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1 **Transient response to changes in uplift rates in the northern Atlas-Meseta system**  
2 **(Morocco)**

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13 **Keywords:** landscape evolution, cosmogenic nuclides, transient topography, quantitative  
14 geomorphology, Atlas Mountains

15

16 **Abstract**

17 Transient topography represents an opportunity for extracting information on the combined effect of  
18 tectonics, mantle-driven processes, lithology and climate across different temporal and spatial scales.

19 The geomorphic signature of transient conditions can be used to unravel landscape evolution,  
20 especially in areas devoid of stratigraphic constraints. The topography of the Western Moroccan

21 Meseta domain (WMM) is characterized by elevated non-lithological knickpoints, that delimit an  
22 uplifted relict landscape, implying a transient response to a change in uplift rate that occurred during

23 the Cenozoic. Here, we determine denudation rates of selected watersheds and bedrock outcrops from  
24 cosmogenic nuclides and perform stream profile, regional and basin-scale geomorphic analysis.

25 Denudation rates of the relict and the rejuvenated landscape range from 15 to 20 m/Myr and from 30  
26 to 40 m/Myr, respectively. Rock uplift rates from river-profile inversions are 10-25 m/Myr from 45

27 to 22 Ma and 30-55 m/Myr from 22 to 10 Ma. Despite the different time scales, the inverted rates are

28 consistent with  $^{10}\text{Be}$  averaged denudation rates (15-20 and 30-40 m/Myr) and river incision values  
29 from Pleistocene lava flows (<10 and ~50 m/Myr) for the rejuvenated and relict regions of the WMM.  
30 These results agree with geological data and indicate that the observed ~400 m of surface uplift in the  
31 WMM started to develop possibly during the early Miocene (first phase). Given the wavelength of  
32 the topographic swell forming the topography of the WMM, uplift is here interpreted to reflect  
33 localized crustal thickening through magma addition or lithospheric thinning through mantle  
34 delamination. More recently, the occurrence of late Miocene marine sediments at ~1200 m of  
35 elevation indicates that the adjacent Folded Middle Atlas during the last 5-7 Ma experienced surface  
36 uplift at ~170-220 m/Myr. Considering the cumulative amount of surface uplift that varies eastward  
37 from 400 to 800 and 1200 m from the Meseta to the Tabular and the Folded Middle Atlas, as well as  
38 the spatio-temporal pattern of alkaline volcanism (middle Miocene and Pliocene to Present), we  
39 suggest that the most recent episode (second phase) of surface uplift was induced by a larger-scale  
40 process that most likely included upwelling of asthenospheric mantle and to a lesser extent crustal  
41 shortening in the Folded Middle Atlas.

42

## 43 **1. Introduction**

44 The competition between crustal deformation, mantle driven uplift and surface processes modulates  
45 the growth and the decay of topography across diverse temporal and spatial scales (England and  
46 Molnar, 1990; Faccenna and Becker, 2020; Babault et al., 2022). Analytical solutions and numerical  
47 models suggest that topography should attain a steady state configuration when uplift is balanced by  
48 surface erosion (Whipple, 2001; Willet and Brandon, 2002). Conversely, when such a balance is not  
49 respected the landscape should be in disequilibrium conditions (*i.e.*, a transient landscape; *e.g.*,  
50 Olivetti et al., 2016; Godard et al., 2019; Clementucci et al., 2022; 2023). Transient landscapes  
51 represent the unique possibility to unravel the topographic evolution in areas devoid of stratigraphic  
52 constraints since the landscape still contains geomorphological features relative to the pre-

53 perturbation stage. The transience results from different causes, such as base-level falls, drainage  
54 reorganizations, climate changes and/or variations in uplift rates at crustal and deeper scales (*e.g.*,  
55 Snyder et al., 2002; Roberts and White, 2010; Miller et al., 2013, Ballato et al., 2015; Sembroni et  
56 al., 2017; Gallen, 2018; Fernandes et al., 2019; Faccenna and Becker, 2020; Racano et al., 2021;  
57 Lanari et al., 2022). Therefore, the topography represents the superimposition of processes operating  
58 at multiple timescales and acting at different rates, wavelengths, and amplitudes. Although diverse  
59 approaches have been used to unpick these different signals, the combination of quantitative  
60 geomorphology with denudation data from cosmogenic nuclides and river profile inversion represents  
61 a powerful tool to infer the magnitude, timing, and rates of uplift through time (Miller et al., 2013;  
62 Goren et al., 2014; Pastor et al., 2015). This comprehensive approach allows for exploration of the  
63 uplift history of areas lacking stratigraphic constraints, with the potential to deconvolve the signals  
64 of topographic growth operating at different spatial scales. The surface expression of large-scale uplift  
65 and associated causes, in fact, remains often elusive mostly because the rates at which uplift occurs  
66 is poorly understood. Accordingly, the integrated approach outlined above can provide fundamental  
67 insights into geodynamic processes.

68 In this study, we focus on the Western Moroccan Meseta and the adjacent Tabular Middle Atlas, two  
69 tectonically quiescent domains of the Atlas-Meseta system (Fig. 1b). Despite quiescence, these relief  
70 features are characterized by elevated, extensive, low-gradient erosional surfaces bounded by steep  
71 hillslopes that are adjusting through fluvial incision, to a relative base level drop. This landscape is  
72 considered to represent a transient topography resulting from a Neogene phase of large-scale surface  
73 uplift, most likely driven by mantle upwelling (*i.e.*, topographic rejuvenation, *e.g.*, Missenard et al.,  
74 2006; Babault et al., 2008; Frizon de Lamotte et al., 2009; Miller and Becker, 2014; Clementucci et  
75 al., 2023). The relict surfaces are characterized by a protracted phase of hillslope lowering,  
76 documented by low temperature thermochronology. Data suggests slow hillslope exhumation rates  
77 since the latest Cenozoic ( $< 28$  m/Ma if we consider a maximum cooling of  $50^{\circ}\text{C}$  over the last 70 Ma  
78 and a geothermal gradient of  $25^{\circ}\text{C}$ ; see thermal modelling in Barbero et al., 2010 and also the recent

79 review of Charton et al., 2020). These conditions provide a natural setting for investigating the  
80 mechanisms of large-scale uplift in tectonically inactive (or slow deforming) areas and quantifying  
81 rock uplift changes through time since the relict topography retains features of the pre-uplift event.

82 In this work, we combined denudation rates derived from in situ-produced cosmogenic nuclides  
83 ( $^{10}\text{Be}$ ) with regional and basin-scale geomorphic analysis and river profile inversions. Specifically,  
84 we determined bedrock outcrops and basin-wide denudation rates from river-borne sediments to  
85 gauge them with basin-averaged geomorphic metrics (slope, local relief, and normalized steepness  
86 index). In addition, we estimated the magnitude of base-level fall by projecting the upper relict  
87 channels toward the present-day river mouth (*e.g.*, Miller et al., 2013; Sembroni et al., 2020). This  
88 allowed us to quantify the long-term magnitude of uplift of the Western Moroccan Meseta and the  
89 surrounding Tabular and Folded Middle Atlas domains. Moreover, we reconstructed the Cenozoic  
90 uplift history of the entire northern Atlas-Meseta system by combining the rock uplift evolution  
91 through time inferred from fluvial modelling with available geological data. Our results show  
92 consistent rates of denudation and rock uplift of the rejuvenated and the relict portions of the  
93 landscape through time and highlight the transient adjustment of hillslope and channels in response  
94 to a Cenozoic increase in rock uplift rates. Finally, we retraced back in time the uplift and the  
95 topographic evolution of the northern sector of the Atlas-Meseta orographic system and discussed  
96 possible driving mechanisms of the topographic rejuvenation.

