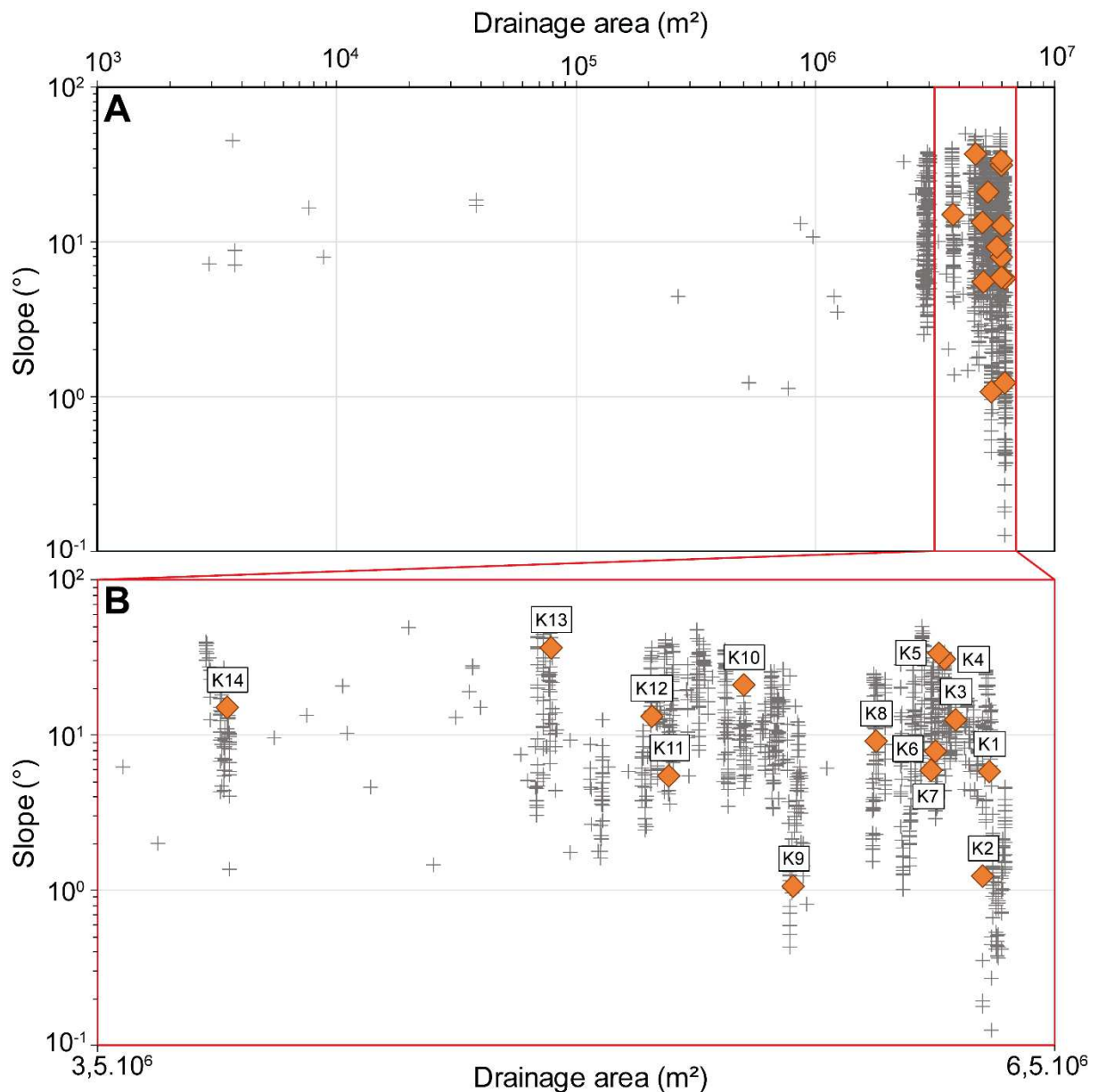
535 **5.1.2. Dynamics of eustatic knickpoints**

