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# Cosmogenic data about offset uplifted river terraces and erosion rates: implication regarding the central North Anatolian Fault and the Central Pontides

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Aurélia Hubert-Ferrari, Laureen Drab, Jerome van Der Woerd, Lucilla Benedetti, Jean van Campenhout. Cosmogenic data about offset uplifted river terraces and erosion rates: implication regarding the central North Anatolian Fault and the Central Pontides. *Mediterranean Geoscience Reviews*, 2021, 3 (1), pp.129-157. 10.1007/s42990-021-00057-6 . hal-03397038

**HAL Id: hal-03397038**

**<https://hal.science/hal-03397038v1>**

Submitted on 9 Nov 2021

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1  
2 **Cosmogenic data about uplifted river terraces and erosion rates: Implication**  
3 **regarding the central North Anatolian Fault and the Central Pontides**  
4

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15 **Key Points:**

- 16 • 1 mm/yr uplift along the central transpressive segment of the North Anatolian Fault
- 17 • Maximum geological slip rate of 14 mm/yr for the central North Anatolian Fault over the  
18 last 85ka
- 19 • MIS 5a strath planation along the Kizilirmak River corresponds to a major Mediterranean  
20 river aggradation event and to high denudation rate in the Central Pontides mountains
- 21 • Variable displacement per event along the central segment of the North Anatolian Fault  
22 that last ruptured in 1943 and 1668.
- 23 • Holocene cosmogenic-based denudation rates in the Central Pontides are high and mostly  
24 controlled by tectonics
- 25 • Cumulated deformation in the Central Pontides is only partly controlled and induced by  
26 the North Anatolia Fault
- 27 • Frost-cracking in carbonate mountains is a dominant mechanism during Glacial Periods  
28

## 29 **Abstract**

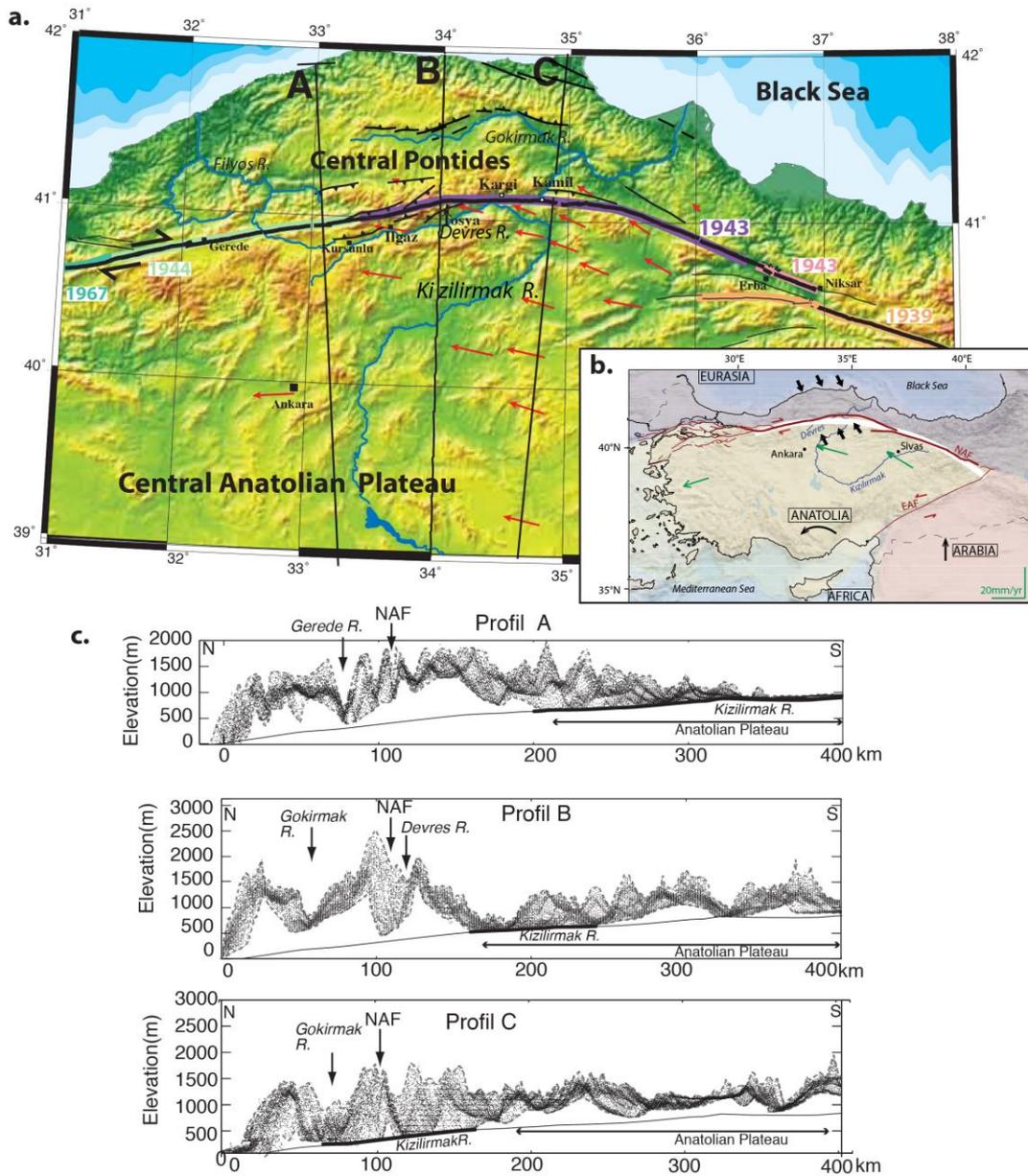
30 River terraces are geomorphological markers recording deformation. Here, we use river terraces  
31 along the Kızılırmak River in Turkey to unravel the transpressive deformation along the convex  
32 arc formed by the central North Anatolian Fault (NAF), a continental transform fault.  $^{10}\text{Be}$ ,  $^{26}\text{Al}$ ,  
33  $^{36}\text{Cl}$  cosmogenic exposure ages of T3 and T2 strath terraces constrained their formation at  
34  $85\pm 15\text{ka}$  and  $66\pm 7.8\text{ka}$ , respectively, during climatic degradations and evidenced frost-cracking  
35 occurrence bringing younger carbonate cobbles on them. T1, a younger fill terrace was probably  
36 emplaced during the last glacial-interglacial transition. Terraces were deformed. The most recent  
37 one records the cumulated  $14\pm 2\text{m}$  deformation of the 1944 and 1668 earthquakes. T3 offset by  
38 750 m constrains a geological slip rate of 8 to 14 mm/yr comparable to the 15 mm/yr geological  
39 rate of the Kızılırmak River over 2 Ma. T2 and T3 evidenced an uplift of 1 mm/yr. Compared to  
40 the 0.28 mm/yr obtained in the adjacent catchment, a larger portion of the shortening in the  
41 Central Pontides is accommodated close to the driving plate boundary, the NAF. We also  
42 evidenced high cosmogenic-based erosion rates in Pontides during the Holocene, and even  
43 higher rates during T3 planation. Erosion rates were combined with present-day relief to infer a  
44 first order minimal shortening of 12-16 km using simple mass balance principles. This long-term  
45 shortening is larger than the one induced by the Anatolian rotation suggesting a far field effect of  
46 the collision.

## 47 **1 Introduction**

48 For a transform plate boundary, the plate relative motion is defined by the rotation around a given Eulerian pole, and  
49 a pure transform fault follows a small circle around this pole. When the transform fault geometry differs from a  
50 small circle, it results into extensional or compressional deformation. Over the life span of the fault, large subsiding  
51 sedimentary basins and mountain ranges are thus formed. An example of the latter is the convex bend of the North  
52 Anatolian Transform Fault (NAF) in its central part.

53  
54 The NAF in the eastern Mediterranean area is a ~1500 km long right-lateral transform fault and its geometry is  
55 similar to a small circle around an Eulerian pole located near the Sinai [Reilinger *et al.*, 2006]. The NAF  
56 accommodates the extrusion of the Anatolian microplate westward toward the Aegean subduction zone (Figure 1).  
57 Here we focus on its central northward convex arc where the fault curvature is narrower than the ideal small circle  
58 for a smooth rotation of the Anatolian microplate (Figure 1). The fault geometry generates a large compressional  
59 fault-normal deformation accommodated in a ~200 km wide area called the Central Pontides (CP), which also  
60 defines the northern edge of the uplifted Central Anatolian Plateau (CAP). Compression in the CP is attested by a  
61 wide array of evidences. Geodetic observations show that the Anatolian motion with respect with Eurasia is not  
62 parallel to the NAF, implying a significant compressive deformation (Figure 1) [Kreemer *et al.*, 2003; Reilinger *et al.*,  
63 2006; Allmendinger *et al.*, 2007; Yavaşoğlu *et al.*, 2011]. Active uplift in the CP is confirmed by regional  
64 morphometry and geomorphic observations by Yıldırım *et al.* [2011, 2013a]; they proposed a geodynamical model  
65 where the CP would be an active orogenic wedge extending from the CAP to the Black Sea coast. Deformation  
66 would result from a positive flower-structure geometry and be developed over a shallow detachment surface linked  
67 to the NAF at depth.

68



69

70 **Figure 1.** Geodynamic setting. **a.** The central NAF forming a broad convex arc, and secondary  
 71 thrust faulting of the CP orogenic wedge; river network indicated in blue; location of the three A,  
 72 B, C profiles displayed below in Figure 1c. **b.** Inset with the Anatolian plate bounded to the north  
 73 by the NAF; thick white line indicates the geometry of the Eulerian small circle. **c.** Three swath  
 74 profiles perpendicular to the NAF evidencing the relief of the CP resulting from shortening.  
 75  
 76  
 77

78 The relationship between the NAF strike-slip motion and shortening within the CP wedge still remains an open  
 79 question. We focus here on a set of strath and fill terraces mostly in the Kargi Basin that are deformed by the NAF  
 80 and on watersheds potentially affected by folding and thrusting along the NAF. Regarding the former, we used  
 81 terrestrial cosmogenic exposure dating to constrain the terrace ages; for the later cosmogenic based erosion rates

82 constrain Holocene denudation rates in the CP. Geomorphological and cosmogenic data allow us to discuss the  
83 terrace formation, origin and incision, to infer a new geological slip rate along the central NAF, to evaluate the uplift  
84 gradient in the CP and to obtain a first-order evaluation of cumulated shortening in the CP to be compared with the  
85 one deduced from the NAF kinematics.

## 86 **2 Tectonic Geomorphology of the NAF along its central part**

### 87 **2.1 Strike-slip Deformation**

88 Most of the strike-slip deformation is localized along a narrow zone as attested by right-lateral offsets at a range of  
89 scale [e.g. *Hubert-Ferrari et al.*, 2002]. The largest apparent offset is made by the Kızılırmak River: between the  
90 Kargi and the Kamil releasing structures [*Barka and Kadinsky-Cade*, 1988] the river displays a 30 km long right-  
91 lateral offset [e.g. *Hubert-Ferrari et al.*, 2002; *Fraser et al.*, 2010a]. To the east and west of the Kızılırmak River,  
92 dated right-laterally offset alluvial surfaces imply a localized right-lateral motion of  $18.6 +3.5/-3.3$  mm/yr [*Kozacı et*  
93 *al.*, 2009], and  $18 \pm 3.5$  mm/yr [*Hubert-Ferrari et al.*, 2002] to  $20.5 \pm 5.5$  mm/yr [*Kozacı et al.*, 2007], respectively.  
94 The fault-slip rate is similar to the GPS derived slip rate ranging from  $18.7 \pm 1.6$  to  $21.5 \pm 2.1$  mm/yr obtained using  
95 an local network [*Yavaşoğlu et al.*, 2011] and to the InSAR derived slip rate of 21 mm/yr (14–29, 95% CI) obtained  
96 by *Hussain et al.* [2016].  
97

98 There is no large geometrical discontinuity along the central NAF trace (Figure 1a). The main discontinuities are the  
99 small Kargi and the Kamil releasing step-overs that the Kızılırmak River exploits to cross the CP. These  
100 discontinuities are not large enough to arrest seismic rupture. Indeed, the Mw 7.6 Tosya earthquake on 26 November  
101 1943 ruptured the whole central NAF from west to east over 280 km [*Barka*, 1996]. The antecedent 1668  
102 earthquake also ruptured the NAF central bend. Paleoseismic trenching has revealed that strain along this segment is  
103 released with a relative temporal uniformity [*Fraser et al.*, 2010a].  
104

### 105 **2.2 Shortening and uplift in Central Pontide orogenic wedge**

106 Around the central NAF, distributed shortening occurs uplifting the CP orogenic wedge [*Yıldırım et al.*, 2011, 2013].  
107 Topographic swath profiles across the NAF in Figure 1c show that the corresponding a high topographic bulge  
108 centered along the NAF. The three swath profiles highlight the following characteristic and changes in topography  
109 (Figure 1c). The lowest altitudinal level corresponds to the floodplain of the Kızılırmak River that flows over 1350  
110 km from the CAP to the Black Sea coast. Since ~2.5 Ma, the Kızılırmak River has slowly incised the CAP [*Doğan*,  
111 2010, 2011], which was initially internally drained; it established its present course across the NAF and its outlet at  
112 the Black Sea coast around 2 Ma [*Hubert-Ferrari et al.*, 2002; *Şengör et al.*, 2005; *Yıldırım et al.*, 2011]. The CAP  
113 in the profiles is clearly identifiable by topography with a reduced relief (i.e. profile A in Figure 1c). Just to the  
114 north of the CAP, the relief increases even if the Kızılırmak baselevel stays in strain continuity with the CAP level  
115 to the south. This relief is related to the CP, a mountain chain related to the Tethyan closure that rose during the  
116 latest Cretaceous to early Tertiary [*Sengör and Yılmaz*, 1981; *Okay and Tüysüz*, 1999; *Cavazza et al.*, 2012]. The  
117 shortening was followed by a post-collisional extensional/transensional phase [e.g. *Çinku et al.*, 2011; *Ottaria et al.*,  
118 2017]. More to the north (i.e. ~ 200 km to 100 km south of the Black Sea coast), the topographic bulge of the CP  
119 range increases and reaches a maximum close to the NAF in the Ilgaz Mountains (i.e. profile B in Figure 1c). In  
120 profiles A and B, the lowest altitudinal levels are ~500 m higher than the floodplain of the Kızılırmak River sampled  
121 in profile C. Indeed, the Kızılırmak River abuts against the CP and curves eastward. The topographic bulge in  
122 profiles A and B is deeply incised by the Gerede, Devres, Gökırmak Rivers, which have carved large the V-shaped  
123 valleys.  
124

125 Shortening is accommodated by different structures and reaches the Black Sea coast, where marine terraces are  
126 uplifted at a rate of 0.02 to 0.26 mm/yr [*Yıldırım et al.*, 2013b) in the Sinop peninsula, and of  $0.28 \pm 0.07$  mm/yr  
127 farther east at the location of the Kızılırmak Delta [*Berndt et al.* 2018]. More to the south, the deformation is  
128 concentrated mostly in two distinct deformational belts (Figure 1a). The first push-up structure forms the Sinop  
129 range and is characterized by south-vergent thrusts [*Andrieux et al.*, 1995; *Yıldırım et al.*, 2011, 2013a]. There,  
130 terraces and pediments have been uplifted over the past ~350 ka at a rate of  $0.11 \pm 0.03$  mm/yr [*Yıldırım et al.*, 2013a].  
131 The second push-up structure is centered along the NAF forming the Ilgaz Range [*Andrieux et al.*, 1995; *Yıldırım et*  
132

133 *al.*, 2011, 2013a]. There, several compressive structures have been mapped, the main ones are located just south of  
134 the NAF and bound the Tosya, Ilgaz and Cerkes sedimentary basins [Barka, 1984; Over *et al.*, 1993; Andrieux *et al.*,  
135 1995; Hubert-Ferrari *et al.*, 2002]. These structures are seismically active as attested by the M=6.9 1951 Kursunlu  
136 earthquake, which ruptured the NAF and the thrust fault to the south [Ambraseys, 1970]. In this second deformation  
137 structure, the microseismicity study of Karasözen *et al.* [2013] has also evidenced shortening accommodated by NE-  
138 SW thrust faulting and by transpression along the central NAF.  
139