97

## 98 **2. Geological setting**

99 The Atlas-Meseta of Morocco (NW Africa) includes mountain ranges (Anti-Atlas, High Atlas and  
100 Middle Atlas) elevated tabular areas (Western Meseta, Tabular Middle Atlas and High Plateaus), and  
101 sedimentary basins (Missour and Saiss among others; Fig. 1a). The WSW-ENE oriented, 4-km-high  
102 High Atlas represents the highest mountain range of the Atlas-Meseta system. It consists mainly of  
103 Mesozoic-Cenozoic syn- to post-rift deposits that were uplifted in the Eocene and Miocene (Arboleya

104 et al., 2004; Lanari et al., 2020a). The central sectors of the High Atlas merge towards the NE with  
105 the SW-NE-striking Middle Atlas (Fig. 1a). This range is formed by the same deposits of the High  
106 Atlas that were deformed most likely from the late Miocene, but with some angular unconformities  
107 suggesting a more complex Meso-Cenozoic history of deformation and sedimentation (Charrière,  
108 1984). Topographically, the Middle Atlas can be divided into two morpho-structural domains known  
109 as the Tabular and Folded Middle Atlas (TMA and FMA; Fig. 1b), which are commonly interpreted  
110 as the flank (footwall) and the depocenter (hanging wall) of a Mesozoic rift, respectively (Gomez et  
111 al., 1996; 1998). The TMA domain ranges between 1500 and 2000 m of elevation and consists of  
112 Mesozoic limestones that are slightly tilted westward. The FMA reaches 3000 m of elevation and  
113 includes north-west- to south-east-verging folds mostly detached from the underlying basement along  
114 Triassic evaporites (Charrière, 1984; Gomez et al., 1998). The folded range is bounded to the  
115 northwest by the North Middle Atlas fault (NMAF) and to the southeast by the South Middle Atlas  
116 Fault (SMAF; Fig. 1b). The elevated Western Moroccan Meseta (WMM) and High Plateau (HP) rises  
117 to an elevation of 1500 m, without any evidence of Cenozoic tectonic deformation (Gomez et al.,  
118 1999; Barbero et al., 2010). Particularly, the WMM is characterized by a complex assemblage of  
119 Paleozoic rocks deformed during the Variscan orogeny (Hoepffner et al., 2005; Fig. 1b). This includes  
120 Ordovician, Silurian, and Devonian schists and metasedimentary rocks, locally intruded by late  
121 Carboniferous granitoids (320 and 270 Ma; Hoepffner et al., 2005 and references therein). This  
122 domain is partially covered by undeformed Mesozoic and Eocene marine sedimentary rocks (*e.g.*,  
123 Phosphatic series; Salvan, 1954; El Kiram et al., 2019; El Attmani et al., 2021). The Rif Mountains  
124 to the north reaches peaks of up to 2500 m and represents a fold and thrust belt that experienced NW-  
125 SE shortening due to the convergence of Africa and Eurasia (Jolivet and Faccenna, 2000; Abbassi et  
126 al., 2020; Agharroud et al., 2021). There, contractional deformation migrated southward until 8 Ma  
127 when the outermost tectonic units were emplaced onto the South Rifian Corridor (Krijgsman et al.,  
128 1999; Capella et al., 2018; Abbassi et al., 2020; 2022).

129 The High and Middle Atlas domains are characterized by strain partitioning with a total amount of  
130 shortening of ~24%, accommodated by both thrust and oblique/strike-slip faults (Gomez et al., 1999;  
131 Lanari et al., 2020b). The amount of shortening across the thrust faults ranges between ~12% and 15  
132 % (Missenard et al., 2006; Domenech et al., 2018; Lanari et al., 2020a; 2023) suggesting that crustal  
133 thickening is insufficient to isostatically support the modern topography (Arboleya et al., 2004;  
134 Missenard et al., 2006). Moreover, geophysical studies highlight the presence of an anomalously thin  
135 lithosphere beneath the entire Atlas-Meseta system (Miller and Becker, 2014; Miller et al., 2015).  
136 This is associated with continental intraplate volcanism that seems to be coeval with the main tectonic  
137 events (Missenard et al., 2006; El Azzouzi et al., 2010; Lanari et al., 2020a). The lavas are well  
138 exposed in the FMA, TMA, the WMM over a surface of about 960 km<sup>2</sup> and have a geochemical  
139 affinity with the Canary mantle plume composition ranging from basanite to alkali basalt (Duggen et  
140 al., 2009; El Azzouzi et al., 2010). The late Cenozoic phase of uplift is documented by the occurrence  
141 of late Miocene (Messinian) shallow-water marine deposits in the Skoura basin at ~1200 m of  
142 elevation (Babault et al., 2008) and the progressive shallowing upward trend of the Miocene marine  
143 sediments of the Saïss and Guercif basin (Fig. 1a; Krijgsman et al., 1999).

144

### 145 **3. Methods**

#### 146 **3.1. Topographic, stream analysis and long-term incision**

147 A Shuttle Radar Topography Mission Digital Elevation Model (SRTM DEM, pixel size of 30 m) was  
148 used to extract the drainage network. Hillslope metrics, such as slope and local relief with a circular  
149 sampling window of 2.5 km radius, as well as channel and basin metrics were extracted using ArcGIS  
150 and the MATLAB software packages TopoToolbox (Schwanghart and Scherler, 2014) and  
151 Topographic Analysis Kit (TAK, Forte and Whipple, 2019), together with additional MATLAB  
152 functions (*e.g.*, Gallen, 2017). The relationships between river channel steepness and erosion/uplift  
153 rates have been demonstrated in various geological settings (Kirby and Whipple, 2012). In

154 detachment-limited conditions, these relationships are modulated by the stream-power model, which  
155 can be integrated, assuming spatially invariant uplift and erodibility, to estimate the integral quantity  
156  $\chi$  (details in the section S1; Perron and Royden, 2013). This allows transforming river longitudinal  
157 profiles to  $\chi$  versus elevation ( $z$ ) plots (here and thereafter defined as  $\chi$  -  $z$  plot). Consequently, the  
158 slope in  $\chi$  space is defined as the steepness index ( $k_s$ ) when the reference area ( $A_0$ ) is equal to 1. To  
159 compare  $k_s$  values of longitudinal profiles, a reference concavity index ( $\theta_{ref}$ ) of 0.45 is applied to  
160 derive the normalized channel steepness indices ( $k_{sn}$ ; Kirby and Whipple, 2012 and references  
161 therein). The  $\theta_{ref}$  was calculated by minimising the scatter in  $\chi$  space of all rivers draining the study  
162 area (Perron and Royden, 2013; Goren et al., 2014; Fig. S1). Our  $\theta_{ref}$  coincides with the value typically  
163 used to derive normalised channel steepness (Snyder et al., 2000; Kirby and Whipple, 2012).

164 Knickpoints were identified and discretized based on the shape of the streams in the longitudinal  
165 profiles and the  $\chi$  -  $z$  plots and using available geological maps (Service Géologique du Maroc) and  
166 satellite imagery (Google Earth). Importantly, non-lithological knickpoints cluster around similar  $\chi$   
167 values and separate stream segments with different  $k_{sn}$  values (Perron and Royden, 2013;  
168 Clementucci, 2022). Using this approach, the knickpoints were divided into non-lithological, minor,  
169 lithological and man-made dam. Streams with knickpoints identified as transient (non-lithological)  
170 were used for reconstructing river projections to estimate the magnitude of long-term incision. Such  
171 profiles can be reconstructed using the  $k_{sn}$  values ( $\theta_{ref} = 0.45$ ) of the river segments upstream of the  
172 non-lithological knickpoints in the  $\chi$  space, assuming that the paleo-river network remained  
173 approximately the same through time (Perron and Royden, 2013; Smith et al., 2022). Full details of  
174 equations and stream analysis are provided in the Supplementary material.