536

537 Comparing river profiles with the coastal sequence topographic profiles, we observed
538 that eustatic knickpoints are lower in elevation than their associated CRT distal edg-
539 es, and the morphology of knickpoints is smoother than the staircase shape of the
540 sequence (Fig. 7B). More precisely, the initial steep segment downstream of the
541 knickpoint decreased in slope by rotation of the segment at the base of the knickzone
542 (Gardner, 1983). These observations indicate that these knickpoints have propagat-
543 ed upward with vertical incision and a rotation mode (Gardner, 1983; Castillo et al.,
544 2013). If the erosive efficiency was constant along the stream and if knickpoint retreat
545 was steadily active, an upstream increase in knickpoint retreat length and an up-
546 stream decrease in knickpoint amplitude would be observed (Gardner, 1983;
547 Schumm, 1993; Snyder et al., 2002; Whipple and Tucker, 2002; Loget and Van Den

548 Driessche, 2009). However, our results show that the knickpoint retreat length does
549 not increase upstream (Fig. 7B). The knickpoint retreat lengths are comparable (from
550 209 m to 376 m) and knickpoint morphologies remain preserved, even the earliest
551 ones (300 to 400 ka ago, K11, K13). Furthermore, no relationship can be noticed be-
552 tween the knickpoint retreat lengths and their assumed age ($R^2 = 0.08$; Fig. 10A). It
553 suggests that knickpoint retreats ceased before their full propagation. In addition, the
554 slope-area scaling relationships of the D1 channel (Figs. 9A; 9B) displays a vertical-
555 step knickpoint form, despite the small spacing between each knickpoints, indicative
556 of stationary knickpoints (e.g., Korup et al., 2010; Kirby and Whipple, 2012).

557



558 **Fig. 9.** Slope-area relationship (\log_{10} scale) of river D1. **A)** Full set and **B)** Zoomed-in,
559 with knickpoint values. Each grey cross corresponds to one pixel (4 m^2) along the
560 stream profile of catchment D1.

561

562 The knickpoint activity (or inactivity) may be also highlighted by the values of the
563 denudation rate deduced by the concentration of ^{36}Cl of the samples along stream D.
564 During knickpoint activity, denudation rates should be higher downstream than up-
565 stream (e.g., Brocard et al., 2016). Instead, our results show that denudation rates do
566 not vary between D4 and D2 despite the presence of knickpoints between these
567 samples (Fig. 7B). Even more strikingly, the upstream sample, D5, presents a denu-
568 dation rate higher than the downstream D4 sample (Fig. 7B), although this higher
569 denudation rate could be enhanced by a local increase in stream flow and sediment
570 supply due to the proximity of the sample to an upstream confluence and potential
571 river capture event (Fig. 8B).

572

573 Only samples D2 and D1, upstream and downstream of K2 (which is associated with
574 the post-MIS 5e regression) are in agreement with theoretical knickpoint dynamics
575 (Fig. 7B). K2 would thus be the only knickpoint that is still active along the stream. It
576 is another argument to suggest that the full propagation of eustatic knickpoints K13 to
577 K3 was never reached, and knickpoints slowed down before that. A plausible expla-
578 nation is that the small size of catchment D1 coupled with its partly karstic dynamics
579 induces a low stream discharge and a low sediment supply, and thus an insufficient
580 ability of the river to adjust to the base-level fall. This observation was already pro-
581 posed by Castillo et al. (2013), who detected in Scotland a drainage area threshold of
582 4 km^2 for full knickpoint retreat. Another explanation for inhibition of knickpoint reces-