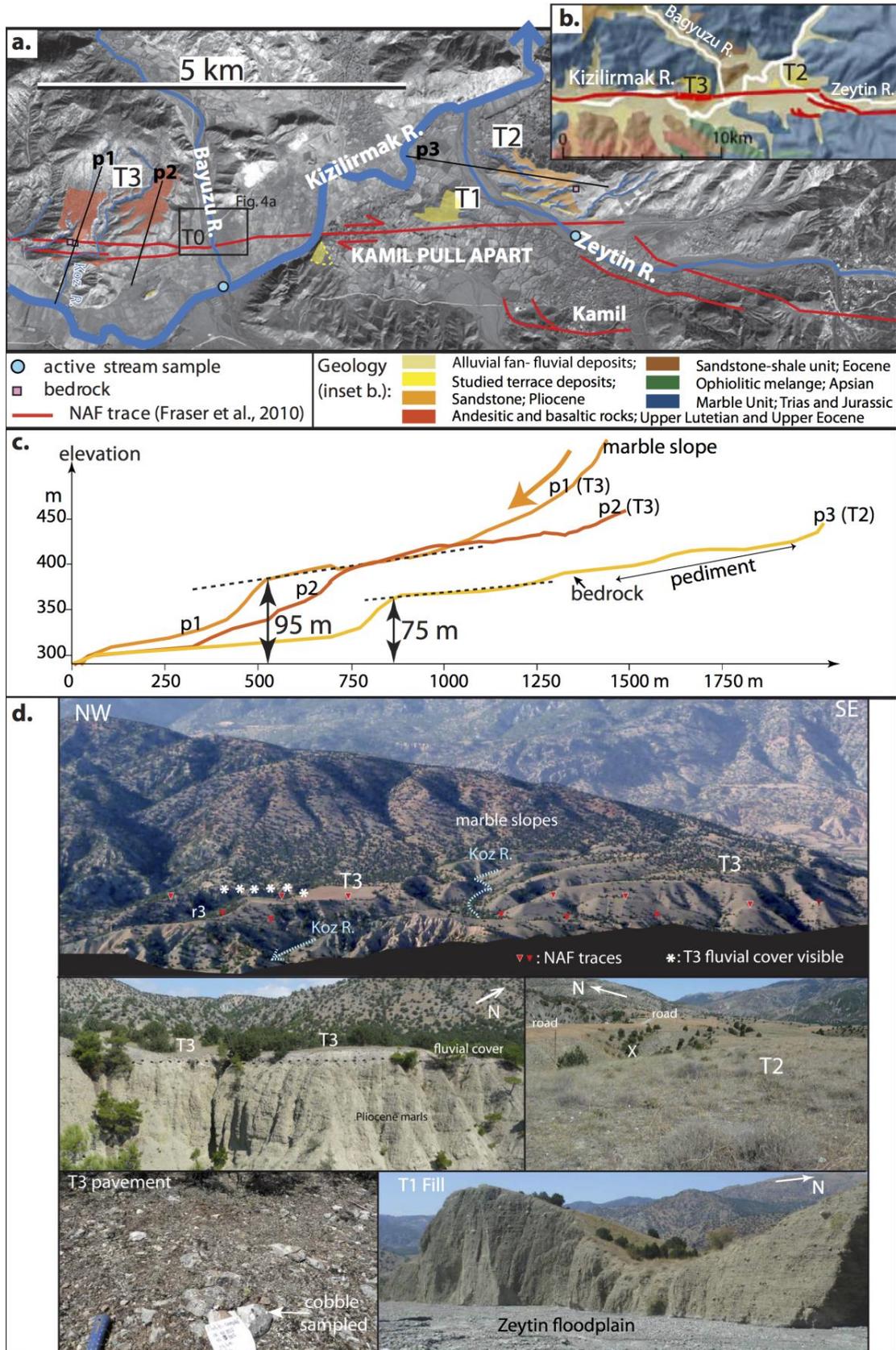
### 140 **3 Sites studied**

141

#### 142 3.1 Strath and fill terraces in the Kamil Basin

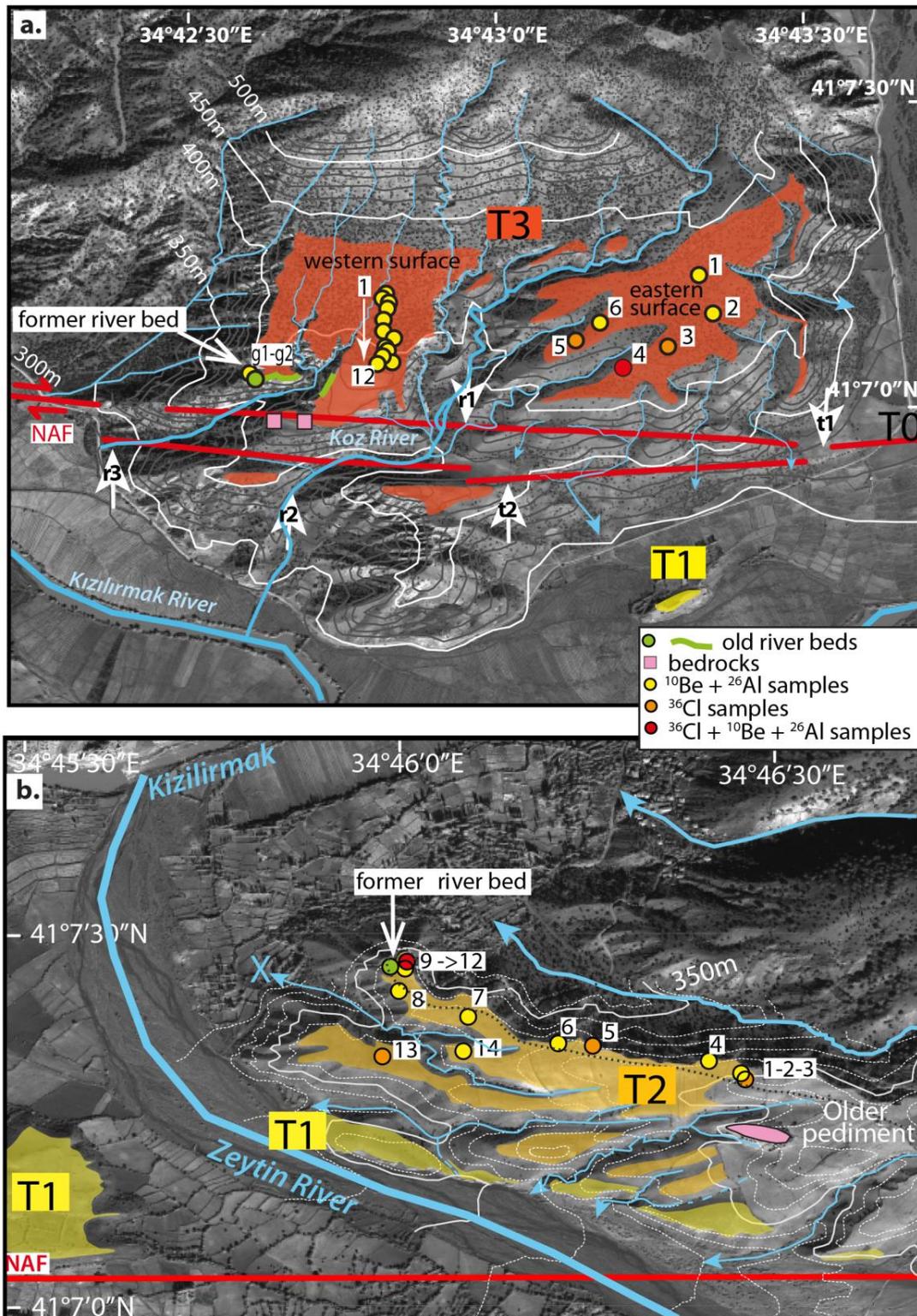
143

144 Along the Kızılırmak River, there are a number of terrace remnants standing ~70 m or higher above the present  
145 floodplain [Fraser *et al.*, 2010a]. **T3** and **T2** are a set of two close strath terraces indicating river incision triggered  
146 by tectonic uplift. They are located at the western end of the Kamil pull-apart (Figure 2). **T1** and **T0** are fill terraces  
147 that are also observed at that location (Figure 2). Terraces were labeled according to their height with respect to the  
148 Kızılırmak floodplain, **T3** being the highest one.  
149



151 **Figure 2.** Maps and characteristics of terraces in Kamil Basin. **a.** Location with respect to the  
152 NAF and the river network on an Ikonos image; frame of Figure 4b is indicated. **b.** Location with  
153 respect to geology. **c.** Characteristics of strath T2 and T3 standing respectively by 75 and 95 m  
154 above the floodplain as evidenced by topographic profiles showing the T2 and T3 elevation, the  
155 connection of the western T3 surface with the hillslope and the location of bedrock outcrop at the  
156 eastern end of T2. **d.** Photographs of T1, T2 and T3. Top: view of T3; view point south of T3;  
157 location of the NAF and of the visible fluvial cover are indicated. Middle right: view of T3  
158 carved in Pliocene marls. Middle left: T2 and its incision by a gully (label X); in the background  
159 the road built on its surface. Bottom: view of the 20-25 m thick aggradational T1 on the southern  
160 edge of T2 (Figure 3b).  
161  
162

163 **T3** is located 95 m above the Kızılırmak floodplain (Figures 2 and 3a). It is bounded to the north by a steep hillslope  
164 made of Triassic-Jurassic marbles, to the east by the Bagyuzu River and to the west by a small tributary of  
165 Kızılırmak channel. **T3** was identified on both sides of the NAF. To the south of the NAF, two **T3** remnants are  
166 bounded by steep slopes and are highly eroded. To the north of the NAF, **T3** is composed of two large surfaces with  
167 a 3.5° slope, separated by the deep incision of the Koz River. The two surfaces show differences. The eastern **T3**  
168 surface is deeply incised and isolated because it separated from the hillslope by gullies. Its well-rounded edges show  
169 no clear natural depth profiles. Few rounded pebbles and cobbles with a diverse lithology can be found on the  
170 eastern **T3** surface. The surface bears no trace of anthropic perturbations (agricultural fields or roads) at the time of  
171 the sampling. On the opposite, the western **T3** surface is less incised and in direct continuity with slopes of marble  
172 range to the north. It is slightly more modified: its southern part has been cleared for agricultural purpose. The  
173 surface is covered by numerous poorly rounded cobbles forming a nice pavement with a uniform marble lithology  
174 identical to the upslope relief (Figure 2d). Natural depth sections are present along its southern edge. The depth  
175 profile shows a 2 to 3 m thick alluvial deposits resting upon Pliocene marls (Figures 2 and S1). The alluvial deposits  
176 are composed of thick packages of well-rounded cobbles/pebbles separated by few sandy layers.



177

178 **Figure 3.** Strath terraces with topography on an Ikonos image and location of cobbles samples  
 179 for cosmogenic nuclide dating **a.** T3 with arrows indicating the offset of the Koz River (r1 to r2)  
 180 separating the western and the eastern T3 surfaces, and the offset of the T3 edges (t1 to t2) that

181 matches a larger offset of the Koz River (r1 to r3). **b.** T2 limited to the east by a marble bedrock  
182 (pink); gully labeled X in Figure 2d is indicated. The fill terrace T1 is mapped.  
183

184 **T2** is located 75 m above the Kızılırmak River (Figures 2 and 3b). It is limited to the west by the Kızılırmak and to  
185 the north by one of its tributary. To the east, **T2** is connected to a smooth pediment surface inclined towards its  
186 surface. T2 and pediment surface are separated by gullies and by a marble bedrock outcrop. To the south, **T2** is  
187 bounded by **T1** a younger very homogenous aggradational fill terrace. The **T2** surface is deeply incised by gullies  
188 and is covered by cobbles having various lithologies. **T2** is more modified than **T3**: a road was built along its entire  
189 length and the surface was cultivated. Aligned reworked cobbles and boulders form the edges of former fields.  
190 Along the road cut at **T2** western end, a depth-profile evidenced a 1.30 m thick fluvial deposit composed of  
191 polygenic pebbles and channels filled of clayed sand with visible cross-bedding structures (location in Figure 3b and  
192 section in Figure S1). At that location, a debris flow deposit locally covers the **T2** surface.  
193

194 The **T1** thick aggradation fill is visible mostly near the intersection of the Zeytin and the Kızılırmak Rivers, though a  
195 small T1 remnant is also visible south of **T3** (Figures 2 and 3b). The homogeneous ~20 to 25 m thick aggradational  
196 package shows no major discontinuity and no paleosol formation. These observations suggest that it was deposited  
197 over a short period of time, after the incision and abandonment of **T2** and **T3**. T1 is also visible in the Kargı Basin  
198 located 35 km more to the west (Figure 1a).  
199

### 200 3.2 Deformation pattern

201  
202 Fault mapping done by *Fraser et al.* [2010a] reveals the occurrence of a ~1 km pull-apart basin at the confluence  
203 between the Zeytin and the Kızılırmak Rivers (Figure 2a). West and east of pull-apart, the NAF is very linear and  
204 continuous. Across **T3**, it displays two parallel strands marked by numerous geomorphic features (Figures 2 and 3a).  
205 To the east of the Koz River, the two strands are identified by small stream offsets and captures, upslope facing  
206 scarps and a small flat pull-apart (Figure 3a). The southern strand is visible in section in the Koz River. To the west  
207 of the Koz River, the northern strand deformed **T3** forming a 1m high north facing scarp and the bedrock outcrops  
208 (pink squares in Figures 2a and 3a); the southern strand is marked by a side-hill bench. East of **T3**, a single NAF  
209 active trace is evidenced across the Baygyuzu floodplain and **T0** a low terrace (Figures 2a and 4a). Farther east, the  
210 NAF could not be precisely mapped because of intense farming activity and high sedimentation/erosion rates. Local  
211 people pointed traces of the 1943 fault rupture [*Fraser et al.*, 2010a]. On the other side of the Kızılırmak  
212 floodplain, the NAF runs to the south of the present Zeytin floodplain and bounds to the south a remnant of **T1**  
213 (Figure 3b). Right-lateral offsets across **T3** and the Baygyuzu floodplain are described in the following as they  
214 provide information regarding the NAF deformation pattern.  
215

216 Across **T3**, two large cumulated right-lateral offsets are evidenced. The most obvious one is the apparent ~370 m  
217 offset of the Koz River indicated in Figure 3a by arrow r1 for the catchment north of the NAF incising **T3** and by  
218 arrow r2 for the narrow channel south of the NAF. However, the right-lateral offset of the Koz River is probably  
219 larger: south of the NAF, the initial river channel was probably the one located farther west (arrow r3, Figure 3a).  
220 The r3 channel is larger than r2, but it has a smaller catchment north of the NAF insufficient to generate the stream  
221 power necessary to carve its deep and wide channel. This r1-r3 offset is consistent with the 750 m right-laterally  
222 offset of the **T3** eastern edge indicated by white arrows t1 and t2 in Figure 3a. Indeed, the original **T3** surface can be  
223 reconstruct using a 750 m backward left-lateral translation. As a result, the **T3** remnants and the r3 channel, south of  
224 the NAF fall in front of the eastern **T3** surface and the Koz River north of the NAF, respectively (Figure 3a). The  
225 morphology therefore suggests a minimal cumulative displacement of 750 m of an incision phase posterior to the **T3**  
226 bevelling.  
227

228 East of **T3**, on both sides of the Baygyuzu River, **T0** is also deformed (Figure 4). Its surface is farmed and stands  
229 ~3m above the ~100 to 200 m wide floodplain (Figure 4a and 4d). It is crossed by a fresh 0.5 to 1m a continuous  
230 south-facing scarp (Figure 4c). Close to the river, **T0'** an additional inset paired terrace stands 1 to 2 m above the  
231 riverbed (Figures 4a and 4d). Theodolite profiles shows that the floodplain is warped (Figure 4d). On the western  
232 side of the river, the **T0/T0'** riser is protected from active river erosion and records a cumulated right-laterally offset  
233 of 14±2m based on theodolite measurements (Figure 4b). **T0'** shows a possible right-laterally offset of 2 m, identical  
234 to the 1943 earthquake slip documented at that location [*Barka*, 1996]. The low slip in the Kamil area during the

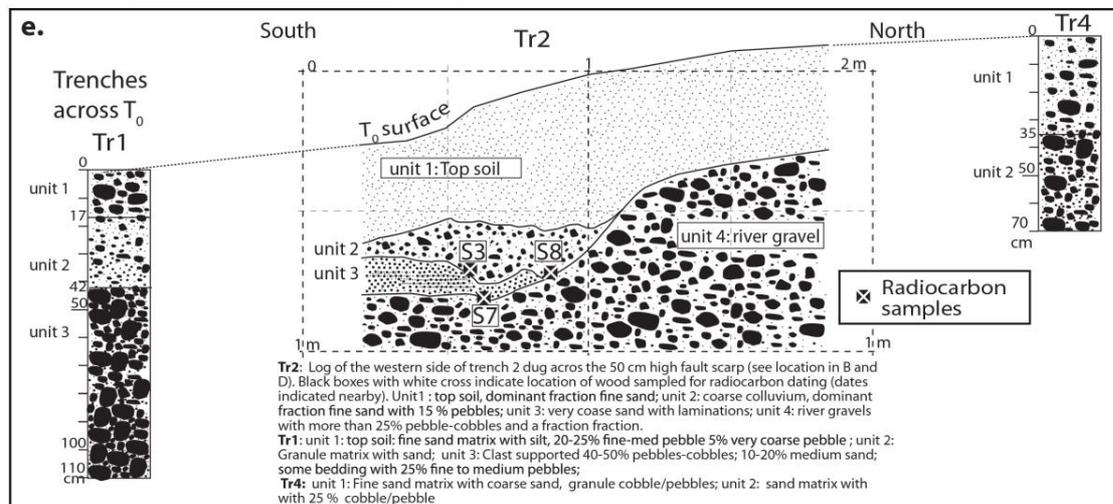
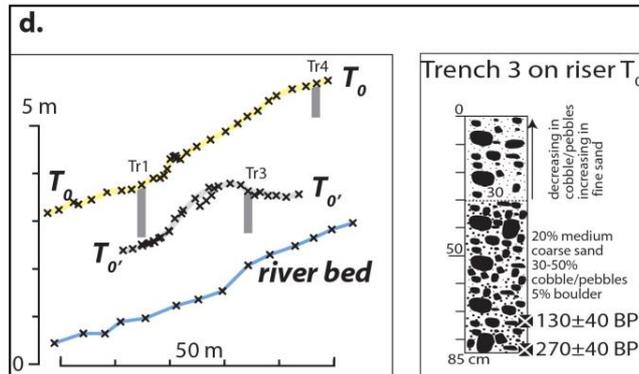
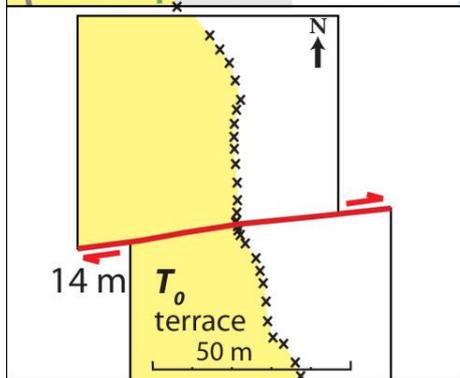
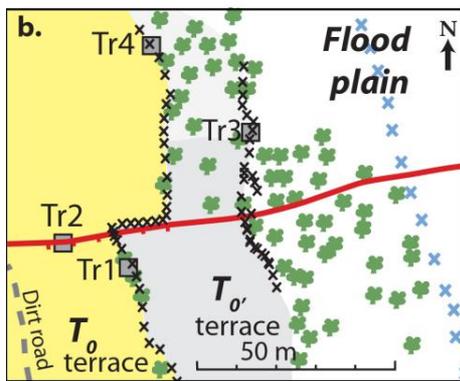
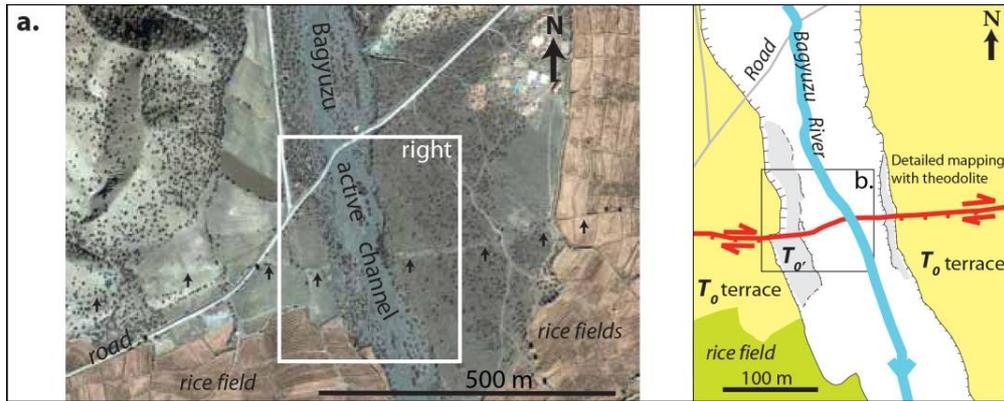
235 1943 earthquake was also documented by a water channel offset in the nearby Alibey village located 12 km East of  
236 Kamil (Figure S2).