175

### 176 3.2. $^{10}\text{Be}$ -derived denudation rates

177 We measured the concentration of in situ-produced cosmogenic  $^{10}\text{Be}$  in quartz from seven river-borne  
178 samples collected in active channels and from four bedrock outcrops (Fig. 1c; Table 1). The only  
179 lithologies exposed in the WMM that contain quartz are Paleozoic basement rocks such as schists,  
180 metasedimentary rocks, and granites. Our sampled catchments cover most of this area (Figs 1b and  
181 S2), from the elevated relict to the steeper landscape portions. In one case we sampled a catchment  
182 with Paleozoic rocks at the periphery of the uplifted area (sample 53) to compare denudation rates  
183 from different sectors of the WMM (Fig 1c). The basin-wide denudation rates were determined only  
184 from quartz-bearing rocks, which usually represent 50 to 100% of the total area of the sampled  
185 catchments (Table S1). The portions of the sampled catchments with Mesozoic limestones were not  
186 considered in the scaling modelling (Clementucci et al., 2022 and references therein). Details of  
187 sample preparation, from the initial mineral separation to the final conversion of in situ-produced  
188  $^{10}\text{Be}$  to basin-wide denudation rates are provided in the Supplementary material S2. Catchments 58,  
189 59, 60 and 62 are sub-catchments of two larger basins named 61 and 63, while catchment 53  
190 corresponds to the westernmost sampling location (Fig. 1c). The upstream areas range between 30  
191 and 100 km<sup>2</sup> and 320 and 350 km<sup>2</sup> for the sub-catchments and the larger basins, respectively. In  
192 particular, we selected samples 58 and 59 upstream of the low-relief surfaces and samples 61 and 63  
193 downstream of the relict landscape to extract the denudation rates of the adjusted and steeper  
194 topography. Catchments 53, 58, 59, 62 and 63 are characterized by uniform quartz-bearing  
195 lithologies. Conversely, the contribution of quartz, in catchments 60 and 61, is mostly from two  
196 granite massifs exposed in the highest topography of the Moroccan Meseta region. To quantify the  
197 local denudation rates of the granite massifs forming the landscape of the western Meseta, we sampled  
198 four bedrock outcrops: two from the summit of an erosional surface (samples 56A, 56B) and two  
199 from sub-horizontal ridge crests located close to the margin of the relict topography (samples 57A,  
200 57B, Table 1 and Fig. 1c).

201 In situ-produced  $^{10}\text{Be}$  concentrations were converted to basin-wide denudation rates and bedrock  
202 erosion rates using the MATLAB scripts of Balco et al. (2008), which are based on the time-

203 dependent scaling functions of Stone (2000)'s scheme that consider three different categories of  
204 particles responsible for the in-situ production of  $^{10}\text{Be}$  (Braucher et al., 2011). The geomorphic  
205 shielding (Dunne et al., 1999), scaling factor of Stone (2000) and the mean elevation of sampled  
206 catchments were determined for each pixel of the digital elevation model (DEM), considering only  
207 the areas contributing with quartz-bearing lithologies. In the scaling model,  $\lambda$  describes the  
208 radioactive decay constant of  $^{10}\text{Be}$ . Denudation rates from  $^{10}\text{Be}$  concentrations were calculated using  
209 a  $^{10}\text{Be}$  sea level high latitude production rate of  $4.02 \pm 0.33$  atoms  $^{10}\text{Be}$  (g-SiO<sub>2</sub>)/yr (Borchers et al.,  
210 2016), and half-lives of  $(1.387 \pm 0.012) \times 10^6$  years (Chmeleff et al., 2010; Korschinek et al., 2010).  
211 At cosmogenic steady-state, the cosmogenic  $^{10}\text{Be}$  in river-borne quartz mineral records a time  
212 integrated spatially averaged denudation rate, which represents fluviially mixed denudation products  
213 of all the processes occurring in each watershed (Granger et al., 1996). This integration occurs over  
214 the time needed to remove one attenuation length (*e.g.*, roughly 60 cm; Lal, 1991).

215 We also applied a sediment mixing correction to estimate a value of denudation for the downstream  
216 knickpoint portion of the catchment 63 (basin 64), knowing the denudation and drainage area of the  
217 whole catchment and the upper sub-catchment, upstream of the non-lithological knickpoints (Fig. 2;  
218 according to Granger et al., 1996; Miller et al., 2013; Rosenkranz et al., 2018):

$$219 \quad D_{1-2} = \frac{D_1 A_1 - D_2 A_2}{A_1 - A_2} \quad (1)$$

220 where  $A_1 - D_1$  and  $A_2 - D_2$  are the drainage area and basin-wide denudation rate of the whole  
221 catchment and above the non-lithological knickpoint, respectively.  $D_{1-2}$  is the basin-wide denudation  
222 of the adjusted topography downstream of non-lithological knickpoints.

223

### 224 **3.3. Predicted $^{10}\text{Be}$ -derived denudations and incision of volcanic bedrock**

225 The basin-averaged  $k_{sn}$  values, precipitation rates (IMERG data; Huffman et al., 2015), slope and  
226 local relief for the portions of the sampled catchments that include only quartz-bearing lithologies  
227 were extracted for comparing  $^{10}\text{Be}$ -derived denudation rates. The comparison between denudation  
228 rates and  $k_{sn}$  allowed extracting the averaged erodibility parameter  $K$  for basement rocks in the  
229 Western Meseta and constraining  $n$  equal to 1. We also evaluate the power best-fit to better explore  
230 the relationship between channel steepness and erosion, and evaluate the power-law coefficients,  $K$   
231 and  $n$ . Finally, values of  $k_{sn}$  values were directly converted to denudation rates (see details in Adams  
232 et al., 2020, and Clementucci et al., 2022).

233 To compare our inferred and measured, short-term denudation rates, with longer-term rates we  
234 estimated fluvial incision rates by using the 1-Myr-old lava flows as a temporal and geometrical  
235 benchmark because they were emplaced over the relict and the rejuvenated landscape of the WMM  
236 domain (Tephrite and Basanite data from Rachidi, 1995).