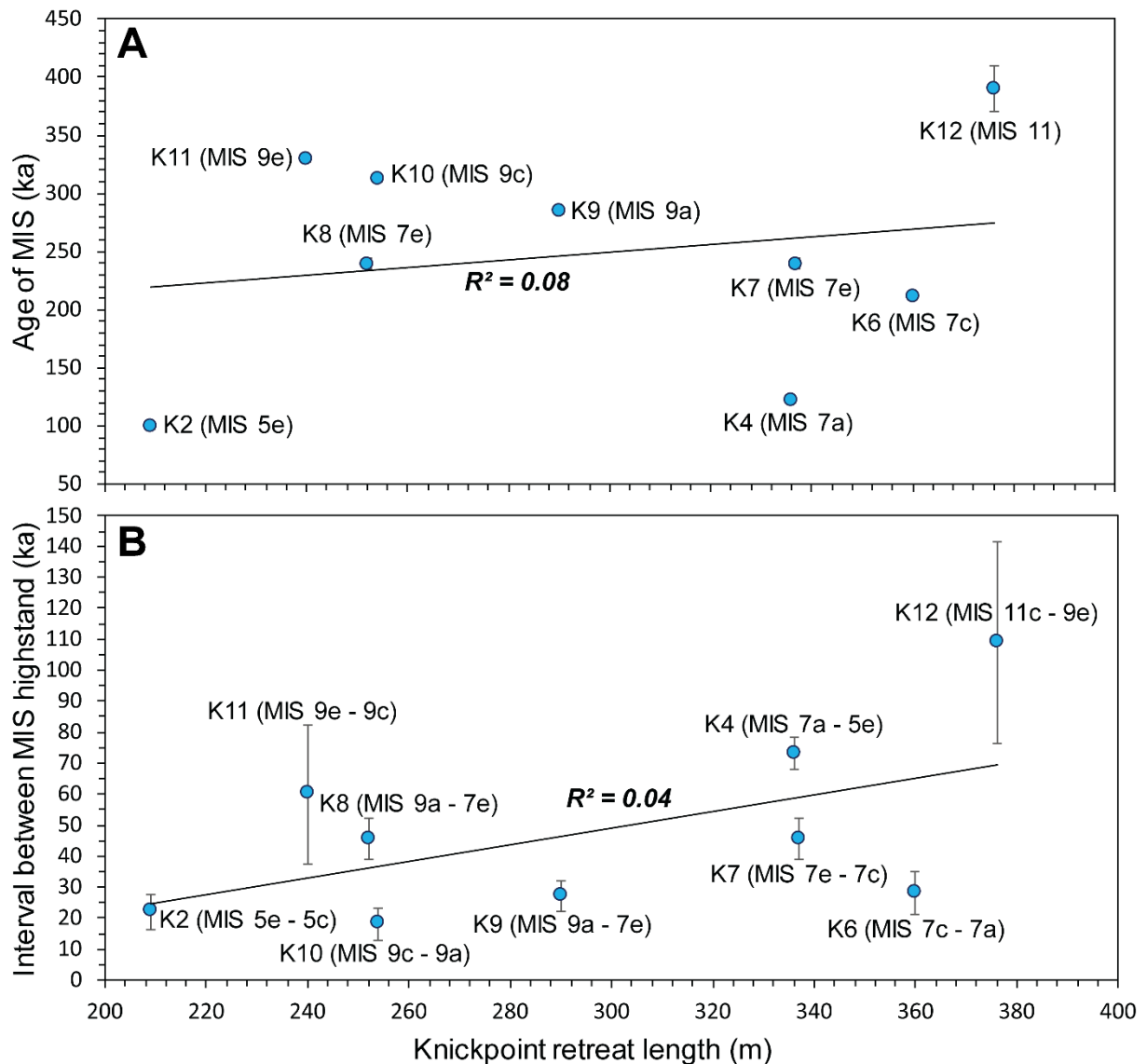
583 sion is the decreasing efficiency of the regressive erosion of the knickpoint produced
584 by the decrease of the slope gradient downstream with the sea level rise during
585 transgression. The transgression would erase the imbalance since the base level will
586 almost return to its initial position (Fig. 1B). In addition, the knickpoints studied here
587 are generated by a high-frequency external forcing (i.e. sea level variations; Fig. 7A),
588 which does not allow them to adjust to the conditions before new ones appear.

589

590 **5.1.3. Timescale of eustatic knickpoint retreat**

591

592 The long-term horizontal propagation rate of the only knickpoint still active (i.e. K2),
593 produced by the last major regression (i.e. MIS 5e), is $\sim 1.71 \text{ mm.a}^{-1}$ (i.e. a retreat
594 length of $\sim 209 \text{ m}$ in $\sim 122 \text{ ka}$). The most likely hypothesis regarding the inactivity of
595 knickpoints older than K2, is that a knickpoint slows down when a new one is formed
596 by a new regression. To test such hypothesis, we quantified the correlation between
597 the time interval between two interglacial highstands that enclose knickpoint for-
598 mation and the knickpoint retreat length. However, no correlation between these two
599 parameters was found ($R^2 = 0.04$; Fig. 10B). The propagation time of the knickpoints
600 is shorter than the time intervals between two highstands.