237  
238 Four ~1m deep trenches were excavated to constrain the stratigraphy, deformation and age of the terraces (Figures  
239 4b, 4d, and 4e). Tr2 in **T0** is the reference trench Tr2 dug across the fault scarp; Tr1, Tr3 and Tr4 were dug in the  
240 risers. In all trenches, the bottom unit (unit 4 in Tr2, unit 3 in Tr1, unit 2 in Tr3 and Tr4) contains more than 25% of  
241 pebbles/cobbles and a significant sand fraction (Figures 4d and 4e). This coarse grain-size distribution is similar to  
242 the present floodplain deposit. This unit is overlain by finer grained units with a sharp contact in **T0** (Tr1, Tr2, Tr4)  
243 and a gradational contact in **T0'** (Tr3). The transition between the pebbly bottom unit and the overlying finer grained  
244 units is interpreted to correspond to the time at which the terraces were incised. The finer grained units are  
245 interpreted to result from exceptional flood events and from deflation, which would rework fine sands from the  
246 floodplain and transport them on the terrace surface. In **T0**, the large variation in grain-size of the upper most units  
247 between the different trenches is supposed to be related mostly to anthropogenic modifications for agricultural  
248 purpose: cobbles were removed from the main surface (i.e Tr2) and stored on its edges (i.e. Tr1).

249  
250 In Tr2, the top unit 1 and the bottom unit 4 are folded across the scarp (Figure 4e); folding of unit 4 is about twice  
251 more important than the warping of unit 1, which implies that the scarp results from at least two deformational  
252 episodes. No distinct fault trace could be identified due to the restricted depth of the Tr2 trench and to the difficulty  
253 of identifying fault terminations in gravels. Two additional units are present on the down-through side of the scarp:  
254 unit 2, a coarse wedge composed of 15 % pebbles in a fine sandy matrix, overlying unit 3, a finer grained unit  
255 composed of coarse sands with laminations. We interpreted unit 2 as a colluvial wedge resulting from the collapse of  
256 a fault scarp (free face) after an earthquake, and unit 3 as an overbanked deposit on top of the river gravels (i.e. unit  
257 4). The base of the colluvial wedge (unit 2) is therefore interpreted as an earthquake event horizon.

258  
259 The deposition chronology is constrained by radiocarbon dating. In Tr3 (**T0'**), the wood sample at the trench bottom  
260 (i.e 85 cm) gave an uncalibrated age of 270±40 yrs and a calibrated age with an 86% probability of occurrence  
261 during the 1486-1676 A.D. period (Figure 4d). In Tr2 (**T0**), two large wood samples were collected at the base of  
262 unit 2, the colluvial wedge (Figure 4e) and would have been trapped during the scarp collapse. The uncalibrated  
263 ages of 30±50yrs BP and 80±30yrs B.P., and the respective calibrated ages imply a 70.5% probability of occurrence  
264 during the 1805-1931A.D. period and a 70.5% probability of occurrence during the 1810-1926 A.D. period. A small  
265 sample was collected at the boundary between the overbank sandy unit 3 and the river gravel unit 4 to constrain the  
266 incision age of **T0**. We obtain an uncalibrated age of 350±40yrs B.P. and a calibrated age implying a 95%  
267 probability of occurrence during the 1455-1638 AD interval.

268  
269 The stratigraphy and the calibrated ages suggest that the terrace history is in relation with the two last earthquakes  
270 rupturing the central NAF in 1943 A.D. and 1668 A.D. [Barka, 1996]. **T0** has been incised and abandoned shortly  
271 after the penultimate AD 1668. In this scenario, the top of the bottom unit 4 in **T0** is the 1668 A.D. event horizon.  
272 Tr2 stratigraphy and dating also imply that the 14 m **T0/T0'** riser offset results from the 1943 A.D. and 1668 A.D.  
273 cumulated ruptures. The cumulated displacement is similar to the 15.5 m of right-lateral displacement of large old  
274 water canal built before the 1943 earthquake in the village of Alibey, located 12 km to the east of the investigated  
275 site (see Figure S2). The ~2m historical offsets related to the 1943 earthquake in the Kamil area [Barka, 1996] imply  
276 that the 1668 A.D. surface slip was greater than 10 m. This is in agreement with the larger magnitude of the 1668  
277 A.D. earthquake and the conclusions of Fraser *et al.* [2010a, 2010b]. They inferred that the displacement per event  
278 along the central NAF is variable between seismic cycles, based on a paleoseismic trenching study located east of  
279 Kamil pull-apart.



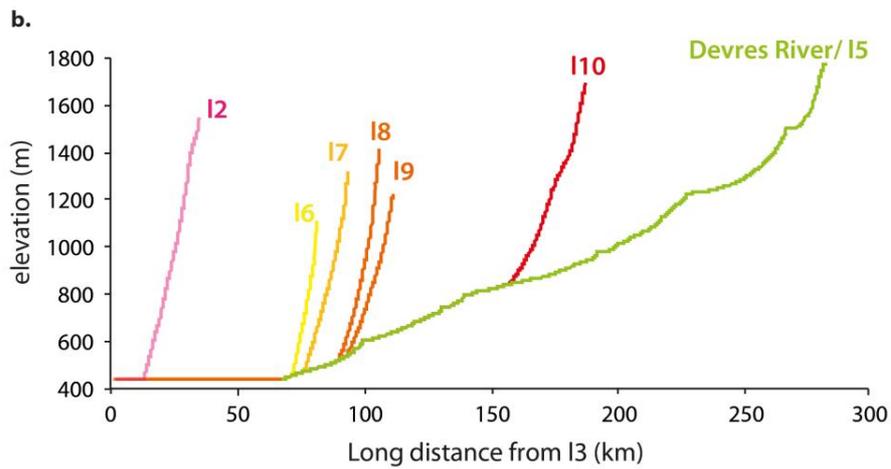
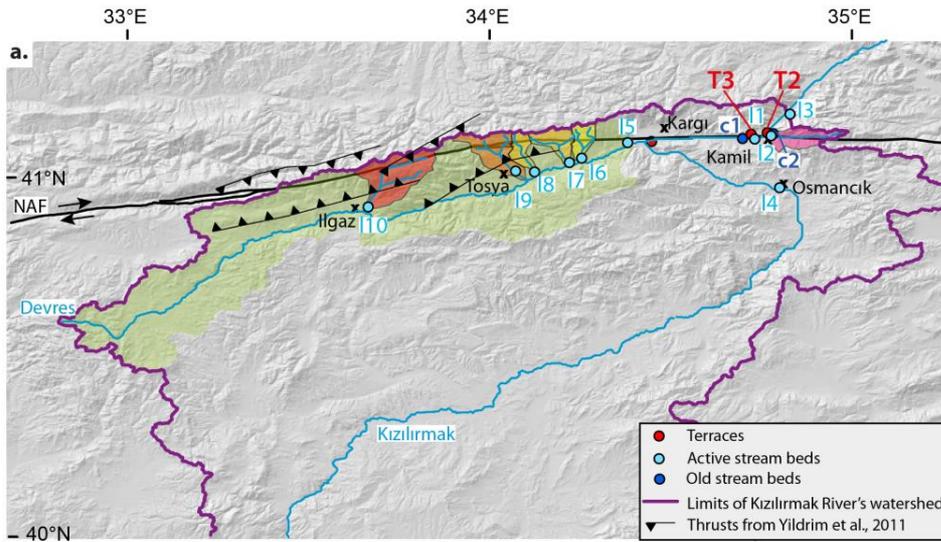
281 **Figure 4.** T0 and T0' offset by the NAF. **a.** Left: Ikonos image of the site, showing the NAF  
282 cutting the Bagyuzu active river bed and older alluvial deposits; fault scarp facing south marked  
283 by black arrows; box indicates location of figure to the right. Right: geomorphological map with  
284 T0 in yellow and T0' in grey; box indicates location of Figure 4b. **b.** Top: map of T0 and T0' on  
285 the river western side. Risers and riverbed were measured in the field with a theodolite (i.e.  
286 crosses: individual measurements); grey squares indicate trench locations. Bottom:  
287 reconstruction of a straight T0 riser using a back left-lateral motion of 14 m; T0/T0' riser is  
288 offset by about 2 m. **c.** Photo of the offset T0/T0' riser and of the fault scarp. **d.** Left: theodolite  
289 profiles projected north showing T0 and T0' relative heights with respect to the riverbed;  
290 trenches location indicated. Right: Tr3 log in T0' riser and <sup>14</sup>C ages obtained. **e.** Trenches across  
291 T0. Middle: log of the Tr2 western side across the 50 cm high scarp; black boxes with white  
292 cross indicate location of wood samples for radiocarbon dating (dates indicated in the text). Left:  
293 Tr1 log. Right: Tr4 log.

294  
295

### 296 3.3 The Kızılırmak watersheds studied

297

298 To evaluate the denudation of the CP Range, we seek to obtain catchment-averaged denudation rates using  
299 cosmogenic nuclide concentrations. We focus on the Kızılırmak catchment directly affected by the NAF within the  
300 CP orogenic wedge, and sampled 9 river catchments: the Kızılırmak River (present-day and past river beds), three of  
301 its main tributaries, the Devres, the Zeytin and the Bagyuzu Rivers, and five subparallel tributaries of the Devres  
302 River (Figure 5, Text S1).  
303



304

305 **Figure 5.** Studied watershed for erosion rates. **a.** Location of the river sampled for cosmogenic-  
 306 based erosion rates. The studied catchments are outlined with different color. **b.** River profiles of  
 307 some studied catchments.

308

309

## 310 4 Method

### 311 4.1 Cosmogenic-based erosion rates

312

313 Cosmogenic nuclide concentrations in river sediments were used to infer catchment-average denudation rates. We  
 314 use the sandy fraction of 11 active riverbeds (Figure 5) to infer erosion rates over the Holocene, and two former  
 315 river beds in T2 and T3 (Figure 3) to try to obtain a rate over the last glacial period. Additional details about  
 316 regarding sampling and method are included as supplemental materials (Text S2, Figure S3). Sample locations are  
 317 included in Table S1.

318

## 319 4.2 Terrestrial cosmogenic nuclide exposure dating

320  
321 A key issue regarding tectonogeomorphology is the ability to constrain the age of deformed geomorphic markers  
322 like alluvial terraces, rockfalls and landslides [e.g. *Tapponnier et al.*, 2001]. This is possible by measuring terrestrial  
323 cosmogenic nuclides. For the studied Kızılırmak terraces, we used a combination of three radionuclides  $^{10}\text{Be}$ ,  $^{26}\text{Al}$ ,  
324 and  $^{36}\text{Cl}$  to constrain their exposure history. Sample locations are given in Table S1, and results in Tables 2 and 3.  
325 Details about the materials, methods and specific sampling strategy for minimizing the erosion bias can be found as  
326 supplemental materials (Text S2, Figures S2 and S3).

327  
328 The sample ages are represented using density probability function to assess the data dispersion and possible pluri-  
329 modal distribution (Figure 6). Following *Brown et al.* [2005], a pluri-modal distribution may indicate post-  
330 depositional reworking and in that case, the oldest ages would represent the age of the surface. In other cases, a large  
331 dispersion may represent a variable inheritance, the youngest ages would have the smallest inheritance and would be  
332 representative of the terrace abandonment [e.g. *Meriaux et al.*, 2005; *Le Dortz et al.*, 2009]. In the present paper, we  
333 discussed the geomorphologic processes at play on the terraces to interpret exposure dates [*Applegate et al.*, 2012],  
334 and did not follow directly the previous interpretations.

335

## 336 5 Results and interpretation

### 337 5.1 Denudation Rates

338  
339 The erosion rates obtained (Table 1) are generally higher than the average worldwide drainage erosion rate (i.e. 218  
340 m/Ma in *Portenga et al.* [2011]).

341  
342 Regarding the Kızılırmak River, its average erosion rate is weakly constrained to 380 m/Ma, but our data imply a  
343 minimum erosion rate of 160 m/Ma, which is 3 times higher than the 50-60 m/Ma inferred on the CAP [*Çiner et al.*,  
344 2015]. The low erosion rate on the plateau might be related to its increase in aridity with respect to its border. The CAP  
345 has an average rainfall of 200 to 600 mm/yr whereas the CP receives an average rainfall between 300 and 1200  
346 mm/yr. The compilation of  $^{10}\text{Be}$  erosion rate data shows that arid region drainage basins tend to erode more slowly  
347 than others [*Portenga et al.*, 2011]. However, *Von Blanckenburg* [2006] that denudation rate in basins having a  
348 similar granitic geology strongly falls only below a rainfall threshold of 200 mm/yr. So the more arid climate of the  
349 CAP may not be the cause of its lower denudation rate. Another factor is tectonics. The CP are active uplifting  
350 whereas the CAP is mostly stable [e.g. *Reilinger et al.*, 2006], and denudation is correlated with tectonics [*Von*  
351 *Blanckenburg*, 2006; *Portenga et al.*, 2011] because of the strong control of tectonics over rock weathering [*Edmont*  
352 *and Huh*, 1997]. So we infer that the higher denudation rates in the CP compared to the CAP are linked to its active  
353 deformation and its related higher relief.

354  
355 The catchments in the CP Range have an average  $^{10}\text{Be}$  computed rate of 395 mm/ka, which is of the same magnitude  
356 as the Kızılırmak River (Table 1). Catchments show a large range of erosion rates. The highest rates occur in the N-  
357 S oriented catchments directly affected by thrust faulting: i.e. L1, Baygyuru (482±120m/Ma), L6 (710±170 m/Ma)  
358 and L8 (324±67 m/Ma) across the Tosya Basin and L10 (514±191 m/Ma) across the Ilgaz Basin. L6, at the eastern  
359 end of the Tosya Basin, also has a headwater located in easily erodible ophiolitic rocks and has one of the steepest  
360 river gradients (Figure 5). The lowest rate concerns the Zeytin catchment, L2 (134±36 m/Ma). It may be surprising  
361 given that it strikes along the NAF, which would have damaged rocks close to its main strand potentially enhancing  
362 erosion. Its lower erosion rate might be related to the strong perturbation induced by the large active landslide  
363 affecting its catchment and to the absence of active thrusts. The east-west oriented Devres River shows a  
364 denudation rate of 220 mm/ka that is much lower than its northern tributaries. Indeed, the northern part of the  
365 Devres catchment (i.e. Tosya and Ilgaz Basins) is crossed by the NAF and by active thrust and folds, and is limited  
366 by the high peaks of the Ilgaz Mountains (Figures 1 and 5). The Devres catchment has a lower denudation rate than  
367 the tributaries sampling this actively uplifting range, because it has a lower slope on average and is also sampling  
368 lower and less actively deforming ranges. Our results thus suggest a strong tectonic control of the denudation rates  
369 in CP and in Anatolia, as documented elsewhere in the geological record (i.e., *Armitage et al.*, 2011).