237

### 238 **3.4. Rock uplift history**

239 To unravel the rock uplift rates over time, we performed a linear inversion of the rivers draining the  
240 Paleozoic basement in the Moroccan Meseta domain. We constrained the averaged erodibility value  
241 ( $K$ ) of the Paleozoic basement rocks, using the stream power river incision model ( $K = E/k_{sn}^n$ ) for  $n$   
242 = 1. The  $K$  was estimated using the forced-origin linear regression in the plot  $k_{sn}$  and denudation  
243 rates. Although the variation of  $K$  over time is difficult to constrain, our averaged estimate can be  
244 considered reliable because short-term denudation rates are consistent with the long-term  
245 exhumation rates derived from thermochronological data over other quiescent sectors of the Atlas-  
246 Meseta system (e.g., Anti-Atlas and Haouz basin; Lanari et al, 2020a; Clementucci et al., 2022;  
247 Western Meseta; Barbero et al., 2010). Assuming block uplift conditions in a selected catchment  
248 (no spatial uplift variations) and  $n = 1$ , the travel time of a perturbation along a river profile ( $\tau$ ) is  
249 given by:

250

251

$$\tau = \int_{x_b}^x \frac{dx'}{K A_0^m A(x')^m} \quad (2)$$

252

253

254

255

By removing  $K$  from Equation (1) we obtain  $\chi$ . Following the approach of Goren et al. (2014), a non-dimensional uplift can be inferred from the integration of the stream-power model by assuming that trunks with same  $\chi$  share a common uplift history and organizing the equation in a matrix form for each data point:

256

$$A^*U^* = z \quad (3)$$

257

258

259

where  $A^*$  is an  $N \times q$  matrix,  $q$  is the number of  $\chi$  intervals,  $U^*$  is the non-dimensional uplift and  $z$  is elevation. This is an overdetermined inverse problem, as there are more known data points than unknown parameters. As such, a least-squares estimate for  $U^*$  is used (Goren et al., 2014):

260

$$U^* = U^*_{pri} + (A^{*T}A^* + \Gamma^2I)^{-1} \circ^{*T} (z - A^*U^*_{pri}) \quad (4)$$

261

262

263

264

Where  $\Gamma$  is a dampening coefficient that determines the smoothness imposed on the solution,  $I$  is the  $q \times q$  identity matrix and  $U^*_{pri}$  represents the prior guess for  $U^*$ , estimated by taking the average slope of the  $\chi$ -plot (Goren et al., 2014). In this way, from the integration of the stream-power model,  $\chi$  and  $U^*$  can be scaled for  $K$  to infer rock uplift rates ( $U$ ) and time ( $\tau$ ):

265

$$U = K A_0^m U^* \quad (5)$$

266

$$\tau = \frac{\chi}{K A_0^m} \quad (6)$$

267

268

269

270

271

272

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274

To reduce the noise, we removed streams with a length lower than 10 km. The linear inversion approach is built on the assumption of spatially uniform uplift, which to a first approximation, can be considered reasonable given that the analysed catchments do not cross any fault that may have been active during the late Cenozoic. Moreover, the analysed catchments are entirely in the WWM where they occupy relatively narrow areas, and hence do not record major along-strike variations in uplift rates. Thus, adopting this approach, by combining the inversions from different catchments, it is also possible to investigate spatial variations in rock-uplift histories (Pavano et al., 2021; Racano et al., 2021; Zhong et al., 2022).

275

276

## 277 4. Results

### 278 4.1. Topographic and river analysis

279 The WMM domain consists of a NE-SW striking, ~ 130 x 260 km topographic swell, with a maximum  
280 elevation of ~1500 m, and a low relief topography that locally has been deeply dissected by fluvial  
281 incision (Figs. 3 and 4). Within the WMM, a series of smaller scale geomorphic features such as  
282 summit erosional surfaces, ridge crests and fluvial terraces developed onto and inset into the lava  
283 deposits are visible (Figs. 4 and 5). The TMA presents a tabular, low-relief topography while the  
284 FMA is characterized by an alternation of steep ridges and wide, low-slope valleys (Figs. 3 and S3).  
285 Based on the geometry of the river network, the study area was divided into the Central-Western  
286 Meseta (CWM), the North-Western Meseta (NWM), and the South-Western Meseta (SWM). The  
287 CWM is characterized by rivers draining directly into the Atlantic Ocean, while the rivers of the  
288 NWM and SWM represent the main respective tributaries of the Atlantic draining Oued Sebou and  
289 Oum Er Rbia, (Fig. 3a). A set of regionally widespread non-lithological knickpoints occur at different  
290 elevations in the three domains. These features mark a sharp variation in the  $k_{sn}$ , local relief and slope  
291 between the deep valleys and the upstream landscape (dashed line in Figs. 3a, 3b and S3). Particularly,  
292 high values of  $k_{sn}$  ( $> 80 \text{ m}^{0.9}$ ; Fig. 3b), slope ( $> 25^\circ$ ; Fig. S3a), and local relief ( $> 500 \text{ m}$ ; Fig. S3b),  
293 are found in the FMA domain and in the downstream portions of the non-lithological knickpoints of  
294 the WMM and the TMA domains. The lowest values of topographic and channel parameters are  
295 observed in the lower portions of the landscape (Oum Er Rbia and Sebou basins) and upstream of the  
296 non-lithological knickpoints (Figs. 3 and S3).

297 The NWM sector is characterized by transient longitudinal profiles. Most of the rivers flowing from  
298 the TMA and the WMM present lithological knickpoints between 1500 and 2000 m of elevation at  $\chi$   
299 values of 20 to 25 (Fig. 6a and 6b). A pattern of widespread non-lithological knickpoints is located

300 between 700 and 1500 m and is associated with a gradual increase in elevation from 200 to 450 km  
301 of distance from the river mouth (Fig. 6a and Table S2). These non-lithological knickpoints cluster  
302 at  $\chi$  values of 13 – 17 and separate steep downstream segments from low-gradient upstream channels.  
303 A cluster of minor knickpoints is located at lower elevations and separates gentle downstream river  
304 segments from steeper upstream portions (Figs. 6a and 6b).  
305 Rivers of the CWM sector show concave-up longitudinal profiles downstream of the non-lithological  
306 knickpoints and straight low-gradient upper segments (Fig. 6c). These non-lithological knickpoints  
307 present a progressive increase in elevation from 300 m close to the river mouth to ~1000 m upstream  
308 toward the TMA domain. Most of these non-lithological knickpoints cluster at  $\chi$  values of 10 – 15,  
309 and separate downstream steep segments from low-gradient upstream portions (Fig. 6d). Downstream  
310 of these non-lithological knickpoints, the river segments are characterized by gentle low-gradient  
311 river profiles, which contain several minor knickpoints (Fig. 6c).  
312 The SWM sector is characterized by both equilibrated and transient longitudinal profiles. The main  
313 slope break is located at high elevation, where two non-lithological knickpoints lie in the FMA  
314 domain (~1900 m and ~1500 m; Fig. 6e and 6f). The average elevations of the non-lithological  
315 knickpoints are 627 ( $\sigma = 116$ ) m, 1255 ( $\sigma = 86$ ) m and 1724 ( $\sigma = 135$ ) m for the WMM, TMA and  
316 FMA domains, respectively (Table S2).

317

## 318 **4.2. Long-term river incision**

319 The magnitude of long-term river incision can be estimated by the difference between the  
320 reconstructed river profiles projected from the non-lithological knickpoints and the modern base  
321 level. Rivers draining the WMM domain (mainly from CWM and NWM sectors) show a mean long-  
322 term incision of 415 ( $2\sigma = 55$ ) m, based on 33 river projections (Fig. 7a and Table S3). The mean  
323 values of long-term incision of rivers draining the TMA domain is 823 ( $2\sigma = 66$ ) m, based on 8 river  
324 projections (Fig. 7a and Table S3). The river projections from the FMA domain show an average  
325 long-term incision of 1086 ( $2\sigma = 64$ ) m, although based only on 2 rivers (Fig. 7a and Table S3).

326 There, rivers flow along the SWM sector. Overall, both elevations of the non-lithological knickpoints  
327 and magnitude of long-term incision increase progressively from the WMM to the TMA and FMA  
328 domains (Fig. 7b).