601 **Fig. 10.** Relationships between knickpoint retreat length calculated for the stream of
 602 catchment D1 with **A)** the corresponding highstand correlated to a MIS and **B)** the
 603 age interval between two successive highstands enclosing the knickpoint. The ages
 604 of MIS 11c, 9e, 9c, 9a, 7e, 7c, 7a, 5e, 5c and 5a are 390 ± 20 , 330 ± 5 , 312 ± 5 , 285
 605 ± 5 , 239.5 ± 8.5 , 211.5 ± 5.5 , 195 ± 5 , 122 ± 6 , 100 ± 5 and 82 ± 3 ka, respectively
 606 (Cutler et al., 2003; Murray-Wallace and Woodroffe, 2014; Thompson and Goldstein,
 607 2005).

608

609 Knickpoint migration rate depends on several parameters such as the drainage area,
 610 lithology and amplitude of base-level fall (e.g., Loget Van Den Driessche, 2009). The

611 local stream gradient creating potential for abrasion, plucking and undercutting of
612 bedrock and sediment supply could also impact this propagation rate (e.g., Whipple
613 et al., 2013). Upstream of knickpoint K10, which is associated with the MIS 9c high-
614 stand, the stream gradient is high while it decreases downstream (Fig. 7C). However,
615 the knickpoint retreat lengths of K11 and K13 are not greater than those of the lower
616 downstream knickpoints. Thus, the local stream gradient does not seem to control
617 the propagation rate. The knickpoint migration must vary according to other parame-
618 ters, such as variations in regression/transgression rates or the geometry of the se-
619 quence that control the stream gradient during each regression. However, these forc-
620 ings are difficult to constrain (e.g., Caputo, 2007). In addition, during Pleistocene re-
621 gressions, the original offshore morphology of the foundations (i.e. the bedrock on
622 which the reefs have been built over the last 1 Ma; Pirazzoli et al., 1993) has been
623 obliterated by the construction of more recent reefs. In the end, our results only allow
624 us to conclude that the timescale on which the knickpoint retreat is effective is short
625 (i.e. a few thousand years).

626

627 **5.2. Dynamics of coastal stream denudation**

628 **5.2.1. Vertical incision along the stream**

629

630 In principle, at a constant incision rate, the older the incised CRT, the higher the finite
631 vertical incision would be, which is at odds with our results (Fig. 7C). Besides, vertical
632 incision does not increase significantly downstream of each knickpoint (Fig. 7C)
633 which indicates that the incision induced by knickpoint retreat is negligible. Finite ver-
634 tical incision values are comparable (~35 m) from the CRT associated with MIS 5e to
635 the CRT associated with MIS 9c and increases upstream, with a maximum of ~74 m

636 located at the distal part of the CRT associated with MIS 11c (Fig. 7B). Between MIS
637 11c CRT and MIS 9c CRT, the seaward slope of the sequence is higher than the
638 seaward slope between the MIS 9c CRT and the MIS 5e CRT (Figs. 7B; 7C). We
639 conclude that vertical incision rates are moderately influenced by eustatic knickpoint
640 dynamics, but rather by the long wavelength slope gradient of the catchment.