370

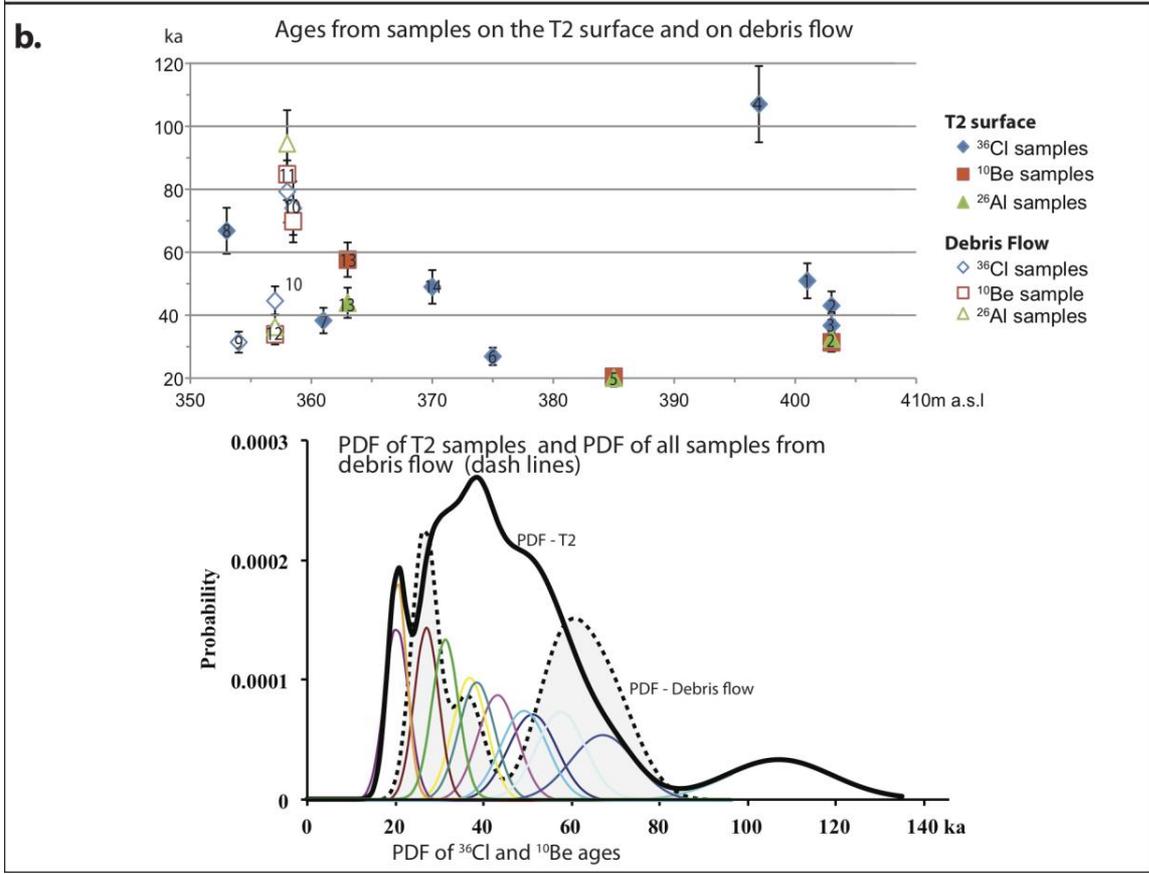
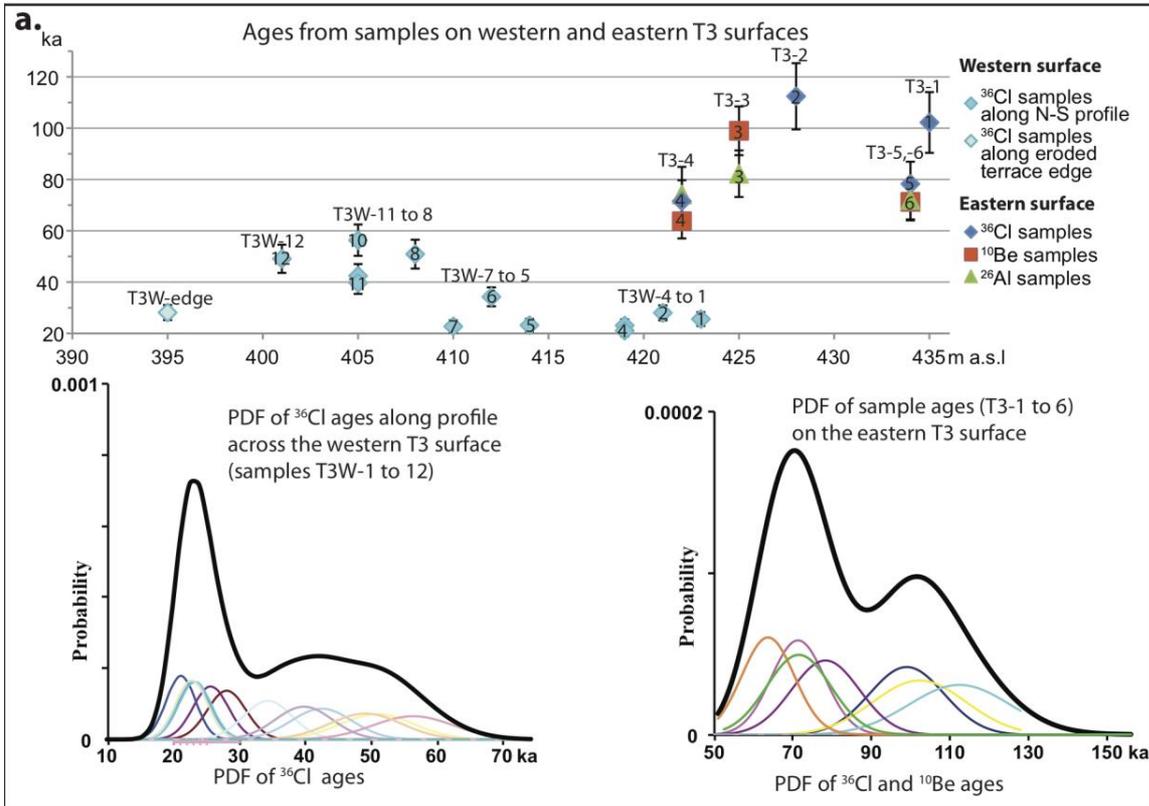
371  $^{26}\text{Al}$  measurements obtained from two former river beds in T2 and T3 (Figure 3 and S1; Table 1 and S1) when  
372 corrected of post-depositional production of  $^{26}\text{Al}$  gave very low concentrations ranging from 27 000 at/g to 10 000  
373 at/g. These measurements suggest that the denudation rates during the Last glacial period were larger than during the  
374 Holocene. Higher denudation rates may be related to an increase in physical weathering in the mountainous regions  
375 during cold period (e.g. Hales and Roering, 2007; Matsuoka, 2008; Fuller et al., 2009; D'Arcy et al., 2017). This  
376 mechanism was suggested in particular regarding in the carbonate mountainous regions in the Mediterranean area  
377 (i.e. Benedetti et al., 2002; Tucker et al., 2011).  
378

## 379 5.2 Ages of T3 and T2 with no erosion and inheritance

380  
381 On **T3**, we distinguished the eastern surface from the western one (Figure 3a), because they show a completely  
382 different age pattern (Figure 6). On the **eastern T3** surface, three  $^{26}\text{Al}/^{10}\text{Be}$  (T3-3 to 5) and four  $^{36}\text{Cl}$  ages (T3-1, 2,  
383 4, 6) were obtained (Figure 6, Tables 1, 3, S1 and S4). The  $^{10}\text{Be}$  ages obtained (T3-3:  $99\pm 9$  ka; T3-4:  $64\pm 7$  ka; T3-5:  
384  $71\pm 7$ ka) are clustered and are concordant with  $^{26}\text{Al}$  ages (Table 1). The four  $^{36}\text{Cl}$  ages (T3-1:  $102\pm 12$ ka; T3-2:  
385  $112\pm 13$  ka; T3-4:  $72\pm 8$  ka; T3-6:  $78\pm 9$  ka; Table 2) are also compatible with the  $^{10}\text{Be}$  ages.  
386

387 On the **western T3** surface, we obtained fourteen  $^{36}\text{Cl}$  ages (T3W-1 to 12, T3W-g1, g2; Figures 3 and 6, Tables 2,  
388 S1 and S4). No  $^{10}\text{Be}/^{26}\text{Al}$  exposure age sample was obtained because no quartz rich cobbles were found on the  
389 surface. All exposure ages are younger than on the **eastern T3** surface (Figure 6). Regarding the twelve samples  
390 taken along a north-south profile in the most preserved central part of the terrace (T3W-1 to 12), their ages get  
391 younger upstream toward the hillslope. Representing the sample ages using probability functions, we identify two  
392 clusters, one around 22 ka for samples located close to the hillslope, and a secondary one around 40-50 ka for the  
393 samples located father south (Figure 6). The samples taken near the steep eroded T3 edge (T3W-g1, g2) have ages  
394 of  $28\pm 3$  ka and  $11\pm 1$ ka (Table 2). This later young age is attributed to local enhanced erosion near the terrace edge  
395 (see Figure S1).  
396

397 On **T2**, fourteen samples (T2-1 to 14; Tables 1, 2, S1 and S4) were processed given the complex natural and human  
398 processes that could have modified it (Figure 3b). Among them, four samples were located close to T2 edge where  
399 the road cut evidenced a debris flow on top of the terrace alluvial deposit (T2-9 to 12). Excluding these samples in a  
400 first step, the three  $^{26}\text{Al}/^{10}\text{Be}$  ages obtained show a wide spread (T2-2:  $31\pm 3$  ka; T2-5:  $20 \pm 2$ ka; T2-13:  $58\pm 5$ ka;  
401 Figure 6; Table 1); the eight  $^{36}\text{Cl}$  ages obtained show a similar spread from to  $27\pm 3$  ka to  $107\pm 12$  ka (Figure 6, Table  
402 2). When we represent the sample ages using probability functions, we evidenced two clustered centered  
403 respectively on 25 and 40 ka (Figure 6). The four surface samples from the debris flow also show a wide age range  
404 from  $31\pm 3$  ka to  $85\pm 8$  ka (T2-9 to 12 in Tables 1, 2). The cosmogenic ages of the debris flow imply that the oldest  
405 exposure age of the alluvial surface (T2-4:  $107\pm 12$  ka) is an outlier, and it was excluded. The age spread in the  
406 debris flow is related to the fact that it reworked already exposed cobbles with a significant inheritance. Only the  
407 youngest samples (T2-9:  $31\pm 3$  ka, T2-12:  $34\pm 4$ ka and  $45\pm 5$ ka, Tables 1 and 2) were used to infer its emplacement  
408 that would have occurred around 30-45 ka. We used these ages as a constraint for **T2** that must be older than 45 ka.  
409



411 **Figure 6.** T3 and T2 cosmogenic exposure ages. **a.** Top: T3 exposure ages represented versus  
412 elevation above sea level (a.s.l.). Bottom right, probability density function of  $^{36}\text{Cl}$  exposure ages  
413 for samples T3W-1 to T3W-12 following a north-south profile on the western surface. Bottom  
414 left: probability density function of  $^{36}\text{Cl}$  and  $^{10}\text{Be}$  exposure ages for all samples the eastern T3  
415 surface. **b.** Top: T2 exposure ages represented versus elevation above sea level (a.s.l.). Bottom,  
416 probability density function of exposure ages. Samples corresponding to the debris flow (T2-9 to  
417 12) are identified.

### 418 5.3 Evaluation of Erosion Rates and inheritance on T2 and T3

419  
420 Possible corrections related to erosion rates were evaluated. Erosion reduces the cosmogenic isotope concentrations  
421 giving rise to ages that are too young. Several constraints could be inferred. First, we have developed a sampling  
422 strategy to minimize this bias (see Text S2). Second, we considered that the erosion rates on the inner part of the  
423 terraces, particularly **T3**, were likely to an order of magnitude smaller than the obtained averaged denudation-rate  
424 around 200m/Ma obtained using river sand. Third, we inferred that  $^{36}\text{Cl}$  ages are not in equilibrium because of their  
425 agreement with Be-Al ages, and thus computed a maximum erosion rate of 6 mm/yr. Finally, *Yıldırım et al.* [2013]  
426 based on  $^{10}\text{Be}$  depth profile on a terrace inferred a possible erosion rate of 1 mm/ka in the nearby Gökırmak  
427 catchment. All these elements point to a low to negligible erosion rate of the inner part of the terraces.  
428

429 We also critically assess erosional processes on the terraces. The former Kızılırmak alluvial deposits visible in  
430 sections across **T2** and **T3** are mostly composed of cobbles with few coarse sand layers. The main erosion processes  
431 on these surfaces after their incision and abandonment would be driven by overland flow and deflation. Large  
432 overland flows could be erosive particularly during cold and arid glacial periods with a restricted vegetation cover,  
433 but cobbles are still likely to have a long residence on the inner flat part of the terrace. Deflation would affect only  
434 the finest particles, and concentrate the cobbles at the surface. This process would have a relative minor impact  
435 because of the original large grain-size of the alluvial deposits as evidenced in the depth section (Figure S1). The  
436 erosion rate by these two combined processes is thus likely to be minimal. On **T2**, cultivation has triggered the  
437 exhumation of buried cobbles and may have increased the erosion rate of the finer particles, but we are lacking any  
438 way to quantify these parameters. We thus rely more on the exposure ages of **T3**.  
439

440 The prior exposure is the other important bias, cobbles could have gained an initial concentration before their  
441 deposition on the terrace. *Yıldırım et al.* [2013] evaluated in the nearby Gökırmak catchment possible inherited  $^{10}\text{Be}$   
442 concentrations ranging from 140 000 to 40 000 atoms.g<sup>-1</sup>. Similarly, *Çiner et al.* [2015] evaluated the inherited  
443 concentration in Kızılırmak terraces in the CAP between 0 and 15-25 x 10<sup>3</sup> atoms.g<sup>-1</sup> on a 160±30 ka terrace.  
444 Another way to assess the presence of inherited nuclides is to date the active riverbed [e.g. *Hetzl et al.*, 2006]. We  
445 obtained  $^{10}\text{Be}$  concentration ranging from 10 000 to 50 000 atoms.g<sup>-1</sup> in riverbeds. To evaluate the most adequate  
446 inheritance, we tested different inheritance scenario within the 10 000 to 50 000 atoms.g<sup>-1</sup> range using the few  
447 radionuclide concentrations obtained at depth in **T2** and **T3** (see Figure S1). The two profiles could be fitted with no  
448 inheritance or with a small one of 10 000 atoms.g<sup>-1</sup>.  
449

450 We thus considered that inheritance is negligible, and that most of the age spread is related to other specific  
451 geomorphological or anthropic processes further discussed in the following. We choose not to apply any systematic  
452 corrections for erosion and prior exposition.  
453

### 454 5.4 Terrace ages, age spread and the inferred frost-cracking process

455  
456 The exposure ages for the two surfaces show a broad spread (Figure 9), but the large number of exposure ages  
457 allows for identification of probable geomorphological processes responsible for the sprawl. The **T3** surface, which  
458 is the most preserved regarding anthropic modifications, shows the clearest pattern. The **T3** cobbles located west  
459 and east of the Koz River belong to the same surface (Figure 2), but have different exposure ages (Figure 6a). So  
460 different geomorphological processes were at play on these surfaces. The younger exposure ages on the **western T3**

461 surface are thus interpreted to reflect hillslope processes during the Glacial Period, posterior to the terrace bevelling  
462 and entrenchment.

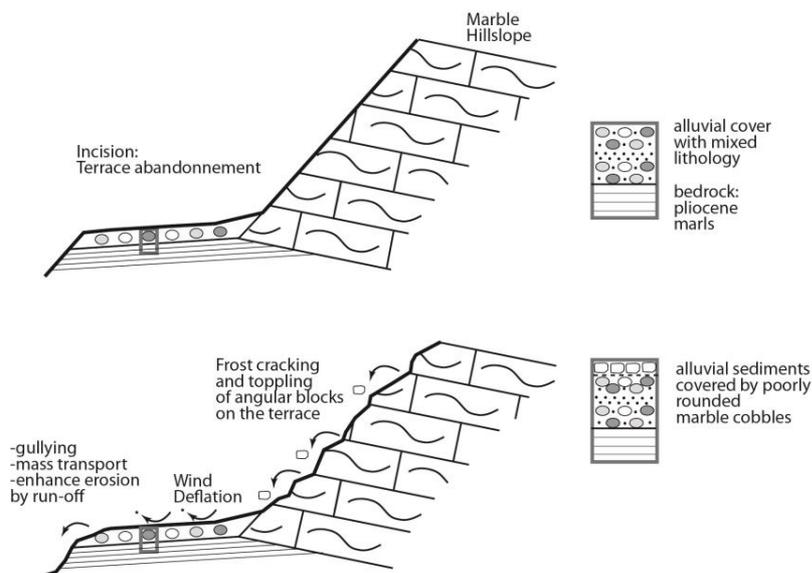
463  
464 During cold intervals, a dominant erosional process on bare marble hillslopes of the CP range would be frost  
465 cracking [Anderson *et al.*, 2013]. This specific process at play during the Glacial Period was evidenced around the  
466 Mediterranean [Tucker *et al.*, 2011]. It leads to a larger degradation of carbonate slopes during the Glacial Period  
467 compared to the Holocene [e.g., Armijo *et al.*, 1992; Piccardi *et al.*, 1999; Morewood and Roberts, 2000]. Marbles  
468 samples along the north-south profile on the **western T3** surface are interpreted to come from the hillslope by frost  
469 cracking.

470  
471 The intensity of frost cracking depends on two main variables: first, the time spent in the frost cracking window  
472 (ranging from -8 to -4°C) and second, the water availability directly linked to Winter/Spring precipitation [Anderson  
473 and Anderson, 2010]. A cold and humid climate would be much more favorable than a cold and dry one. High-  
474 resolution pollen data from the southern Black Sea cores record vegetation changes in the CP [Mudie *et al.*, 2007;  
475 Shumilovskikh *et al.*, 2012, 2013 and 2014] and attest for the occurrence of large changes in temperature and  
476 humidity implying that frost cracking would not be a steady phenomena [Anderson *et al.*, 2013]. The two age  
477 clusters at 23-2+3 ka and between 40 to 55 ka on the **western T3** surface correspond to the two coldest intervals  
478 during the last 135 ka in the CP [see Badertscher *et al.*, 2011], and particularly to the two more humid periods  
479 identified using pollen data around 45-54 ka and 20-28 ka in the CP [Langgut *et al.*, 2011; Shumilovskikh *et al.*,  
480 2014]. These more humid phases correspond to glacial advances in Turkey. The first one fits the 53-44 ka glacial  
481 advance [Reber *et al.*, 2014] in Eastern Black Sea Mountains in Turkey, and the second one, the better known Last  
482 Glacial Maximum (LGM) advance in Turkey. The LGM in Turkey is characterized by cooler temperature and a  
483 doubling in precipitation at 22±4ka in comparison with the previous period [Akçar *et al.*, 2014; Reber *et al.*, 2014].

484  
485 The age distribution for the **western T3** surface can thus be simply related to the fact that the surface acts as a  
486 pediment in direct connection with a carbonate hillslope (Figure 7). Periodic frost cracking on the hillslope brings  
487 new carbonate cobbles on its surface, the last episode being the LGM. Cobbles originating from frost cracking  
488 would then be transported away from the slope when large overland flow occurs. So older marble cobbles would be  
489 found farther away from the slope. This geomorphological scenario is consistent with the exposure ages obtained  
490 along the profile across **T3** (T3W-1 to 12; Figure 3a): many LGM carbonate cobbles are found near the hillslope and  
491 there is a trend toward older ages away from the hillslope (Figure 6a). It also provides an explanation for the  
492 numerous carbonate cobbles present on the **western T3** surface forming a pavement (Figure 2e) and the few older  
493 cobbles with a mixed lithology found on the **eastern T3** surface. The **eastern** and **western T3** surfaces have  
494 different histories because the **eastern T3** surface is separated from the hillslope by a gully system forming the head  
495 catchment of the Koz River (Figure 3a), so the eastern surface is disconnected from the hillslope. **T3** abandonment  
496 and incision can thus only be inferred by using samples on the eastern surface; an abandonment age of 85±15ka for  
497 **T3** is thus computed by averaging its <sup>10</sup>Be and <sup>36</sup>Cl exposure ages. **T3** age is compatible with <sup>10</sup>Be and <sup>326</sup>Al  
498 exposure ages at depth in **T3** (Table 1; Figure S1).