329 A few valleys of the WWM have been filled by Quaternary lava flows downstream and upstream of  
330 major non-lithological knickpoints (Fig. 1a). Subsequently, these lava flows were dissected through  
331 fluvial incision leaving well developed terraces. Downstream of major non-lithological knickpoints,  
332 the current valley floor is  $\sim 50$  and  $\sim 100$  m below the base and the top of the lava flows, respectively  
333 (Figs. 4 and 5b). Considering that the lava yielded radiometric ages of  $1 \pm 0.1$  Ma (Rachdi, 1995),  
334 fluvial incision rates vary from  $\sim 100 \pm 10$  to  $\sim 50 \pm 5$  m/Myr, respectively. Importantly, the latter  
335 estimate ( $\sim 50 \pm 5$  m/Myr) represents the amount of river channel lowering after the lava emplacement  
336 using the unconformity as a reference surface (strath of the terrace). Conversely, in the relict surfaces  
337 of the WMM domain the lava flows are poorly incised and the fluvial incision rate are  $<10$  m/Myr  
338 (Fig. 4).

339

#### 340 **4.3. $^{10}\text{Be}$ -derived denudation rates**

341  $^{10}\text{Be}$  concentrations from the largest catchments of the WMM yield denudation rates of  $19.8 \pm 1.4$   
342 and  $32.2 \pm 2.3$  m/Myr (samples 61 and 63; Fig. 1c and Table 1). Denudation rates from the sub-  
343 catchments located upstream of the relict landscape are  $17.1 \pm 1.3$  and  $19.5 \pm 1.4$  m/Myr (samples 58  
344 and 59), whereas the sub-catchments downstream of non-lithological knickpoints present rates of  
345  $17.4 \pm 1.2$  and  $40.0 \pm 5.6$  m/Myr (samples 60 and 62; Fig. 1c and Table 1). In the western side of the  
346 Moroccan Meseta, sample 53 yields a denudation rate of  $14.8 \pm 1.0$  m/Myr. The unmixed rate from  
347 catchment 64 (*i.e.*, the denudation rate of the incised portion of the landscape of catchment 63, which  
348 was obtained by subtracting the contribution of the relict landscape of sub-catchment 59 and the area  
349 of the steep sub-catchment 62 downstream of non-lithological knickpoints; Fig. 2), yields a  
350 denudation rate of  $35.2 \pm 2.6$  m/Myr. This shows a good match with the estimates of denudation from

351 the same sub-catchment 62 (Fig. 2 and Table S1). The sampled catchments are characterized by a  
352 uniform distribution of quartz, which is mostly sourced from the lower Paleozoic metamorphic  
353 basement, except for samples 60 and 61. These two basins are influenced by the occurrence of two  
354 large granite outcrops located in the high-standing low relief surface of the WMM (Fig. 4), which  
355 most likely provided more quartz than the Paleozoic metamorphic rocks. Local denudation rates of  
356 bare bedrock surfaces on the summit plateau (relict surface) and on the ridge crests of the granite  
357 massifs vary from  $3.5 \pm 0.2$  to  $4.1 \pm 0.3$  m/Myr (samples 56A, 56B), and from  $13.1 \pm 0.9$  to  $14.4 \pm 1.0$   
358 m/Myr (samples 57A, 57B), respectively (Table 1). It is worth noting that the denudation rates of the  
359 granitic ridge crests: 1) are significantly higher than the rates of the flat summit surfaces, and 2) are  
360 close to the values determined for the watersheds of samples 60 and 61, where the two granite massifs  
361 are exposed and may provide most of the quartz that yielded the measured  $^{10}\text{Be}$  concentration.

362

#### 363 **4.4. Basin-wide denudation rates versus topographic metrics**

364 The basin-averaged  $k_{sn}$  values range from 16.7 to 53.5  $\text{m}^{0.9}$  (Fig. 8a and Table S1), while basin-  
365 averaged slope values vary from 6 to  $13^\circ$  (Fig. 8b and Table S1) and the basin-averaged local relief  
366 range from 222 to 440 m (Fig. 8c and Table S1). The topographic and channel metrics exhibit a  
367 medium to low correlation with the basin-wide denudation rates with  $R^2$  of 0.13, 0.61 and 0.71 for  
368  $k_{sn}$ , slope and local relief, respectively (dashed lines in Fig. 8a, 8b, 8c). However, a stronger  
369 correlation between the topographic metrics and basin-wide denudation rates is obtained considering  
370 only the catchments characterized by a homogeneous distribution of bearing-quartz lithologies of the  
371 Paleozoic basement (*i.e.*, excluding samples 60 and 61, which quartz is mostly sourced from the  
372 granites above the elevated flat surfaces). In this case, the coefficient of correlation increases to 0.76,  
373 0.87 and 0.97 for the basin-averaged  $k_{sn}$  values, slope, and local relief, respectively (Fig. 8a, 8b, 8c).  
374 The lowest topographic and channel metrics are observed for samples 53, 58 and 59, which represent  
375 the westernmost sample (53) and the samples upstream of the non-lithological knickpoints.

376 Conversely, samples 62 and 64 (downstream of the non-lithological knickpoints) show the highest  
377 values of basin-averaged  $k_{sn}$  values, slope and local relief, whereas samples 60, 61 and 63, show  
378 slightly lower values, because they represent the mixed estimates, giving that both the upstream and  
379 downstream portions of the catchments are contributing (Fig. 8a, 8b, 8c and Table S1). Finally, basin-  
380 wide denudation rates are poorly correlated with the basin-averaged precipitation ( $R^2=0.38$ ; Fig. 8d).

381

#### 382 **4.5. Timing: base-level fall history**

383 To constrain the base level history, the linear inversion of six river profiles has been performed using  
384  $n = 1$ ,  $m/n = 0.45$  and  $K$  of  $7.34 \pm 0.58 \times 10^{-7} \text{ m}^{0.1}/\text{yr}$ . The parameter  $n = 1$  describes the linear  
385 relationship between the erosion rates and  $k_{sn}$  (Fig. 8a), as expected for inactive to slow tectonic  
386 settings (Godard et al., 2019; Clementucci et al., 2022). The estimation of  $n$  has been made testing  
387 the stream-power law fits, confirming that the assumption of  $n = 1$  is reasonable (Fig. 8a). The six  
388 catchments were selected as they flow over the same rocks from which the  $K$  value was estimated  
389 (Figs. 9a and S5, S6). Results show similar rock uplift histories (Figs. S5 and S6), which are  
390 summarized in Figure 9b with the mean and the standard error and deviation of the six inversions.  
391 Overall, we observe almost constant rock uplift rates of 15-20 m/Myr from 30-33 until  $\sim 25$  Ma,  
392 followed by an increase up to  $\sim 40$  m/Myr between 20 and 15 Ma and by a general decrease to  $\sim 25$   
393 m/Myr during the last 10 Ma (Fig. 9b). Importantly, within this decreasing trend, a peak in rock-uplift  
394 occurs around 5-6 Ma with values of up to 35 m/Myr despite the large standard deviation.

395

## 396 **5. Discussion**

### 397 **5.1. Transient topography in Western Moroccan Meseta and Middle Atlas**

398 The study area is characterized by high-standing relict surfaces bounded by non-lithological  
399 knickpoints and deeply incised valleys downstream of these knickpoints. This elevated landscape is  
400 characterized by low  $k_{sn}$  and include low-topographic slopes and local relief surfaces carved onto  
401 Paleozoic metamorphic rocks and Mesozoic limestones that gently dip toward the western sectors  
402 (Figs. 3, 4, 5; Barbero et al., 2010; Barcos et al., 2014). A few lithological knickpoints lie at about  
403 1500 m of elevation at the boundary between the WMM and TMA domains (see bold yellow points  
404 in Fig. 6a, 6b). These knickpoints are marked by a local variation in  $k_{sn}$  values and other topographic  
405 metrics (slope and local relief) and coincide with a ~500-m-high morphological escarpment  
406 representing the stratigraphic contact between the Paleozoic basement and the undeformed Jurassic  
407 limestones, reflecting a sharp change in rock erodibility. Conversely, downstream of non-lithological  
408 knickpoints the landscape is characterized by steep slopes and  $k_{sn}$  values at regional scale (Figs. 3, 4,  
409 5 and S2). This topographic dichotomy suggests that the landscape and hence the river network is not  
410 in equilibrium (Crosby and Whipple, 2006; Kirby and Whipple, 2012).