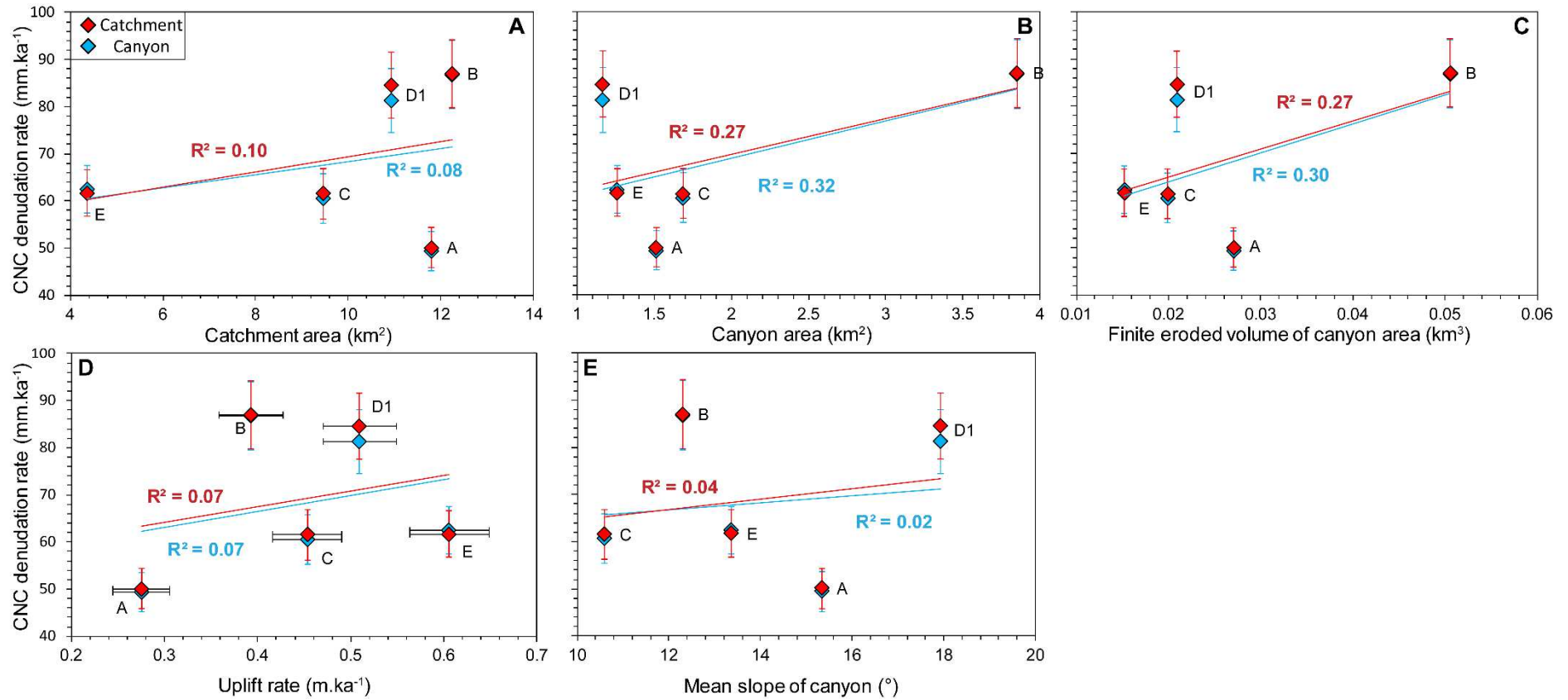
641

642 **5.2.2. Catchment scale denudation rates**

643

644 For catchments located in a karstic environment, using the catchment area extracted
645 from a DEM may be biased since a large part of this area may experience a much
646 higher chemical weathering rate compared to the mechanical erosion rate (Au-
647 themayou et al., 2018). As a result, the denudation rates calculated in this study may
648 be biased (section 3.2.). Nevertheless, we tried to compare the catchment- and can-
649 yon-scale CNC denudation rates with different uplift rates and morphometric parame-
650 ters (i.e. drainage area, finite eroded volume, mean slope of canyon area, etc...) to
651 appreciate the influence of these forcings on drainage dynamics (Table 1; Figs. 11A;
652 11B; 11C; 11D; 11E). However, in both cases (i.e. the relationships with CNC denu-
653 dation rates of catchment or canyon area), there is no significant correlation of denu-
654 dation rates with catchment and canyon areas, uplift rates, the finite eroded volume
655 and the mean slope of canyons (Fig. 11). Moreover, we have previously shown that
656 the denudation rate varies along the stream profile and that the catchment-scale
657 denudation rate measured at the outlet mainly reflects the erosion of the last knick-
658 point associated with the eustatic drop of the last regression, especially if the outlet is
659 close to the fossil sea cliff of the last emerged CRT. Thus, CNC denudation rates

660 from the catchment outlet do not reflect the erosion process at the catchment scale,
661 which prevents any possibility of seeing correlations with morphometric parameters.