499  
500 On **T2**, two main processes are inferred. First, frost-cracking is likely to be present because part of the **T2** surface is  
501 in continuity with a pediment and the carbonate bedrock, which itself is connected to carbonate slopes (Figures 2c  
502 and 3b). Indeed <sup>36</sup>Cl ages belonging to the two main frost-cracking periods, LGM (T2-6: 27±3 ka) and 40 to 55 ka  
503 (T2-1: 51±6ka, T2-7: 38±4ka, T2-14: 49±5ka), are also present on the **T2** surface Figure 6b). Second, human  
504 ploughing, which leads to younger exposure ages for exhumed cobbles can be a bias, even if we sampled away from  
505 visible fields and selected cobbles with a large alteration ring. Given this two potential bias, we consider that  
506 samples most representative of the terrace age should have the oldest ages and should come from an isolated terrace  
507 remnant. Sample T2-8 (66.8±7.3 ka) is thus considered the best to represent the terrace age because it is the oldest  
508 exposure age and it comes from a surface surrounded by deep gullies. This inference is consistent with the fact that  
509 T2 bevelling must be (1) older than the debris flow emplaced around 30-45 ka, and (2) younger than **T3**. Finally this  
510 age is also coherent with cosmogenic concentrations we have at depth in **T2** (Table 1; Figure S1).

511



512

513 **Figure 7.** Sketch displaying the geomorphological processes at play in a cross-section since  
 514 terraces incision and abandonment (top diagram): the terrace surface acts as a pediment (bottom  
 515 diagram) where new marble cobbles are supplied by frost cracking by the hillslope, and are in  
 516 transit on the surface; on the right, typical sedimentary sections across the terraces.

517

518

519

520

## 521 **6 Discussion**

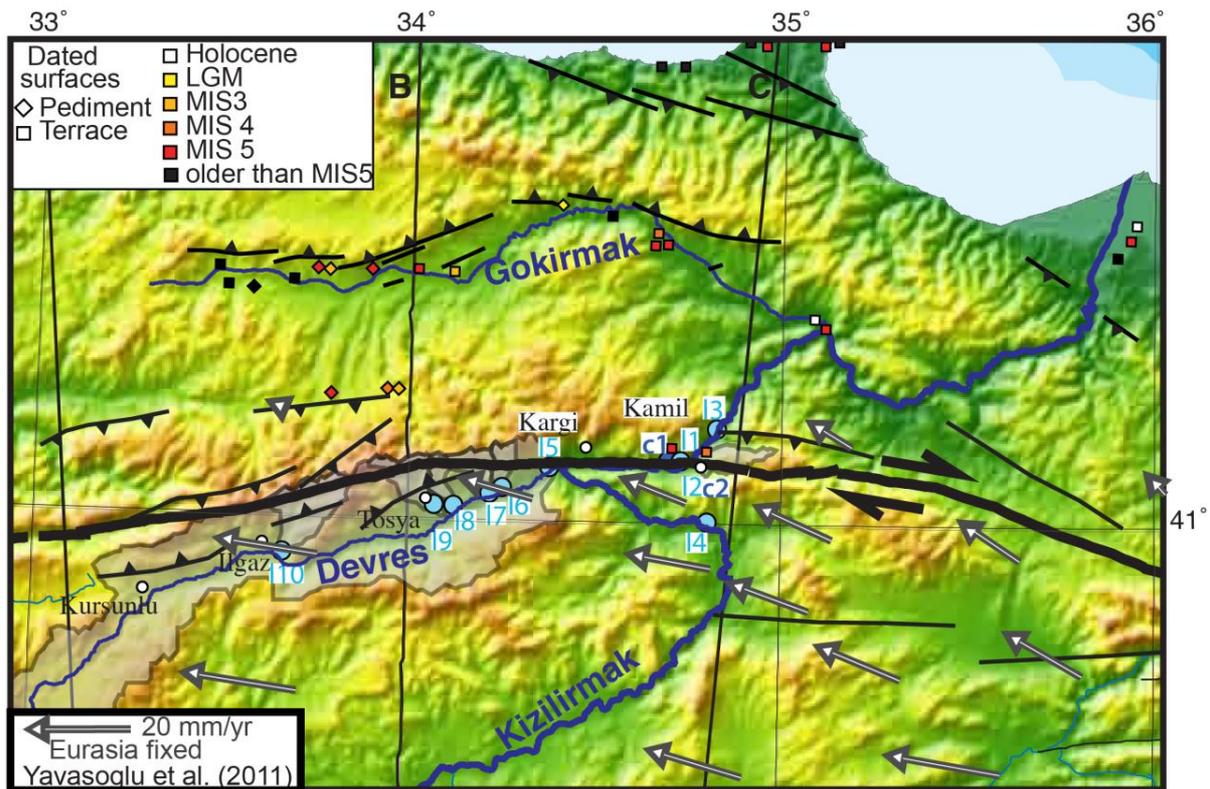
522

### 523 6.1 Terrace formation, incision and possible climate-related factors

524

525 The  $85 \pm 15$  ka age of **T3** age concordant with ages of strath terraces ( $81 \pm 8$  ka and  $99 \pm 8$  ka  $^{10}\text{Be}$  ages and  $78 \pm 7$  ka  
 526  $^{36}\text{Cl}$  age) and pediments ( $70 \pm 7$  ka  $^{21}\text{Ne}$  age) in the Gökırmak River, a tributary of the Kızılırmak River [Yıldırım *et*  
 527 *al.*, 2013a] (Figure 8). More to the west, a strath terrace with an  $88 \pm 5.1$  ka age was also mapped along the Filyos  
 528 River [McClain *et al.*, 2017] (Figure 1a). **T3** in Kamil thus results from regional episode of strath planation that took  
 529 place during MIS 5a/b. The **T3** formation is also broadly coincident with the abrupt replacement of mixed forest by  
 530 steppe species in the eastern Mediterranean area during MIS 5a [Litt *et al.*, 2014]. The vegetation and climatic  
 531 changes are likely to have increased the sediment supply in the CP, as evidenced by the high erosion rates obtained  
 532 from the Kızılırmak paleochannels. High sediment supply would have lead to the strath planation in Kamil and more  
 533 to the north or to the west in the Gökırmak and Filyos catchment, respectively.

534



535

536 **Figure 8.** The convex NAF central arc forming an orogenic wedge associated with thrust  
 537 faulting. GPS vectors from *Yavaşoğlu et al.* [2011] outlined the expected convergence in the  
 538 region of Kargı, Kamil, Tosya and Ilgaz. Dated uplifted surfaces are indicated with colors for  
 539 their exposure ages (north of the Kızilirmak, work of *Yıldırım et al.* [2013a and b] and *Berndt et*  
 540 *al.* [2018]). Location of sand samples for erosion rates are indicated with blue circles, the  
 541 catchment of the Devres River is outlined in gray.

542

543 Subsequent incision would be related to a modification of the erosional capacity of the river related to change in  
 544 discharge and sediment load linked to vegetation and climatic changes [*Fuller et al.*, 2009]. This episode is broadly  
 545 recorded in the whole Mediterranean area. Indeed, according to *Macklin et al.* [2002], the largest alluviation in the  
 546 Mediterranean area took place around 88 ka. This major river aggradation episode has been related to accelerated  
 547 catchment erosion and lacustrine sedimentation [*Allen et al.*, 1999; *Fuller et al.*, 1998; *Macklin et al.*, 2002].

548

549 The  $68 \pm 6$  ka age of **T2** also corresponds to the ages of strath terrace (i.e.  $68 \pm 6$  ka,  $^{36}\text{Cl}$  age) and pediments ( $60 \pm 5$  ka  
 550  $^{10}\text{Be}$  age;  $70 \pm 7$  ka  $^{21}\text{Ne}$  age) in the Gökırmak catchment [*Yıldırım et al.*, 2013a] (Figure 8). **T2** would thus result  
 551 from another regional episode of planation level that occurred during MIS4 (60-75 ka). This planation is lightly  
 552 older than the youngest strath terrace formation in the Filyos Basin at  $50.9 \pm 2.8$  ka [*McClain et al.*, 2017] (Figure  
 553 1a), but it corresponds also to a  $\sim 60$  ka alluvial optima documented in the Duzce Basin [*Pucci et al.*, 2008]. This time  
 554 period corresponds to a large climate degradation recorded in the Sofular Cave located 100 km west of our study  
 555 area [*Fleitmann et al.*, 2009] and in the Lake Van record in eastern Turkey. There, the pollen record evidences the  
 556 nearly complete disappearance of arboreal pollen (*Pinus* and *Quercus*) [*Litt et al.*, 2014; *Pickarski et al.*, 2015],  
 557 which was synchronous with the second largest decrease in water level during the last 90 ka [*Çağatay et al.*, 2014]  
 558 and with the emplacement of lowstand deltas [*Cukur et al.*, 2014]. Changes in vegetation and in catchment  
 559 hydrology, which are the primary control of sedimentation, may have triggered this second episode of strath  
 560 planation in the Kamil Basin. In the Mediterranean, there are few alluvium record from the MIS4 period [*Macklin et*  
 561 *al.*, 2002], so this strath planation episode could be specific to the Eastern Mediterranean area.

562  
563 In Kamil, **T1** and **T0** attest for a large fluvial aggradation [Fraser et al., 2010a]. The ~25 m thick T1 aggradational  
564 fill corresponds to a large sediment delivery (Figure 2d). About 30 km more to the west, in the Kargi Basin, a fill  
565 terrace standing 30 m above the floodplain also exists. In the CAP, a large ~18m thick sediment infill at  
566 15,390±150yrs <sup>14</sup>C BP [i.e 16.5 cal ka ago; Doğan, 2011] was also evidenced in the Kızılırmak floodplain.  
567 According to Doğan [2011], it occurred after a main downcutting phase of the river, which started after later stages  
568 of MIS 5 or early MIS 4. This downcutting to aggradation change occurred during the most pronounced climate  
569 change in the Mediterranean area, the last glacial–interglacial transition [Langgut, 2011]. The LGM to Holocene  
570 transition in Turkey is characterized by drastic vegetation [e.g. Valsecchi et al., 2012], precipitation [Jones et al.,  
571 2007] and temperature changes [Göktürk et al., 2011]. The LGM has specific characteristics in Anatolia. First,  
572 evapotranspiration ratio was low, so there was a positive water balance with high lake levels in Anatolian [Roberts  
573 et al., 2011; Jones et al., 2007]. Second, high snowfall and restricted vegetation cover were resulting in strong river  
574 discharge. Doğan [2010] inferred that these two factors led to a high discharge/sediment supply ratio during the  
575 glacial period in Turkey resulting in valley downcutting. The change during the Holocene transition to a more  
576 negative hydraulic balance resulted in a shift from downcutting to aggradational filling along the Kızılırmak as  
577 evidenced in the CAP. Pucci et al. [2008] also documented this alluviation phase at the transition from arid to humid  
578 conditions in the Duzce Basin. We thus inferred that T1 in the Kamil Basin resulted from the same process and was  
579 emplaced during the LGM to Holocene transition.  
580

581 The terraces in the Kamil Basin are thus a response to climatic fluctuations like at other upstream and downstream  
582 locations along the Kızılırmak River [i.e. Yıldırım et al., 2013a; Doğan, 2011; Çiner et al., 2005]. Other river  
583 terraces in Turkey [Westaways et al., 2004], in the Mediterranean area [Bridgland, 2000; Macklin et al., 2002] have  
584 also systematically been attributed to climate forcing.  
585

## 586 6.2 Geological strike-slip motion along the NAF

587  
588 **T3** provides some constraints on the NAF quaternary slip rate. We documented a 750 m long offset of T3 risers and  
589 of the Koz stream. The incision of the Koz River has separated the **eastern** and **western T3** surfaces and predates  
590 the emplacement of marble cobble by frost cracking. The 750 m offset would thus be older than 55 ka, the age of the  
591 oldest marble cobbles on the **western T3** surface bought by frost-cracking. Similarly, the T3 riser offset is younger  
592 than **T3** bevelling at 85±15ka. The geological slip rate on the NAF can thus be bracketed between 8 mm/yr and 14  
593 mm/yr.  
594

595 The obtained slip rate can be compared to other geological rates. The upper bound of our geological rate is  
596 compatible with the lower bound of Holocene slip nearby [Hubert-Ferrari et al., 2000; Kozacı et al., 2007; Kozacı  
597 et al., 2009] (see section 2.1). The Kamil rate can also be compared to the longer term geological slip rate obtained  
598 considering that the Kızılırmak established its course across the CP ~2 Ma [Hubert-Ferrari et al., 2000; Yıldırım  
599 et al., 2011] and its 30 km long offset between the Kamil and the Kargi pull-apart. The resulting geological rate of 15  
600 mm/yr over 2 Ma corresponds well to maximum slip rate inferred in Kamil.  
601

602 However, the maximum slip rate obtained is lower than the geodetic rate inferred using a local network measured  
603 (17 to 22 mm/yr) [Yavaşoğlu et al., 2011] and using Insar velocity profiles (21 mm/yr, average with 14-29 mm/yr  
604 95%CI) [Hussain et al., 2016]. Lower geological rates compared to geodetic rates can be linked to different factors.  
605 First, even if most of the deformation takes places on the NAF offsetting **T3**, a small part can be accommodated on a  
606 relatively broad zone around. Indeed, the geology is composed of a series of amalgamated terrains separated by  
607 various inactive E-W fault structures that are optimally oriented in the present-day stress field to accommodate some  
608 deformation. In that case, Vallage et al. [2016] have shown that geologic structures can accommodate a significant  
609 part of the deformation in a band associated with the main long-term fault plane. Second, the geodetic and Insar data  
610 may also not be fully representative of the geological time-scale deformations. This is the case for the Karakorum  
611 strike-slip fault whose geological rate is 10 times larger than its geodetic rates [Chevalier et al., 2005]. Similarly, the  
612 Garlock Fault in California shows no present-day accumulating deformation, but it has a ~ 5mm/yr geological slip  
613 rate [Peltzer et al., 2011]. Reconciling both rates would require non-steady mantle flow and lower crustal fault creep  
614 [Chuang and Johnson, 2011]. These two options were already debated by Gasperini et al. [2011] in the Marmara

615 region, as they obtained a NAF geological slip rate that is about one half of the one expected from plate-motion  
616 [Polonia *et al.*, 2004]. Along the NAF, both mechanisms may be at play.  
617

### 618 6.3 Uplift gradient in the Central Pontides

619  
620 T3 and T2 also provide information on the river incision rate and rock uplift over the last 130 ka in the CP. Given  
621 the height and age of the terraces, an identical incision rate of 1mm/yr is inferred for both terraces. The obtained  
622 incision rate based on two terrace remnants is integrated over a glacial/interglacial cycle and can thus be applied as a  
623 proxy for uplift following *Hancock and Anderson* [2002] or *Wegmann and Pazzaglia* [2002]. In the Gökırmak  
624 watershed located just north of the Kamil Basin, river incision rates were similarly inferred to represent uplift rates  
625 (Figure 8) [*Yıldırım et al.*, 2013a].

626  
627 Our rate can be compared to the 0.28 mm/yr rate [*Yıldırım et al.*, 2013a] derived in the Gökırmak catchment located  
628 40 km to the northeast because they are not separated by a knickpoint (Figure 8). The fluvial incision rate at Kamil  
629 by the Kızılırmak River is 3 times higher than the fluvial incision rate in the Gökırmak catchment. The uplift rate  
630 close to the NAF is thus three times higher than in the Sinop Range to the north. This conclusion is in agreement  
631 with the CP topography as investigated by *Yıldırım et al.* [2011] and illustrated in the present paper by topographic  
632 sections (Figure 1). The CP close to the NAF shows higher fluvial base levels, higher ridge levels and higher relief  
633 compare to the Sinop range to the north (Figure 8).

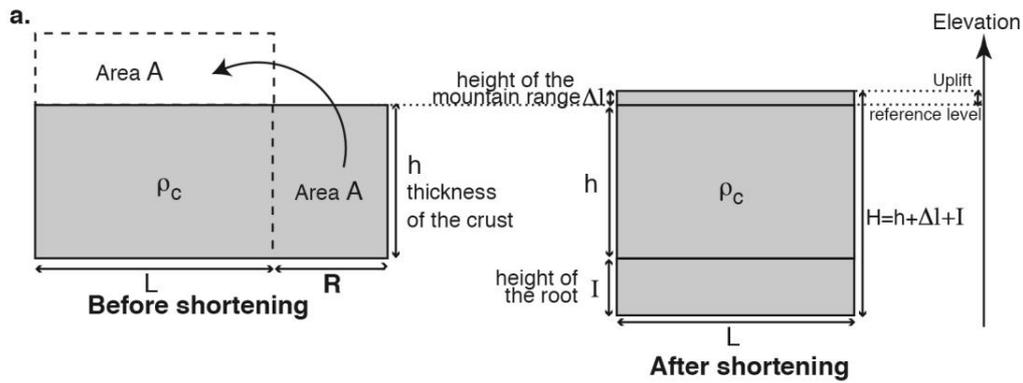
634  
635 The larger incision rate at the study location is also in agreement with the proposed tectonic model of the area. The  
636 CP are interpreted as a positive flower structure related to the convex bend of the NAF that is too narrow to  
637 accommodate without off-fault deformation the rotation of the Anatolian Plate. According to *Yıldırım et al.* [2013a],  
638 the related shortening is accommodated in a wide orogenic wedge, which reaches the Black Sea Coast and is  
639 responsible for the uplift of the CP. We evidence a non-uniform uplift within the CP Wedge with higher rate close to  
640 the NAF. It implies that the transpressional deformation is not accommodated evenly within the wedge. Therefore  
641 even regarding shortening in the orogenic wedge, the NAF is still the main structure in the deformation pattern.  
642

### 643 6.4 Erosion Rates, cumulated shortening and the role of the NAF

644 The 395 mm/ka average erosion rate from the CP Rivers ranging is significantly higher than the 40 mm/ka erosion  
645 rate of the CAP [*Aydar et al.*, 2013]. We compared them to the present-day sediment discharge (solid phase) of  
646 some of the largest rivers in Turkey draining from the CAP to the Black Sea coast. The Sakarya, Kızılırmak and  
647 Yesilirmak Rivers are transporting, respectively 8.8 Mt/yr, 23 Mt/yr, and 19 Mt/yr as bedload [*Meybeck et Ragu,*  
648 1995]. Given their respective drainage area and an average density of 2.7, an average erosion rate of 120 mm/ka can  
649 thus be obtained. The present-day average discharge at the river outlets is thus compatible with the longer-term  
650 denudation rates characterizing the CAP and the higher ones across the CP.