411 The disequilibrium condition can be explained through several processes, such as drainage  
412 reorganization, climate change, eustatic sea-level fall and tectonic uplift (Snyder et al., 2002; Crosby  
413 and Whipple, 2006; Kirby and Whipple, 2012; Miller et al., 2013; Boulton et al., 2014; Ballato et al.,  
414 2015; Rixhon et al., 2017; Stokes et al., 2017). In the WMM, a base-level fall due to eustatic forcing  
415 is unlikely to be the source of the observed non-lithological knickpoints, because it cannot explain  
416 the pattern of  $k_{sn}$  values of the river network. Specifically, a wave of knickpoints due to eustatic causes  
417 cannot exhibit any major slope break in the chi-space because it is not associated with variations in  
418 uplift rate or rock erodibility (Wobus et al., 2006; Kirby and Whipple, 2012; Perron and Royden,  
419 2013). Moreover, there is no geological data documenting a major and protracted sea level drop  
420 during the late Cenozoic (Miller et al., 2020) and the glacial-interglacial cycles occurred over the last  
421 1 Ma would result in multiple phases of incision and filling of the coastal area (*e.g.*, Marra et al.,  
422 2016), rather than a wave of incision reaching the upper reaches of the Meseta. Drainage  
423 reorganization could explain the increase in long-term fluvial incision downstream of the knickpoints

424 due to a gain in drainage area and hence in water discharge (*e.g.*, Yang et al., 2015). However, the  
425 non-lithological knickpoints are observed in the watersheds of all domains (WMM, TMA and FMA;  
426 Fig. 3), even in small catchments where there is no evidence of drainage reorganization (*e.g.*, wind  
427 gaps, knickpoints due to capture processes among others), as instead observed in the Moulouya basin  
428 to the east of FMA (Bartz et al., 2018). Furthermore, increased erosion due to enhanced of average  
429 precipitation can also be discarded because it should produce a decrease in the channel slopes  
430 downstream of non-lithological knickpoints (Miller et al., 2013; Marder and Gallen, 2023; Figs. 3  
431 and S2). Importantly, the non-lithological knickpoints are characterized by a major upstream decrease  
432 in  $k_{sn}$  values even across the same lithology as documented in the  $\chi$  space plots (Fig. 6) and by changes  
433 in the topographic slope and local relief at the regional scale (Figs. 3 and S2). This indicates that the  
434 knickpoints separate portions of the landscape eroding at different rates (*e.g.*, Crosby and Whipple,  
435 2006; Kirby and Whipple, 2012; Boulton et al., 2014; Olivetti et al., 2016). Consequently, the portion  
436 with steep channels downstream of the knickpoints records the response of the fluvial system to an  
437 increase in rock uplift rates, while the upstream low relief topography (relict landscape; Fig. 4)  
438 records the pre-uplift conditions, as also observed in the others domains of the Atlas-Meseta system  
439 (*e.g.*, High Atlas, Siroua and Anti-Atlas range; Boulton et al., 2014; Zondervan et al., 2020;  
440 Clementucci et al., 2023). Overall, these observations indicate that the study area experienced a recent  
441 topographic rejuvenation (regional, large-scale surface uplift) as documented in other regions  
442 worldwide exhibiting similar topographic patterns (Calvet et al., 2015; Miller et al., 2013).

443 Conversely, minor knickpoints lying at lower elevations can be attributed to Quaternary climate  
444 change or a second increase in uplift rates (Hancock and Kirwan, 2007; Molnar and England, 1990).  
445 A similar pattern of minor knickpoints has been described also for the Anti-Atlas domain, where their  
446 origin is still enigmatic (Clementucci et al., 2023). In the Western Meseta, these less elevated  
447 knickpoints do not present a pronounced break point along the river profiles, but they are evenly  
448 distributed along the rivers. Moreover, an increase in rock-uplift is shown around 5-6 Ma in the river-

449 profile inversions. These observations suggest a possible upward knickpoint migration following a  
450 second topographic rejuvenation event (*i.e.*, a second increase in uplift rates at 5-6 Ma), which most  
451 likely occurred at a larger wavelength from the WMM to the TMA and the FMA (and possibly the  
452 HP), as testified by uplifted Messinian marine sediments of the Skoura and Saiss basins (Babault et  
453 al., 2008).

454

## 455 **5.2. Erosional dynamics in the rejuvenated Western Moroccan Meseta**

456 The characterization of a transient landscape is critical for understanding the dynamics of a landscape  
457 that includes the coexistence of portions that are in equilibrium with past and present uplift rates. In  
458 the Western Meseta the lowest bedrock denudation rates are from granite exposed on the tops of the  
459 summit surfaces ( $3.5 \pm 0.2$  and  $4.1 \pm 0.3$  m/Myr) while the highest rates are from a similar granite  
460 exposed along small ridge crests ( $13.1 \pm 0.9$  to  $14.4 \pm 1.0$  m/Myr in Table 1). This four-fold difference  
461 is presumably caused by different hillslope processes and higher physical and chemical weathering  
462 assuming the same exposure time (Riebe et al., 2004). This demonstrates the key role of hillslope  
463 topographic gradients and weathering processes in controlling denudation rates from bedrocks (*e.g.*,  
464 Meyer et al., 2010; Godard et al., 2019). In our case, the highest denudation rates occur on the ridge  
465 morphologies, at the margin of relict landscape, suggesting an abrupt increase in denudation and  
466 hillslope erosion at the transition between the rejuvenated and relict topography, indicating a strong  
467 control of the geomorphic domain on the  $^{10}\text{Be}$ -derived denudation (Figs. 4 and 5).

468 Interestingly, the rates of denudation from the ridge crests (samples 57A and 57B) are very similar to  
469 those from the watersheds of the same areas (samples 60 and 61). This may be due to the widespread  
470 exposure within the catchments of the relict surface sculptured onto the granite rocks that contains a  
471 higher amount of quartz than the adjacent metamorphic rocks. These quartz-rich granite rocks erode  
472 at relatively low rates ( $\sim 4$  m/Myr) with respect to the basin-wide denudation rates from the

473 catchments composed of metamorphic rocks ( $> \sim 17$  m/Myr) and hence have a higher  $^{10}\text{Be}$   
474 concentration than the metamorphic basement. The greater amount of quartz sourced from the relict  
475 landscape appears to increase the final  $^{10}\text{Be}$  concentration for catchments 60 and 61, producing a  
476 decrease in denudation rate estimates. This process is further corroborated by the poor sensitivity of  
477 these two watersheds to the linearity between basin-wide denudation rates and topographic metrics  
478 that are systematically lower than expected (Fig. 8). Low denudation rates are also observed in  
479 watersheds 58 and 59, located upstream of non-lithological knickpoints within the relict portion of  
480 the WMM landscape where values of basin-averaged  $k_{sn}$ , slope and relief are low. These low  
481 denudation rates are consistent with those inferred from the thermochronological data (Barbero et al.,  
482 2010) averaged over the last 70 Ma and reflect the erosional decay of topography during a long period  
483 of relative base level stability (Calvet et al., 2015). Conversely, watersheds 62 and 63 present higher  
484 denudation rates because they receive most of the quartz from the incised landscape downstream of  
485 non-lithological knickpoints since the distribution of quartz-bearing rocks is uniform. In this case  
486 higher rates reflect the increase in uplift rates as documented in other regions that experienced a  
487 topographic rejuvenation (e.g., Olivetti et al., 2016; Miller et al., 2013; Clementucci et al., 2022).