662 **Fig. 11.** Relationships between CNC denudation rate (calculated from the entire drainage area extracted automatically with the
 663 DEM (red diamond) and canyon area (blue diamond)), and **A)** Catchment area, **B)** Canyon area (incised zone), **C)** Finite eroded
 664 volume, **D)** Uplift rate, and **E)** Mean slope of canyon area.

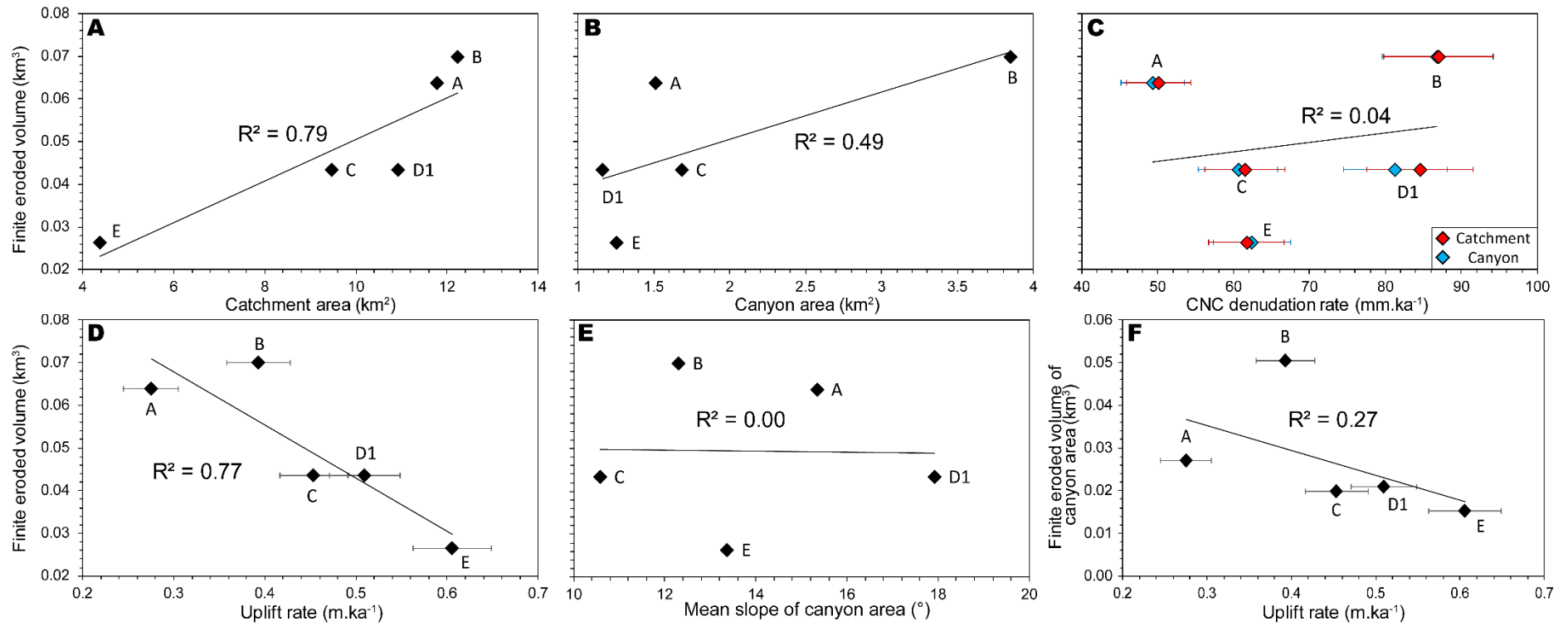
665 **5.2.3. Eroded volume at the catchment scale**

666

667 Because the CNC denudation rate at the outlet is not representative of the catchment
668 denudation, we compare the finite eroded volume at the catchment-scale obtained
669 from catchments with different uplift rates and morphometric parameters (i.e. mean
670 slope, drainage area, etc.) to assess their influence on the long-term drainage dy-
671 namics (Figs. 12A; 12B; 12C; 12D; 12E).