651  
652 The basin average erosion rates are at least two times lower than the 1mm/yr incision rate of the Kızılırmak River.  
653 As a result the Kızılırmak and Devres Rivers form marked V shaped valleys across the CP with a relief reaching  
654 over 1500 m (Figure 1).

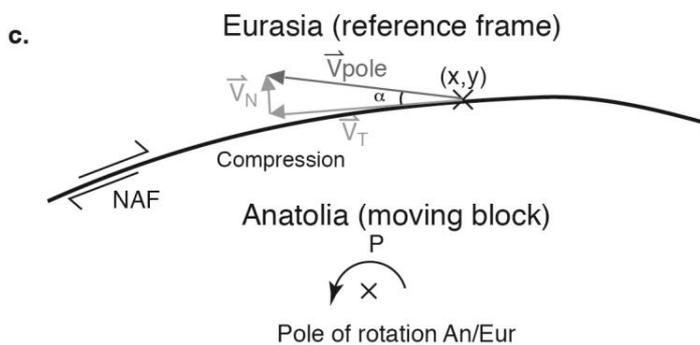
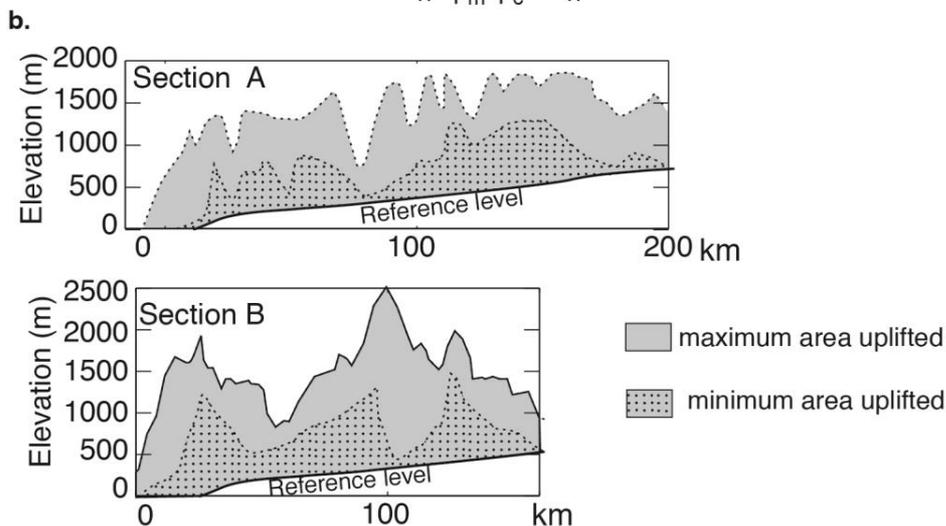
655  
656 We use erosion rates and relief to retrieve a first order mass balance of the CP (Figure 9). We evaluate a first order  
657 cumulated shortening in the CP using the relief formed above a fixed reference (i.e the theoretical topography in the  
658 region without deformation). Our reference level is the Kızılırmak base-level because of its very low incision rate  
659 across the CAP (i.e. 50 mm/ka) [*Çiner et al.*, 2015] and the low erosion rate of the plateau itself (i.e. 40 mm/ka)  
660 [*Aydar et al.*, 2013]. Farther north, it is also an adequate reference if we consider a steady state equilibrium of the  
661 landscape with an incision rate equal to the uplift rate; its geometry is similar to the strait extension of the  
662 Kızılırmak base-level from CAP to the Black Sea coast.



Mass conservation for incompressible rocks  $(L+R) h = L (H+e)$  with  $e$  : height of the surface eroded

Isostatic equilibrium  $\rho_c (h+I+\Delta l) = \rho_c h + \rho_m I$  with  $\rho_c=2.8$  density of the crust  
 $\rho_m=3.3$  density of the mantel

Shortening  $R = \frac{L \Delta l}{h} \frac{\rho_m}{\rho_m - \rho_c} + \frac{e L}{h}$



663

664 **Figure 9.** First order shortening in the CP. **a.** Mass balance considering isostasy, erosion and a  
 665 cumulated shortening  $R$ . **b.** Minimal and maximal uplifted surfaces along profiles A and B with  
 666 respect to the reference level (Figure 1). Once the surfaces are computed, shortening can be  
 667 computed. **c.** Shortening derived from the geometry of the NAF that is different from the small

668 circle of the rotation pole of Anatolia/Eurasian or from GPS vectors that form an angle with  
669 respect to the NAF central bend. A cumulated Anatolian motion of 85 km would imply a 9 km  
670 shortening in the NAF central bend, if the Anatolia/Eurasia kinematics and NAF geometry  
671 stayed constant.

672  
673  
674 On profiles A and B in Figure 1 across the CP, the minimal uplifted area lies in between the lowest topographic  
675 level and the reference level (Figure 9b). Considering (1) an isostatic equilibrium, (2) a width of the range of about  
676 200 km, (3) a crust of 30 to 40 km [Makris and Stobbe 1984; Vanacore et al., 2013], and (4) density of 2.8 and 3.3  
677 for the crust and the mantle, we obtain a minimal shortening of 12 km to 16 km. Considering a minimal erosion rate  
678 of about 120 mm/ka, we would need to add a shortening of 1.2 km over the last 2 Ma, and 3 km over the last 5 Ma.

679  
680 This shortening rate is compared to the long-term shortening induced by the NAF geometry in its central convex  
681 bend over its history (Figure 9c). Considering a cumulated lateral motion of the Anatolian Block of about 85 km  
682 [e.g. Hubert-Ferrari et al., 2002] along the small circle that best approximates the NAF trace from Erzincan in the  
683 East to the Marmara Sea in the west (Figure 1), we obtain a 9 km cumulated shortening in its central part. This  
684 inferred shortening is significantly lower than the minimal shortening inferred in the CP. A first reason is that the  
685 NAF is not the only driver of the shortening. Part of the stress related to the Arabia-Eurasian collision may be  
686 transmitted across Anatolia to the north, and concentrated at the border with the more rigid oceanic lithosphere of  
687 the Black Sea. This would explain the large relief formed by the CP continuously along the whole southern Black  
688 Sea coast and the higher elevations more to east toward the Lesser Caucasus. A second possibility is that part of the  
689 shortening is inherited and might be linked to the westward NAF propagation process. In the central bend area, the  
690 NAF encounters a large number of former active faults, as the CP has a rich tectonic history and represents an  
691 amalgamation of various terrains since the Jurassic. Because of the large number of E-W trending tectonic pre-  
692 existing structures, a distributed deformation prior to the NAF emplacement as a main structure all the way to the  
693 surface, is likely to have taken place. This process was already inferred in Hubert-Ferrari et al. [2002] and was  
694 documented farther west in the Marmara Sea [Karakaş et al., 2018].

695

## 696 **7 Conclusion**

697  
698 Geomorphic mapping, <sup>14</sup>C dating and measurements of cosmogenic nuclide concentration in riverbeds and in  
699 cobbles on strath terraces constrain the deformation pattern of the central transpressive arc of the NAF over different  
700 scales. In the Kamil Basin, T0 the most recent fill terrace was offset by ~14±2m during the last two major 1943 and  
701 1668 earthquakes, which implies that the displacement per event along the 1943 segment is variable between  
702 seismic cycles, a pattern opposite to the 1944 segment [Kondo et al., 2010]. A larger 750 m offset of T3 was  
703 evidenced, which suggests a maximum geological slip rate of 14 mm/yr compatible with the longer-term of 30 km  
704 offset of the Kızılırmak River over the last 2 Ma. Geological slip rates are smaller than the geodetic rates, which  
705 suggests that distributed deformation took place across the numerous inherited E-W trending structures of the CP.  
706 Terrace incision constrain uplift in the CP. T3 and T2 strath terraces have respective exposure ages of 85 ± 15 ka  
707 and 66±7 ka. T3 corresponds to a major Mediterranean river aggradation associated with a high denudation rate in  
708 the mountains, and T2 to a more local one. T3 and T2 stand 95 and 75 m above the Kızılırmak floodplain,  
709 respectively, and their incision provided constraints regarding uplift in the CP. The resulting 1 mm/yr uplift rate is  
710 higher than the 0.28 mm/yr one in the Gökırmak catchment just to the north [Yıldırım et al., 2013a]. Transpressive  
711 deformation in the central orogenic wedge is thus not accommodated uniformly and is higher at the center of the  
712 flower structure formed by the NAF. Finally, we evidenced (1) a 160 m/Ma minimum denudation rate of the  
713 Kızılırmak catchment in the CP, which is 3 times higher than in the CAP, and (2) higher cosmogenic nuclide  
714 denudation rates in catchments directly affected by thrust faulting; both results suggest a strong tectonic control of  
715 erosion rates in the CP and broadly in Anatolia. Erosion rates and relief above the Kızılırmak base level were  
716 combined to infer a minimal shortening rate of 15 to 19 km in the CP. It is significantly larger than the local  
717 cumulated shortening induced by the NAF restraining geometry in its central part. We thus infer that the origin of  
718 the present-day relief in the CP is partly related to compressive stresses linked to the Arabian-Eurasian collision that  
719 are transmitted through the CAP and concentrated on amalgamated faulted terrains lying against a more  
720 homogeneous Black Sea oceanic crust.

721 **Acknowledgments**

722 Our field study was greatly enhanced by the organizing assistance of Erhan Altunel  
723 from Osmangazi University, Eskishir, Turkey. The trenches were opened with the help of Jeff  
724 Frasers. Many thanks to Sevgi Altinok and Cagil Karakas for help in the field. We acknowledge  
725 the European Commission for funding this project as part of the Marie Curie Excellence Grant  
726 Project "Understanding the Irregularity of Seismic Cycles: A Case Study in Turkey" (MEXT-  
727 CT-2005-025617: Seismic Cycles). Supplemental information and data would be found on the  
728 Open Repository and Bibliography of the University of Liege (<https://orbi.uliege.be/>).

729 **References**

- 730 Akçar, N., Yavuz, V., Ivy-Ochs, S., Reber, R., Kubik, P. W., Zahno, C., & Schlüchter, C. (2014).  
731 Glacier response to the change in atmospheric circulation in the eastern Mediterranean  
732 during the Last Glacial Maximum. *Quaternary Geochronology*, 19, 27-41.
- 733 Allen, J. R., Brandt, U., Brauer, A., Hubberten, H. W., Huntley, B., Keller, J., Kraml, M.,  
734 Mackensen, A., Mingram, J., Negendank, Nowaczyk, N. R., Oberhansli, H., Watts, W.A.,  
735 Wulf, S., Zolitschka, B. (1999). Rapid environmental changes in southern Europe during  
736 the last glacial period. *Nature*, 400(6746), 740.
- 737 Allmendinger, R. W., R. Reilinger, and J. Loveless (2007), Strain and rotation rate from GPS in  
738 Tibet, Anatolia, and the Altiplano, *Tectonics*, 26, TC3013, doi:10.1029/2006TC002030.
- 739 Ambraseys, N. N. (1970). Some characteristic features of the Anatolian fault zone.  
740 *Tectonophysics*, 9(2-3), 143-165.
- 741 Anderson RS & Anderson SP (2010). *Geomorphology: The Mechanics and Chemistry of*  
742 *Landscapes*. xvi+ 637pp. Cambridge University Press. ISBN 978 0 521 51978 6.
- 743 Anderson, R. S., Anderson, S. P., & Tucker, G. E. (2013). Rock damage and regolith transport  
744 by frost: An example of climate modulation of the geomorphology of the critical zone.  
745 *Earth Surface Processes and Landforms*, 38(3), 299-316.
- 746 Andrieux, J., Över, S., Poisson, A., & Bellier, O. (1995). The North Anatolian Fault Zone:  
747 distributed Neogene deformation in its northward convex part. *Tectonophysics*, 243(1-2),  
748 135-154.
- 749 Applegate, P. J., Urban, N. M., Keller, K., Lowell, T. V., Laabs, B. J., Kelly, M. A., & Alley, R.  
750 B. (2012). Improved moraine age interpretations through explicit matching of  
751 geomorphic process models to cosmogenic nuclide measurements from single landforms.  
752 *Quaternary Research*, 77(2), 293-304. Armijo, R., Lyon-Caen, H., & Papanastassiou, D.  
753 (1992). East-west extension and Holocene normal-fault scarps in the Hellenic arc.  
754 *Geology*, 20(6), 491-494.
- 755 Armitage, J. J., Duller, R. A., Whittaker, A. C., & Allen, P. A. (2011). Transformation of  
756 tectonic and climatic signals from source to sedimentary archive. *Nature Geoscience*,  
757 4(4), 231.
- 758 Arnold, Maurice, et al. "The French accelerator mass spectrometry facility ASTER: improved  
759 performance and developments." *Nuclear Instruments and Methods in Physics Research*  
760 *Section B: Beam Interactions with Materials and Atoms* 268.11-12 (2010): 1954-1959.

- 761 Aydar, E., Cubukcu, H. E., Şen, E., & Akin, L. (2013). Central Anatolian Plateau, Turkey:  
762 incision and paleoaltimetry recorded from volcanic rocks. *Turkish J Earth Sci*, 22, 739-  
763 746. Badertscher, S., Fleitmann, D., Cheng, H., Edwards, R. L., Göktürk, O. M.,  
764 Zumbühl, A., ... & Tüysüz, O. (2011). Pleistocene water intrusions from the  
765 Mediterranean and Caspian seas into the Black Sea. *Nature Geoscience*, 4(4), 236.
- 766 Balco, G., Stone, J. O., Lifton, N. A., & Dunai, T. J. (2008). A complete and easily accessible  
767 means of calculating surface exposure ages or erosion rates from  $^{10}\text{Be}$  and  $^{26}\text{Al}$   
768 measurements. *Quaternary geochronology*, 3(3), 174-195.
- 769 Ballato, P., Parra, M., Schildgen, T. F., Dunkl, I., Yıldırım, C., Özsayın, E., ... & Strecker, M. R.  
770 (2018). Multiple exhumation phases in the Central Pontides (N Turkey): New temporal  
771 constraints on major geodynamic changes associated with the closure of the Neo-Tethys  
772 Ocean. *Tectonics*, 37(6), 1831-1857.
- 773 Barka, A. A., & Hancock, P. L. (1984). Neotectonic deformation patterns in the convex-  
774 northwards arc of the North Anatolian fault zone. Geological Society, London, Special  
775 Publications, 17(1), 763-774.
- 776 Barka, A. A. (1984). Geology and tectonic evolution of some Neogene-Quaternary basins in the  
777 North Anatolian fault zone, special publication. *Geol. Soc. of Turk*, 209-227.
- 778 Barka, A. A., & Kadinsky-Cade, K. (1988). Strike-slip fault geometry in Turkey and its  
779 influence on earthquake activity. *Tectonics*, 7(3), 663-684.
- 780 Barka, A. (1996). Slip distribution along the North Anatolian fault associated with the large  
781 earthquakes of the period 1939 to 1967. *Bulletin of the Seismological Society of*  
782 *America*, 86(5), 1238-1254.
- 783 Benedetti, L., Finkel, R., Papanastassiou, D., King, G., Armijo, R., Ryerson, F., ... & Flerit, F.  
784 (2002). Post-glacial slip history of the Sparta fault (Greece) determined by  $^{36}\text{Cl}$   
785 cosmogenic dating: Evidence for non-periodic earthquakes. *Geophysical Research*  
786 *Letters*, 29(8), 87-1.
- 787 Berndt, C., Yıldırım, C., Çiner, A., Strecker, M. R., Ertunç, G., Sarıkaya, M. A., ... & Kiyak, N.  
788 G. (2018). Quaternary uplift of the northern margin of the Central Anatolian Plateau:  
789 New OSL dates of fluvial and delta-terrace deposits of the Kızılırmak River, Black Sea  
790 coast, Turkey. *Quaternary Science Reviews*, 201, 446-469.
- 791 Bierman, P., & Steig, E. J. (1996). Estimating rates of denudation using cosmogenic isotope  
792 abundances in sediment. *Earth surface processes and landforms*, 21(2), 125-139.
- 793 Borchers, B., Marrero, S., Balco, G., Caffee, M., Goehring, B., Lifton, N., ... & Stone, J. (2016).  
794 Geological calibration of spallation production rates in the CRONUS-Earth project.  
795 *Quaternary Geochronology*, 31, 188-198.
- 796 Bridgland, D. R. (2000). River terrace systems in north-west Europe: an archive of  
797 environmental change, uplift and early human occupation. *Quaternary Science Reviews*,  
798 19(13), 1293-1303.