488 In slow tectonic settings, there is usually a poor correlation between basin-averaged  $k_{sn}$  values and  
489 denudation rates, and this is generally attributed either to the lithological control on the landscape  
490 dynamics or to a decoupling between hillslope and channel incision (e.g., Olivetti et al., 2016; Peifer  
491 et al., 2021; Clementucci et al., 2022). Our data show a good correlation between denudation rates  
492 and topographic metrics, despite the high degree of transience in the landscape, suggesting that the  
493 landscape is not affected by any lithological control and/or decoupling process, except for catchments  
494 60 and 61. In particular, the correlation between basin-wide denudation and  $k_{sn}$  suggests that the  $n$   
495 parameter of the stream power model can be approximated to 1, as typically observed in slow tectonic  
496 settings, where basin-averaged slope and  $k_{sn}$  are usually lower than  $25^\circ$  and  $200 \text{ m}^{0.9}$ , respectively  
497 (Fig. S4). Finally, the basin-wide denudation rates are insensitive to averaged annual precipitation  
498 rates (Fig. 8d), testifying the lack of a clear dependency of denudation processes to precipitation, as

499 also observed in other slow tectonic ranges characterized by different climatic conditions (Fig. S4;  
500 Burbank and Anderson, 2003; Godard et al., 2019; Clementucci et al., 2022).

501

### 502 **5.3. Topographic evolution and uplift history**

503 The axial zone of the WMM was likely above sea level before the Lutetian (early Cenozoic / middle  
504 Eocene) as suggested by the lack of Eocene sediments (Phosphate Plateau), which can be found only  
505 along its periphery (Er Rbia Basin) where the phosphatic series shows a deepening and thickening  
506 south-westward trend (Fig. 9a; El Kiram et al., 2019). This sedimentation pattern indicates that, while  
507 western Morocco was locally subjected to Eocene subsidence and marine sedimentation, the WMM  
508 was affected by different processes (Charton et al., 2020). In addition, ~ 200- to 270-Myr-old apatite  
509 fission track cooling ages and associated thermal histories indicate limited vertical movements since  
510 the Triassic and suggest that the relict landscape might have started to form even earlier than the  
511 Lutetian, possibly from the latest Cretaceous (Barbero et al., 2010; Charton et al., 2020). Our inverted  
512 rock uplift rates for the oldest resolved time interval (35-22 Ma) of 10-20 m/Myr are in the same  
513 order of magnitude as the <sup>10</sup>Be-derived denudation rates averaged over 50 ka (Table 1) and the lava  
514 incision rates averaged over the last 1 Ma (see U<sub>1</sub> in Fig. 10a), both for the relict landscape, and the  
515 exhumation rates averaged over the last 70 Ma. The occurrence of similar modelled rock uplift and  
516 denudation/incision rates across different time scales, could indicate the persistence of a long-term  
517 balance between rock uplift and denudation (*i.e.*, steady state denudation; *e.g.*, Whipple, 2001; Willett  
518 and Brandon, 2002). However, this observation is based on the overall patterns of denudation at  
519 different time scales and does not consider short-term climate fluctuations, which usually precludes  
520 the attainment of steady-state conditions over time, possibly triggering rapid changes in denudation  
521 rates (Whipple, 2001; Champagnac et al., 2014).

522 Our fluvial inversion results indicate that in the WMM domain, the onset of uplift and associated  
523 headward migration of the knickpoints likely started at about 22 Ma and continued until ~10 Ma, with

524 rates ranging from 30 to 50 m/Myr (see  $U_2$  in Fig. 10b). This range of rock uplift rates falls also within  
525 the range of  $^{10}\text{Be}$ -derived denudation rates and lava flow incision rates downstream of major non-  
526 lithological knickpoints ( $E_2 = 35\text{-}55$  m/Myr, Figs. 9a and 10b). Barcos et al. (2014) described a  
527 maturity stage of the Sebou Basin through a stream length-gradient analysis, which can be a sign of  
528 the partial re-equilibrium of these basins since this early Miocene perturbation (Fig. 10b). These  
529 portions of the landscape are still eroding at rates that could be representative of the uplift rate  $U_2$   
530 (Fig. 10b). Thus, our inverted rates suggest that the entire WMM started to be uplifted from 22-20  
531 Ma, in agreement with the occurrence of uplifted Eocene marine deposits in the WMM and in the  
532 axial zone of the FMA and coeval with the onset of Miocene alkaline volcanism (Fig. 10b; Salvan,  
533 1954; El Kiram et al., 2019; El Attmani et al., 2021). Early Miocene uplift initiation could be also  
534 coeval with the onset of widespread contractional deformation in the FMA (Gomez et al., 1996;  
535 1998), in the High Atlas Mountains (El Harfi et al., 2001; Lanari et al., 2020a; 2020b) and in the Rif  
536 mountains (Fig. 10b; Abbassi et al., 2020). At the same time, the southward migration of the Rifian  
537 frontal thrust produced foreland subsidence with the deposition of unconformable marine deposits in  
538 the South Rifian Corridor (Saiss and Skoura Basins; Fig. 10b; Capella et al., 2018). Particularly, the  
539 Skoura Basin contains a Messinian shallow-water marine sequence possibly deposited in a gulf  
540 bounded by the TMA and FMA (Babault et al., 2008; Capella et al., 2018). In the northern Middle  
541 Atlas and the Rif Belt, uplift started sometime after 5-7 Ma (Charriere and Saint-Martin, 1989;  
542 Babault et al., 2008) at rates of 170-220 m/Myr as testified by the modern elevation of the Messinian  
543 deposits of the Skoura Basin and the closure of the marine South Rifian Corridor (Krijgsman et al.,  
544 1999; Babault et al., 2008). This episode of more recent regional uplift was accompanied by a Plio-  
545 Quaternary peak in volcanism (Fig. 1) and is also registered by the Western Meseta fluvial network  
546 (Fig. 10c). There, our inferred rock uplift rates for the last 5-6 Ma increase up to 35 m/Myr (see  $U_3$   
547 in Fig. 10c). Thus, our modelling rates appear to document a two-stage uplift history of the WMM  
548 that includes uplift initiation at 22-20 Ma (with maximum rates reached at about 15 Ma) followed by  
549 a second pulse at 5-6 Ma.