672

673 Firstly, there is no noticeable relationship between the finite eroded volumes, the
674 CNC denudation rates ($R^2=0.04$) and the mean slope of the canyon areas ($R^2=0.00$;
675 Figs. 12C; 12E). Nevertheless, we were able to observe a significant correlation be-
676 tween the finite eroded volumes and the area of catchments ($R^2=0.79$; Fig. 12A).
677 Such correlation slightly decreases with the canyon area ($R^2=0.49$), but with a linear
678 constraint on a single catchment (i.e. catchment B; Fig. 12B), excluding definitive
679 conclusions regarding such correlations.



680

681 **Fig. 12.** Relationships between finite eroded volume and **A)** Catchment area, **B)** Canyon area (incised zone), **C)** CNC denudation
 682 rate, **D)** Uplift rate, and **E)** Mean slope of canyon area. **F)** Relationship between finite eroded volume of canyon area and uplift rate.

683 The finite eroded volumes and uplift rates also show a possible strong linear correla-
684 tion ($R^2=0.77$; Fig. 12D). However, this relationship shows an inverse trend to what
685 the stream power law predicts about the relationship between erosion and uplift rate
686 in a steady state (e.g., Whipple, 2004; Wobus et al., 2006). The catchments affected
687 by the highest uplift rates (D1 and E) show the lowest finite eroded volumes, while
688 the catchments affected by the lowest uplift rates (A and B) have the highest finite
689 eroded volumes (Fig. 12D). In addition, the catchments affected by low uplift rates
690 are those with the largest total drained areas (Figs. 12A; 12B). These relationships
691 would suggest that the lower the uplift rate, the more the catchment extends its
692 drained area onto the CRTs surfaces near the canyon. This leads to an increase in
693 sediment inputs from chemical weathering of the CRTs surfaces that contribute to the
694 catchment supply, and thus an increase in the finite eroded volume (Figs. 12D; 12F).
695 Such an observation is consistent with the results of Nexer et al. (2015) indicating
696 that the more a catchment is located in an area of high uplift rate, the more elongated
697 and the less widened it is (catchments D1 and E in figure 4). Its surface area thus
698 remains small because it will tend to incise mainly along the main drainage of the
699 catchment rather than expand laterally.

700

701 **6. Conclusion**

702

703 In Sumba Island, the specific morphology of the emerged coral reef terraces se-
704 quence, shaped by the combined effects of constant uplift rate and Quaternary sea-
705 level fluctuations, yields a drainage network characterized by the formation of several
706 knickpoints along coastal stream profiles. We correlated the formation of the majority
707 of these knickpoints to major Quaternary Sea level highstands. Each knickpoint was

708 formed at the distal edge of the reef recently emerged at the beginning of the regres-
709 sion. We highlight that the eustatic knickpoint retreat length does not depend on the
710 age of knickpoint formation and are quite homogenous in the sequence drainage.
711 These eustatic knickpoints migrate upstream until they almost stall before the next
712 sea level transgression. The inability of the river to fully absorb the base-level fall
713 would probably be related to its low stream discharge of small drainage areas, low
714 sediment supply in karstic carbonated conditions of the coral reef terraces sequence,
715 and the high frequency of the eustatic oscillations.

716

717 Catchment-scale denudation rates investigated from ^{36}Cl concentration on five
718 catchments draining exclusively the sequence yielded an average value of 69 ± 16
719 mm.k.a^{-1} (integrated over a few thousand years). No significant correlation was no-
720 ticed between the catchments morphometric parameters, uplift and denudation rates
721 because the denudation rate at the outlet influenced by the younger knickpoint activi-
722 ty is not representative of the catchment denudation rate. Also, the relationships be-
723 tween the finite eroded volumes of the catchments and the morphometric parameters
724 highlight that slower uplift for a catchment may correspond to a greater finite eroded
725 volume. This result is explained by the tendency of catchments to widen with low up-
726 lift rate and to lengthen while incising the sequence deeply with higher uplift rate.

727

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742

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