- 799 Brown, E. T., Bourlès, D. L., Colin, F., Raisbeck, G. M., Yiou, F., & Desgarceaux, S. (1995).  
800 Evidence for muon-induced production of  $^{10}\text{Be}$  in near-surface rocks from the Congo.  
801 *Geophysical Research Letters*, 22(6), 703-706.
- 802 Brown, E. T., Molnar, P., and Bourlès, D. L., 2005. Comment on "Slip-rate measurements on the  
803 630 Karakorum Fault may imply secular variations in fault motion." *Science* 309, 1326b.
- 804 Burbank, D. W., & Anderson, R. S. (2009). *Tectonic geomorphology*. John Wiley & Sons.
- 805 Çağatay, M. N., Öğretmen, N., Damcı, E., Stockhecke, M., Sancar, Ü., Eriş, K. K., & Özeren, S.  
806 (2014). Lake level and climate records of the last 90ka from the Northern Basin of Lake  
807 Van, eastern Turkey. *Quaternary Science Reviews*, 104, 97-116.
- 808 Cavalié, O., & Jónsson, S. (2014). Block-like plate movements in eastern Anatolia observed by  
809 InSAR. *Geophysical Research Letters*, 41(1), 26-31.
- 810 Cavazza, C., I. Federici, A. I. Okay, and M. Zattin (2012), Apatite fissiontrack  
811 thermochronology of the Western Pontides (NW Turkey), *Geol. Mag.*, 149, 133–140.
- 812 Çiner, A., Doğan, U., Yıldırım, C., Akçar, N., Ivy-Ochs, S., Alfimov, V., ... & Schlüchter, C.  
813 (2015). Quaternary uplift rates of the Central Anatolian Plateau, Turkey: insights from  
814 cosmogenic isochron-burial nuclide dating of the Kızılırmak River terraces. *Quaternary  
815 Science Reviews*, 107, 81-97.
- 816 Çinku, M. C., Hisarlı, Z. M., Heller, F., Orbay, N., & Ustaömer, T. (2011). Middle Eocene  
817 paleomagnetic data from the eastern Sakarya Zone and the central Pontides: Implications  
818 for the tectonic evolution of north central Anatolia. *Tectonics*, 30(1).
- 819 Chevalier, M. L., Ryerson, F. J., Tapponnier, P., Finkel, R. C., Van Der Woerd, J., Haibing, L.,  
820 & Qing, L. (2005). Slip-rate measurements on the Karakorum fault may imply secular  
821 variations in fault motion. *science*, 307(5708), 411-414.
- 822 Chmeleff, J., von Blanckenburg, F., Kossert, K., Jakob, J. (2010). Determination of the  $^{10}\text{Be}$   
823 half-life by multicollector ICP-MS and liquid scintillation counting. *Nuclear Instruments  
824 and Methods in Physics Research B* 268, 192- 199.
- 825 Chuang, R. Y., & Johnson, K. M. (2011). Reconciling geologic and geodetic model fault slip-  
826 rate discrepancies in Southern California: Consideration of nonsteady mantle flow and  
827 lower crustal fault creep. *Geology*, 39(7), 627-630.
- 828 Cukur, D., Krastel, S., Schmincke, H. U., Sumita, M., Çağatay, M. N., Meydan, A. F., ... &  
829 Stockhecke, M. (2014). Seismic stratigraphy of lake Van, eastern Turkey. *Quaternary  
830 Science Reviews*, 104, 63-84.
- 831 Daout, S., S. Barbot, G. Peltzer, M.-P. Doin, Z. Liu, and R. Jolivet (2016). Constraining the  
832 kinematics of metropolitan Los Angeles faults with a slip-partitioning model, *Geophys.  
833 Res. Lett.*, 43, 11,192–11,201 doi:10.1002/2016GL071061.
- 834 D'Arcy, M., Roda-Boluda, D. C., & Whittaker, A. C. (2017). Glacial-interglacial climate changes  
835 recorded by debris flow fan deposits, Owens Valley, California. *Quaternary Science  
836 Reviews*, 169, 288-311.

- 837 Desilets, D., Zreda, M., & Prabu, T. (2006). Extended scaling factors for in situ cosmogenic  
838 nuclides: new measurements at low latitude. *Earth and Planetary Science Letters*, 246(3-  
839 4), 265-276.
- 840 Doğan, U. (2010). Fluvial response to climate change during and after the Last Glacial  
841 Maximum in Central Anatolia, Turkey. *Quaternary International*, 222(1-2), 221-229.
- 842 Doğan, U. (2011). Climate-controlled river terrace formation in the Kızılırmak Valley,  
843 Cappadocia section, Turkey: inferred from Ar–Ar dating of Quaternary basalts and  
844 terraces stratigraphy. *Geomorphology*, 126(1-2), 66-81.
- 845 Edmond, J. M., & Huh, Y. (1997). Chemical weathering yields from basement and orogenic  
846 terrains in hot and cold climates. In *Tectonic uplift and climate change* (pp. 329-351).  
847 Springer, Boston, MA.
- 848 Farber, D. L., Mériaux, A. S., & Finkel, R. C. (2008). Attenuation length for fast nucleon  
849 production of  $^{10}\text{Be}$  derived from near-surface production profiles. *Earth and Planetary  
850 Science Letters*, 274(3-4), 295-300.
- 851 Fleitmann, D., Cheng, H., Badertscher, S., Edwards, R. L., Mudelsee, M., Göktürk, O. M., ... &  
852 Kramers, J. (2009). Timing and climatic impact of Greenland interstadials recorded in  
853 stalagmites from northern Turkey. *Geophysical Research Letters*, 36(19).
- 854 Fraser, J., Vanneste, K., & Hubert-Ferrari, A. (2010). Recent behavior of the North Anatolian  
855 Fault: Insights from an integrated paleoseismological data set. *Journal of Geophysical  
856 Research: Solid Earth*, 115(B9).
- 857 Fraser, J., Hubert-Ferrari, A., Vanneste, K., Altinok, S., & Drab, L. (2010). A relict paleoseismic  
858 record of seven earthquakes between 2000 BC and 600 AD on the central North  
859 Anatolian fault at Elmacik, near Osmancik, Turkey. *Bulletin*, 122(11-12), 1830-1845.
- 860 Fuller, I. C., Macklin, M. G., Lewin, J., Passmore, D. G., & Wintle, A. G. (1998). River response  
861 to high-frequency climate oscillations in southern Europe over the past 200 ky. *Geology*,  
862 26(3), 275-278.
- 863 Fuller, T. K., Perg, L. A., Willenbring, J. K., & Lepper, K. (2009). Field evidence for climate-  
864 driven changes in sediment supply leading to strath terrace formation. *Geology*, 37(5),  
865 467-470.
- 866 Gasperini, L., Polonia, A., Çağatay, M. N., Bortoluzzi, G., & Ferrante, V. (2011). Geological slip  
867 rates along the North Anatolian Fault in the Marmara region. *Tectonics*, 30(6).
- 868 Göktürk, O. M., Fleitmann, D., Badertscher, S., Cheng, H., Edwards, R. L., Leuenberger, M., ...  
869 & Kramers, J. (2011). Climate on the southern Black Sea coast during the Holocene:  
870 implications from the Sofular Cave record. *Quaternary Science Reviews*, 30(19-20),  
871 2433-2445.
- 872 Gosse, J. C., & Phillips, F. M. (2001). Terrestrial in situ cosmogenic nuclides: theory and  
873 application. *Quaternary Science Reviews*, 20(14), 1475-1560.
- 874 Granger, D. E., Kirchner, J. W., & Finkel, R. (1996). Spatially averaged long-term erosion rates  
875 measured from in situ-produced cosmogenic nuclides in alluvial sediment. *The Journal of  
876 Geology*, 104(3), 249-257.

- 877 Granger, D. E., & Smith, A. L. (2000). Dating buried sediments using radioactive decay and  
878 muogenic production of  $^{26}\text{Al}$  and  $^{10}\text{Be}$ . *Nuclear Instruments and Methods in Physics*  
879 *Research Section B: Beam Interactions with Materials and Atoms*, 172(1-4), 822-826.
- 880 Hales, T. C., & Roering, J. J. (2007). Climatic controls on frost cracking and implications for the  
881 evolution of bedrock landscapes. *Journal of Geophysical Research: Earth Surface*,  
882 112(F2).
- 883 Hancock, G. S., & Anderson, R. S. (2002). Numerical modeling of fluvial strath-terrace  
884 formation in response to oscillating climate. *Geological Society of America Bulletin*,  
885 114(9), 1131-1142.
- 886 Hetzel, R., Niedermann, S., Tao, M., Kubik, P. W., & Strecker, M. R. (2006). Climatic versus  
887 tectonic control on river incision at the margin of NE Tibet:  $^{10}\text{Be}$  exposure dating of  
888 river terraces at the mountain front of the Qilian Shan. *Journal of Geophysical Research:*  
889 *Earth Surface*, 111(F3).
- 890 Herece E. and Akay E., 2003, Atlas of North Anatolian Fault (NAF). General Directorate of  
891 Mineral Research and Exploration, Special Publication series-2, Ankara, 61 p+13  
892 appendices as separate maps.
- 893 Hubert-Ferrari, A., R. Armijo, B. Meyer, G.C.P. King and A. Barka (2002). Morphology,  
894 displacement and slip rates along the North Antolian Fault (Turkey), *J. Geophys. Res.*,  
895 107; doi:10.1029/2001JB000393.
- 896 Hussain, E., Hooper, A., Wright, T. J., Walters, R. J., & Bekaert, D. P. (2016). Interseismic strain  
897 accumulation across the central North Anatolian Fault from iteratively unwrapped InSAR  
898 measurements. *Journal of Geophysical Research: Solid Earth*, 121(12), 9000-9019.
- 899 Hussain, E., Wright, T. J., Walters, R. J., Bekaert, D. P., Lloyd, R., & Hooper, A. (2018).  
900 Constant strain accumulation rate between major earthquakes on the North Anatolian  
901 Fault. *Nature communications*, 9(1), 1392.
- 902 ~~Ivy-Ochs, S., & Schaller, M. (2009). Examining processes and rates of landscape change with~~  
903 ~~cosmogenic radionuclides. *Radioactivity in the Environment*, 16, 231-294.~~
- 904 Jones, M. D., Roberts, C. N., & Leng, M. J. (2007). Quantifying climatic change through the last  
905 glacial–interglacial transition based on lake isotope palaeohydrology from central  
906 Turkey. *Quaternary Research*, 67(3), 463-473.
- 907 Karakaş, Ç., Armijo, R., Lacassin, R., Suc, J. P., & Melinte-Dobrinescu, M. C. (2018). Crustal  
908 strain in the Marmara pull-apart region associated with the propagation process of the  
909 North Anatolian Fault. *Tectonics*, 37(5), 1507-1523.
- 910 Karasözen, E., Özacar, A. A., Biryol, C. B., & Beck, S. L. (2013). Seismicity, focal mechanisms  
911 and active stress field around the central segment of the North Anatolian Fault in Turkey.  
912 *Geophysical Journal International*, 196(1), 405-421.
- 913 Kohl, C. P., & Nishiizumi, K. (1992). Chemical isolation of quartz for measurement of in-situ-  
914 produced cosmogenic nuclides. *Geochimica et Cosmochimica Acta*, 56(9), 3583-3587.

- 915 Kondo, H., Özaksoy, V., & Yildirim, C. (2010). Slip history of the 1944 Bolu-Gerede  
916 earthquake rupture along the North Anatolian fault system: Implications for recurrence  
917 behavior of multisegment earthquakes. *Journal of Geophysical Research: Solid Earth*,  
918 115(B4).
- 919 Korschinek, G., Bergmaier, A., Faestermann, T., Gerstmann, U.C., Knie, K., Rugel, G., Wallner,  
920 A., Dillmann, I., Dollinger, G., von Gostomski, Lierse Ch., Kossert, K., Maitia, M.,  
921 Poutivtsev, M., Remmert, A., 2010. A new value for the half-life of  $^{10}\text{Be}$  by Heavy-Ion  
922 Elastic Recoil Detection and liquid scintillation counting. *Nuclear Instruments and*  
923 *Methods in Physics Research B*. 268, 187–191.
- 924 Kozacı, O., J.F. Dolan, R.C. Finkel and R.D. Hartleb (2007). Late Holocene slip rate for the  
925 North Anatolian Fault, Turkey, from cosmogenic  $^{36}\text{Cl}$  geochronology: implications for  
926 the constancy of fault loading and strain release rates, *Geology*, 35, 867-870;  
927 doi:10.1130/G23187A.1.
- 928 Kozacı, Ö., Dolan, J. F., & Finkel, R. C. (2009). A late Holocene slip rate for the central North  
929 Anatolian fault, at Tahtaköprü, Turkey, from cosmogenic  $^{10}\text{Be}$  geochronology:  
930 Implications for fault loading and strain release rates. *Journal of Geophysical Research:*  
931 *Solid Earth*, 114(B1).
- 932 Kozacı, O., J. Dolan, O. Yonlü and R. Hartleb (2011). Paleoseismologic evidence for the  
933 relatively regular recurrence of infrequent, large-magnitude earthquakes on the eastern  
934 North Anatolian Fault at Yaylabeli, Turkey, *Lithosphere*, 3, 37-54; doi:10.1130/L118.1.
- 935 Kreemer, C., Holt, W. E., & Haines, A. J. (2003). An integrated global model of present-day  
936 plate motions and plate boundary deformation. *Geophysical Journal International*, 154(1),  
937 8-34.
- 938 Langgut, D., Almogi-Labin, A., Bar-Matthews, M., & Weinstein-Evron, M. (2011). Vegetation  
939 and climate changes in the South Eastern Mediterranean during the Last Glacial-  
940 Interglacial cycle (86 ka): new marine pollen record. *Quaternary Science Reviews*,  
941 30(27-28), 3960-3972.
- 942 Le Dortz, K., Meyer, B., Sébrier, M., Nazari, H., Braucher, R., Fattahi, M., ... & Talebian, M.  
943 (2009). Holocene right-slip rate determined by cosmogenic and OSL dating on the Anar  
944 fault, Central Iran. *Geophysical Journal International*, 179(2), 700-710.
- 945 Lifton, N., Sato, T., & Dunai, T. J. (2014). Scaling in situ cosmogenic nuclide production rates  
946 using analytical approximations to atmospheric cosmic-ray fluxes. *Earth and Planetary*  
947 *Science Letters*, 386, 149-160.
- 948 Litt, T., Pickarski, N., Heumann, G., Stockhecke, M., & Tzedakis, P. C. (2014). A 600,000 year  
949 long continental pollen record from Lake Van, eastern Anatolia (Turkey). *Quaternary*  
950 *Science Reviews*, 104, 30-41.
- 951 Macklin, M. G., Fuller, I. C., Lewin, J., Maas, G. S., Passmore, D. G., Rose, J., ... & Rowan, J. S.  
952 (2002). Correlation of fluvial sequences in the Mediterranean basin over the last 200 ka  
953 and their relationship to climate change. *Quaternary Science Reviews*, 21(14-15), 1633-  
954 1641.

- 955 Makris, J., & Stobbe, C. (1984). Physical properties and state of the crust and upper mantle of  
956 the Eastern Mediterranean Sea deduced from geophysical data. *Marine Geology*, 55(3-4),  
957 347-363.
- 958 Martin, L. C. P., Blard, P. H., Balco, G., Lavé, J., Delunel, R., Lifton, N., & Laurent, V. (2017).  
959 The CREp program and the ICE-D production rate calibration database: a fully  
960 parameterizable and updated online tool to compute cosmic-ray exposure ages.  
961 *Quaternary geochronology*, 38, 25-49.
- 962 Matsuoka, N. (2008). Frost weathering and rockwall erosion in the southeastern Swiss Alps:  
963 Long-term (1994–2006) observations. *Geomorphology*, 99(1-4), 353-368.
- 964 McKenzie, D. (1972). Active tectonics of the Mediterranean region. *Geophysical Journal of the*  
965 *Royal Astronomical Society*, 30(2), 109-185.
- 966 McClain, K., Yıldırım, C., Çiner, A., Akif Sarıkaya, M., Sahin, S., Özcan, O., ... & Öztürk, T.  
967 (2017, April). Quantification of fluvial response to tectonic deformation in the Central  
968 Pontides, Turkey; inferences from OSL dating of fluvial terraces. In EGU General  
969 Assembly Conference Abstracts (Vol. 19, p. 772).
- 970 Mériaux, A. S., Tapponnier, P., Ryerson, F. J., Xiwei, X., King, G., Van der Woerd, J., ... &  
971 Wenbin, C. (2005). The Aksay segment of the northern Altyn Tagh fault: Tectonic  
972 geomorphology, landscape evolution, and Holocene slip rate. *Journal of Geophysical*  
973 *Research: Solid Earth*, 110(B4).
- 974 Meybeck, M., & Ragu, A. (1995). River discharges to the oceans: An assessment of suspended  
975 solids, major ions and nutrients, 245 pp. UN Environ. Programme, Nairobi. Morewood,  
976 N. C., & Roberts, G. P. (2000). The geometry, kinematics and rates of deformation within  
977 an en échelon normal fault segment boundary, central Italy. *Journal of Structural*  
978 *Geology*, 22(8), 1027-1047.
- 979 Mudd, S. M., Harel, M. A., Hurst, M. D., Grieve, S. W., & Marrero, S. M. (2016). The CAIRN  
980 method: automated, reproducible calculation of catchment-averaged denudation rates  
981 from cosmogenic nuclide concentrations. *Earth Surface Dynamics*, 4(3), 655-674.
- 982 Mudie, P.J., Marret, F., Aksu, A.E., Hiscott, R.N., Gillespie, H., 2007. Palynological evidence  
983 for climatic change, anthropogenic activity and outflow of Black Sea water during the  
984 last Pleistocene and Holocene: centennial- to decadal-scale records from the Black and  
985 Marmara Seas. *Quaternary International* 167–168, 73–90.
- 986 Nishiizumi, K. (2004). Preparation of <sup>26</sup>Al AMS standards. *Nuclear Instruments and Methods in*  
987 *Physics Research Section B: Beam Interactions with Materials and Atoms*, 223, 388-392.
- 988 Okay, A. I., and O. Tüysüz (1999), Tethyan sutures of northern Turkey, in *The Mediterranean*  
989 *Basins: Tertiary Extension Within the Alpine Orogen*, vol. 156, edited by B. Durand et  
990 al., pp. 475–515, Geological Society, London, Special Publication, Oxford, UK.
- 991 Ottria, G., Pandolfi, L., Catanzariti, R., Da Prato, S., Ellero, A., Frassi, C., ... & Sayit, K. (2017).  
992 Evolution of an early Eocene pull-apart basin in the Central Pontides (Northern Turkey):  
993 New insights into the origin of the North Anatolian Shear Zone. *Terra Nova*, 29(6), 392-  
994 400.

- 995 Over, S., Bellier, O., Poisson, A., Andrieux, J., & Tutkun, Z. (1993). Late Cenozoic fault  
996 kinematics within basins along the central North Anatolian fault zone (turkey). *Comptes*  
997 *Rendus de l'Académie des Sciens Serie II*, 317(6), 827-833.
- 998 Peltzer, G., Crampé, F., Hensley, S., & Rosen, P. (2001). Transient strain accumulation and fault  
999 interaction in the Eastern California shear zone. *Geology*, 29(11), 975-978.
- 1000 Piccardi, L., Gaudemer, Y., Tapponnier, P., & Boccaletti, M. (1999). Active oblique extension in  
1001 the central Apennines (Italy): evidence from the Fucino region. *Geophysical Journal*  
1002 *International*, 139(2), 499-530.
- 1003 Pickarski, N., Kwiecien, O., Djamali, M., & Litt, T. (2015). Vegetation and environmental  
1004 changes during the last interglacial in eastern Anatolia (Turkey): a new high-resolution  
1005 pollen record from Lake Van. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 435,  
1006 145-158.
- 1007 Polonia, A., Gasperini, L., Amorosi, A., Bonatti, E., Bortoluzzi, G., Cagatay, N., ... & Seeber, L.  
1008 (2004). Holocene slip rate of the North Anatolian Fault beneath the Sea of Marmara.  
1009 *Earth and Planetary Science Letters*, 227(3-4), 411-426.
- 1010 Portenga, E. W., & Bierman, P. R. (2011). Understanding Earth's eroding surface with 10 Be.  
1011 *GsA today*, 21(8), 4-10.
- 1012 Pucci, S., De Martini, P. M., & Pantosti, D. (2008). Preliminary slip rate estimates for the Düzce  
1013 segment of the North Anatolian Fault Zone from offset geomorphic markers.  
1014 *Geomorphology*, 97(3-4), 538-554.
- 1015 Reber, R., Akçar, N., Yesilyurt, S., Yavuz, V., Tikhomirov, D., Kubik, P. W., & Schlüchter, C.  
1016 (2014). Glacier advances in northeastern Turkey before and during the global Last  
1017 Glacial Maximum. *Quaternary Science Reviews*, 101, 177-192.
- 1018 Reilinger, R., McClusky, S., Vernant, P., Lawrence, S., Ergintav, S., Cakmak, R., ... & Nadariya,  
1019 M. (2006). GPS constraints on continental deformation in the Africa-Arabia-Eurasia  
1020 continental collision zone and implications for the dynamics of plate interactions. *Journal*  
1021 *of Geophysical Research: Solid Earth*, 111(B5).
- 1022 Roberts, N., Reed, J. M., Leng, M. J., Kuzucuoğlu, C., Fontugne, M., Bertaux, J., ... &  
1023 Karabiyikoğlu, M. (2001). The tempo of Holocene climatic change in the eastern  
1024 Mediterranean region: new high-resolution crater-lake sediment data from central  
1025 Turkey. *The Holocene*, 11(6), 721-736.
- 1026 Schimmelpfennig, I., Benedetti, L., Finkel, R., Pik, R., Blard, P. H., Bourles, D., ... & Williams,  
1027 A. (2009). Sources of in-situ <sup>36</sup>Cl in basaltic rocks. Implications for calibration of  
1028 production rates. *Quaternary Geochronology*, 4(6), 441-461.
- 1029 Schimmelpfennig, I., Benedetti, L., Garreta, V., Pik, R., Blard, P. H., Burnard, P., ... & Dunai, T.  
1030 (2011). Calibration of cosmogenic <sup>36</sup>Cl production rates from Ca and K spallation in  
1031 lava flows from Mt. Etna (38 N, Italy) and Payun Matru (36 S, Argentina). *Geochimica et*  
1032 *Cosmochimica Acta*, 75(10), 2611-2632.
- 1033 Shumilovskikh, L. S., Tarasov, P., Arz, H. W., Fleitmann, D., Marret, F., Nowaczyk, N., Plessen,  
1034 B., Schlütz, F., and Behling, H. (2012). Vegetation and environmental dynamics in the

- 1035 southern Black Sea region since 18 kyr BP derived from the marine core 22-GC3,  
1036 Palaeogeogr. Palaeoclimatol., 337–338, 177–193.
- 1037 Shumilovskikh, L. S., Arz, H., Fleitmann, D., Marret, F., Nowaczyk, N., Tarasov, P., Wegwerth,  
1038 A., and Behling, H. (2013). Vegetation and environmental changes in Northern Anatolia  
1039 during penultimate deglaciation and Eemian recorded in Black Sea sediments,  
1040 Quaternary Res., 80, 349–360.
- 1041 Schumilovskikh, L. S., Fleitmann, D., Nowaczyk, N. R., Behling, H., Marret, F., Wegwerth, A.,  
1042 & Arz, H. W. (2014). Orbital and millennial-scale environmental changes between 64 and  
1043 25 ka BP recorded in Black Sea sediments. *Climate of the Past*, 10, 939-945.
- 1044 Şengör, A. M. C., & Yılmaz, Y. (1981). Tethyan evolution of Turkey: a plate tectonic approach.  
1045 *Tectonophysics*, 75(3-4), 181-241.
- 1046 Şengör, A. M. C., Tüysüz, O., Imren, C., Sakıncı, M., Eyidoğan, H., Görür, N., ... & Rangin, C.  
1047 (2005). The North Anatolian fault: A new look. *Annu. Rev. Earth Planet. Sci.*, 33, 37-  
1048 112.
- 1049 Siame, L. L., Angelier, J., Chen, R. F., Godard, V., Derrioux, F., Bourlès, D. L., ... & Lee, J. C.  
1050 (2011). Erosion rates in an active orogen (NE-Taiwan): A confrontation of cosmogenic  
1051 measurements with river suspended loads. *Quaternary Geochronology*, 6(2), 246-260.
- 1052 Stone, J.O., 2000. Air pressure and cosmogenic isotope production. *Journal of Geophysical*  
1053 *Research* 105, 23753–23759.
- 1054 Tucker, G. E., McCoy, S. W., Whittaker, A. C., Roberts, G. P., Lancaster, S. T., & Phillips, R.  
1055 (2011). Geomorphic significance of postglacial bedrock scarps on normal-fault footwalls.  
1056 *Journal of Geophysical Research: Earth Surface*, 116(F1).
- 1057 Tapponnier, P., Ryerson, F. J., Van der Woerd, J., Mériaux, A. S., & Lasserre, C. (2001). Long-  
1058 term slip rates and characteristic slip: keys to active fault behaviour and earthquake  
1059 hazard. *Comptes Rendus de l'Académie des Sciences-Series IIA-Earth and Planetary*  
1060 *Science*, 333(9), 483-494.
- 1061 Vallage, A., Klinger, Y., Lacassin, R., Delorme, A., & Pierrot-Deseilligny, M. (2016).  
1062 Geological structures control on earthquake ruptures: The Mw7. 7, 2013, Balochistan  
1063 earthquake, Pakistan. *Geophysical Research Letters*, 43(19), 10-155.
- 1064 Valsecchi, V., Goni, M. F., & Londeix, L. (2012). Vegetation dynamics in the Northeastern  
1065 Mediterranean region during the past 23 000 yr: insights from a new pollen record from  
1066 the Sea of Marmara. *Climate of the Past*, 8(6).
- 1067 Vanacore, E. A., Taymaz, T., & Saygin, E. (2013). Moho structure of the Anatolian Plate from  
1068 receiver function analysis. *Geophysical Journal International*, 193(1), 329-337.
- 1069 Van Der Woerd, J., Klinger, Y., Sieh, K., Tapponnier, P., Ryerson, F. J., & Mériaux, A. S.  
1070 (2006). Long-term slip rate of the southern San Andreas fault from 10Be-26Al surface  
1071 exposure dating of an offset alluvial fan. *Journal of Geophysical Research: Solid Earth*,  
1072 111(B4).

- 1073 Von Blanckenburg, F. (2006). The control mechanisms of erosion and weathering at basin scale  
1074 from cosmogenic nuclides in river sediment. *Earth and Planetary Science Letters*, 242(3-  
1075 4), 224-239.
- 1076 Wegmann, K. W., & Pazzaglia, F. J. (2002). Holocene strath terraces, climate change, and active  
1077 tectonics: The Clearwater River basin, Olympic Peninsula, Washington State. *Geological*  
1078 *Society of America Bulletin*, 114(6), 731-744.
- 1079 Westaway, R., Pringle, M., Yurtmen, S., Demir, T., Bridgland, D., Rowbotham, G., & Maddy,  
1080 D. (2004). Pliocene and Quaternary regional uplift in western Turkey: the Gediz River  
1081 terrace staircase and the volcanism at Kula. *Tectonophysics*, 391(1-4), 121-169.
- 1082 Wright, T., B. Parsons, and E. Fielding (2001), Measurement of interseismic strain accumulation  
1083 across the North Anatolian Fault by satellite radar interferometry, *Geophys. Res. Lett.*,  
1084 28(10), 2117–2120.
- 1085 Yavaşoğlu, H., Tari, E., Tüysüz, O., Çakır, Z., & Ergintav, S. (2011). Determining and modeling  
1086 tectonic movements along the central part of the North Anatolian Fault (Turkey) using  
1087 geodetic measurements. *Journal of Geodynamics*, 51(5), 339-343.
- 1088 Yıldırım, C., T. F. Schildgen, H. Echtler, D. Melnick, and M. R. Strecker (2011), Late Neogene  
1089 and active orogenic uplift in the Central Pontides associated with the North Anatolian  
1090 Fault: Implications for the northern margin of the Central Anatolian Plateau, Turkey,  
1091 *Tectonics*, 30, TC5005, doi:10.1029/2010TC002756.
- 1092 Yıldırım, C., Schildgen, T. F., Echtler, H., Melnick, D., Bookhagen, B., Çiner, A., ... & Strecker,  
1093 M. R. (2013a). Tectonic implications of fluvial incision and pediment deformation at the  
1094 northern margin of the Central Anatolian Plateau based on multiple cosmogenic nuclides.  
1095 *Tectonics*, 32(5), 1107-1120.
- 1096 Yıldırım, C., Melnick, D., Ballato, P., Schildgen, T. F., Echtler, H., Erginal, A. E., ... & Strecker,  
1097 M. R. (2013b). Differential uplift along the northern margin of the Central Anatolian  
1098 Plateau: inferences from marine terraces. *Quaternary Science Reviews*, 81, 12-28.

1099

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1111 Deng, A., and D. R. Stauffer (2006), On improving 4-km mesoscale model simulations, *J. Appl.*  
1112 *Meteorol. Climatol.*, 45(3), 361–381, doi:10.1175/JAM2341.1.

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1114

1115 **Table 1.**  $^{10}\text{Be}$ - $^{26}\text{Al}$  samples: AMS results, Cronus model age (no inheritance, no erosion), and  
 1116 erosion rates (density 2.7 for all samples). Sample locations in Table S1.

Samples	Be measurements				Age	Erosion	Al measurements				Age	Erosion
	Quartz (g)	$^9\text{Be}$ carrier (mg)	$^{10}\text{Be}/^9\text{Be}$ ( $\times 10^{-13}$ )	$^{10}\text{Be}$ (at/g qtz)			$^{10}\text{Be}$ age (yrs)	$^{10}\text{Be}$ Erosion rate (m/Ma)	$^{27}\text{Al}$ natural (mg)	$^{27}\text{Al}$ carrier added (mg)		
T3-3	24	0	4,56414 $\pm 0,12978$	613515 $\pm 21328$	98976 $\pm 9493$	-	0,86	1,30	15,09648 $\pm 0,43872$	3024445 $\pm 185074$	82243 $\pm 9101$	-
T3-4	1	0	0,2505 $\pm 0,01305$	413535 $\pm 23083$	63712 $\pm 6684$	-	0,23	2,14	0,54527 $\pm 0,05223$	2840362 $\pm 312111$	74138 $\pm 10772$	-
T3-5	21	1	2,93369 $\pm 0,08785$	459017 $\pm 16528$	71273 $\pm 6822$	-	1,75	0,27	13,09778 $\pm 0,40262$	2745533 $\pm 170244$	72009 $\pm 7963$	-
T2-2	7,55093	0,24825	0,93717 $\pm 0,03001$	206164 $\pm 7782$	31379 $\pm 2995$	-	0,55	1,33	2,31193 $\pm 0,11674$	1279913 $\pm 94484$	32606 $\pm 3777$	-
T2-5	8,87072	0,24989	0,69218 $\pm 0,03914$	130471 $\pm 7825$	20435 $\pm 2168$	-	4,63	0,00	0,66174 $\pm 0,06061$	770359 $\pm 80384$	20123 $\pm 2759$	-
T2-10	13,5749	0,25188	3,50987 $\pm 0,10864$	435756 $\pm 16059$	69852 $\pm 6707$	-	47,04	0,00	not reliable		-	-
T2-11	20,74936	0,50205	3,17795 $\pm 0,10378$	514499 $\pm 19701$	84799 $\pm 8223$	-	0,47	1,74	14,18664 $\pm 0,40934$	3372687 $\pm 206052$	94586 $\pm 10526$	-
T2-12	20,93114	0,50572	1,2883 $\pm 0,03977$	208273 $\pm 7660$	33925 $\pm 3227$	-	0,81	0,65	8,55187 $\pm 0,25132$	1329743 $\pm 81577$	36281 $\pm 3928$	-
T2-13	20,54854	0,50544	2,21847 $\pm 0,06394$	365127 $\pm 12808$	57637 $\pm 5478$	-	0,38	1,44	8,45114 $\pm 0,26303$	1665464 $\pm 103589$	43954 $\pm 4799$	-
L1	25,7809	0,25042	0,23857 $\pm 0,03463$	15505 $\pm 2272$	-	482 $\pm 120$	45,41	0,00	0,00883 $\pm 0,00883$	34697 $\pm 34742$	-	unreliable
L2	1,04737	0,24772	0,0333 $\pm 0,00563$	52693 $\pm 8970$	-	134 $\pm 36$	0,42	1,36	0,02287 $\pm 0,01144$	86702 $\pm 43605$	604 $\pm 425$	-
L5	25,0548	0,25228	0,54992 $\pm 0,07113$	37050 $\pm 4849$	-	201 $\pm 48$	53,39	0,00	0,01458 $\pm 0,01031$	69295 $\pm 49123$	-	unreliable
L6	12,22249	0,25185	0,08488 $\pm 0,01157$	11702 $\pm 1612$	-	710 $\pm 170$	6,41	0,00	0,01791 $\pm 0,01034$	20939 $\pm 12135$	-	unreliable
L7	23,2152	-	-	-	-	-	56,93	0,00	0,00949 $\pm 0,00949$	51902 $\pm 51968$	-	unreliable
L8	17,3141	0,25162	0,2671 $\pm 0,01763$	25972 $\pm 1791$	-	324 $\pm 67$	31,51	0,00	0,04263 $\pm 0,01907$	173033 $\pm 77873$	360 $\pm 215$	-
L9	20,1526	0,25043	-	-	-	-	68,37	0,00	0,02319 $\pm 0,0116$	175476 $\pm 88183$	357 $\pm 250$	-
L10	21,76207	0,50149	0,10887 $\pm 0,03148$	16786 $\pm 4864$	-	514 $\pm 191$	46,46	0,00	0,01785 $\pm 0,0103$	84977 $\pm 49248$	751 $\pm 672$	-
L3	31,4521	-	-	-	-	-	63,33	0,00	0,03234 $\pm 0,01451$	145228 $\pm 65587$	380 $\pm 220$	-
T3-sand1	20,8317	0,25132	0,9582 $\pm 0,03061$	77350 $\pm 2915$	-	-	19,02	0,00	0,17923 $\pm 0,0317$	365033 $\pm 67103$	-	-
T3-sand2	35,03711	0,50266	-	-	-	-	50,13	0,00	0,16636 $\pm 0,03329$	530841 $\pm 109491$	-	-
T3-sand3	39,4853	0,49031	-	-	-	-	43,95	0,00	0,10279 $\pm 0,03019$	255196 $\pm 76036$	-	-
T2-sand1	14,0597	0,25104	0,4378 $\pm 0,09923$	52304 $\pm 11901$	-	-	-	-	-	-	-	-

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1119 **Table 2.**  $^{36}\text{Cl}$  samples : AMS results, model age (no inheritance, no erosion, density 2.7 for all  
 1120 samples). Sample locations in Table S1.  
 1121

Sample	$^{36}\text{Cl}$ (measured) ( $10^3$ atoms. $\text{g}^{-1}$ rock)	Ages	
		age	error
		yrs	yrs
T3-1	3081±61	102221	11842
T3-2	3402±68	112409	12891
T3-4	2225±44	71547	8143
T3-6	2269±45	78278	8660
T3W-g1	925±18	28138	2934
T3W-g2	358±7	11115	1129
T3W-1	858±19	25581	2674
T3W-2	841±19	28007	2909
T3W-3	756±17	23082	2463
T3W-4	680±15	21061	2230
T3W-5	728±16	23191	2458
T3W-6	1063±24	34261	3677
T3W-7	720±16	22725	2404
T3W-8	1627±36	50891	5615
T3W-9	1423±32	42424	4615
T3W-10	1811±40	56331	6120
T3W-11	1298±29	39718	4329
T3W-12	1511±34	49078	5484
T2-1	1503±30	50926	5560
T2-2	1403±28	43019	4538
T2-3	1207±24	36705	3898
T2-4	3176±63	107048	12108
T2-6	881±17	26914	2771
T2-7	1170±23	38299	4050
T2-8	2020±40	66816	7305
T2-9	916±18	31428	3336
T2-10	2312±46	73992	8509
T2-11	2389±47	79310	9861
T2-12	1394±29	44567	4591
T2-14	1449±29	48994	5334

1122