550 Alternatively, the WMM, could have shared an uplift history like that one recorded by the uplifted  
551 marine sediment of the Skoura and Saiss Basins (Babault et al., 2008). This implies that the highest  
552 knickpoints bounding the elevated relict landscape were originated during the regional 5- to 7-My-  
553 old uplift phase (Babault et al., 2008). Although our linear inversion model is calibrated for  $^{10}\text{Be}$  data,  
554 which integrates erosion rates for the last tens 50.000 years, there are strong indications that short-  
555 and long-term, thermochronologically derived, exhumation rates from the relict landscape for the  
556 Cenozoic are similar (Barbero et al., 2010). This is also valid for the denudation rates downstream of  
557 the most elevated knickpoints, which are consistent with the incision rates inferred from the lava  
558 flows over the last 1 Ma. Thus, we can conclude that our inversion is likely not biased by the time  
559 scale of the  $^{10}\text{Be}$  rates. Moreover, if we apply the approach of profile reconstruction for estimating  
560 the timing of the increase in uplift rates, for a surface uplift of 415 $\pm$  55 m (Fig. 7), an erosion rate  
561 for the relict landscape up to 20 m/Ma and an uplift (equal to erosion) rate downstream of the  
562 knickpoint of 40-50 m/Ma (Fig. 8) we would expect an minimum onset of uplift between 13 and 20  
563 Ma (see equation in figure 5 of Kirby and Whipple 2012). These estimates indicate that the uplift  
564 rates downstream of the relict landscape are too low to be consistent with a Messinian onset of surface  
565 uplift. Thus, the uplift in WMM should have started earlier than 7 Ma. Taken together, these  
566 observations suggest that the WMM and the northern sectors of the FMA, where the Skoura Basin is  
567 located, did not share the same uplift history pre 7 Ma. Consequently, a two-stage uplift history for  
568 the WMM appears to be the most likely scenario.

569

#### 570 **5.4. Implications for uplift mechanisms**

571 The northern sector of Atlas-Meseta system displays a shorter (10-50 km) and longer (>100 km)  
572 wavelength topography associated with processes operating at crustal and deeper scale, respectively  
573 (Fig. 11; Gomez et al., 1998; Boulton et al., 2014; Miller et al., 2015; Pastor et al., 2015). In particular,  
574 the WMM consists of a NE-SW oriented,  $\sim 130 \times 260$  km,  $\sim 1500$ -m-high, topographic swell devoid

575 of Cenozoic deformation (Frizon de Lamotte et al., 2009; Barbero et al., 2010). Barbero et al. (2010)  
576 interpreted the WMM as an open, lithospheric-scale fold that formed in response of shortening  
577 processes (*i.e.*, lithospheric buckling). Although this mechanism has been documented for specific  
578 rheological settings (*e.g.*, Cloetingh and Burov 2011), there are no geophysical data proving  
579 lithospheric folding in the WMM. Alternative mechanisms which could explain the absence of crustal  
580 deformation in the WMM and the occurrence of uplift with a topographic wavelength of a several  
581 tens of km (up to more than 100 km) is the emplacement of igneous intrusion or magma underplating  
582 (*e.g.*, Thybo and Artemieva, 2013; Townsend, 2022) and the removal of mantle lithosphere  
583 (delamination; *e.g.*, Garzzone et al., 2006; Göğüş, and Pysklywec, 2008).

584 Following the scenario constrained by our river-profile inversions, the uplift in the WMM started at  
585 ~22-20 Ma, shortly before the onset of alkaline volcanism (~16 Ma; El Azzouzi et al., 2010; Fig. 9)  
586 and up to 15 Myr earlier than the rise of the northern sectors of the FMA and the South Rifian Corridor  
587 (5-7 Ma; Krijgsman et al., 1999; Babault et al., 2008; Fig 10). These observations suggest that uplift  
588 in the WMM would predate the more recent regional uplift and the increase in uplift rates observed  
589 at 22-20 Ma must be ascribed to localized processes. The cumulative surface uplift in the WMM is  
590 ~415 m with uplift rates varying from 35 to 55 m/Myr during the middle Miocene, and ~30 m/Myr  
591 over the last 5-6 Ma (Figs. 9 and 10). These rates indicate that the amount of rock uplift in the last 5-  
592 6 Ma would correspond to ~150-180 m. If we consider steady constant denudation of the relict  
593 landscape at ~15 m/Myr, the resulting surface uplift during the last 6 Ma will be ~90 m (180 – 90 m,  
594 where 90 m is the surface lowering over the last 6 Ma at 15 m/Myr). Thus, accounting for all the  
595 above considerations the cumulative surface uplift pre-6 Ma would be 325 m (415 – 90 m). Assuming  
596 that Airy isostasy is maintained and considering  $2.8 \times 10^3$  and  $3.23 \times 10^3$  kg/m<sup>3</sup> as mean crustal ( $\rho_c$ )  
597 and asthenospheric mantle ( $\rho_a$ ) density respectively, a ~2000-m-thick intrusion will generate ~300 m  
598 of surface uplift (note that  $(\rho_a - \rho_c)/\rho_c$  is the ratio between elevation gain and crustal thickening;  
599 Turcotte and Schubert, 2002). Similarly, if we assume Airy isostasy and a density of the lithospheric  
600 mantle ( $\rho_m$ ) of  $3.3 \times 10^3$  kg/m<sup>3</sup> the same magnitude of surface uplift will be generated by the removal

601 of a ~14-km-thick blob of mantle (note that  $(\rho_m - \rho_a)/\rho_a$  is the ratio between elevation gain and  
602 thickness of the removed lithospheric mantle; Molnar and Stock, 2009). A similar magnitude of  
603 surface uplift (~500 m) has been also documented for the HP, although timing, rates and mechanism  
604 of uplift are unknown (Fig. 11; Pastor et al., 2015).

605 In the FMA the topographic growth reflects the combination of deep-seated and crustal shortening  
606 and thickening processes, that led to a cumulative surface uplift of about 1200 m as documented by  
607 the river projections from the eastern FMA (Fig 11). Although we do not know the timing of this  
608 surface uplift, the same magnitude of uplift occurred in the northern FMA during the last ~5-7 Ma as  
609 documented by the uplifted, Messinian marine deposits of the Skoura Basin that are in unconformity  
610 over folded Mesozoic limestones (Babault et al., 2008). Thus, it is reasonable to assume that most of  
611 the 1200 m of surface uplift in the entire FMA, were gained between 5-7 Ma and the present day.  
612 Recent surface uplift is also visible in the southern Rifian Corridor (Saiss and Taza-Guercif basins)  
613 where marine sediments experienced ~850 m of surface uplift during the last 6-8 Ma (Krijgsman et  
614 al., 1999; Babault et al., 2008). Overall, this configuration suggests that the northern FMA is  
615 characterized by a complex long-term history of deformation, uplift, and subsidence predating the  
616 last pulse of uplift, which produced ~1200 m of elevation gain at rates of ~170-220 m/Myr (Fig. 10).  
617 This renewed uplift is almost coeval with the major, second phase of volcanism centred in the Middle  
618 Atlas Mountains (Missenard et al., 2006; El Azzouzi et al., 2010) and could reflect large-scale  
619 processes coupled with the reactivation of older tectonic structures (Frizon de Lamotte et al., 2009;  
620 Babault et al., 2008) and possibly with the injection of large magmatic bodies within the crust.

621 Specifically, if we assume that shortening produced crustal thickening and surface uplift without  
622 surface erosion and/or sediments deposition while Airy isostasy was approximately maintained,  
623 thrusting in the FMA would have produced a surface elevation gain of 150 to 730 m over the last 7  
624 Ma at rates of 20 to 100 m/Myr (Garzzone et al., 2006; see equations and assumptions in Table 2).  
625 The assumption of no erosion (or very limited and hence neglectable erosion) over the last 7 Ma is

626 justified by the occurrence of the well-preserved, uplifted, marine deposits. This increase in elevation  
627 would correspond to a crustal thickening of 0.8 to 4.0 km, and if we assume an initial crustal thickness  
628 of 28-32 km, we will expect a ~29- to 36.7-km-thick crust (Table 2). These predictions agree with  
629 crustal thickness estimates obtained by Gomez et al. (1999) and Miller and Backer (2014; Fig. 11).  
630 Consequently, the remaining 470-1050 m of surface uplift should reflect deep-seated processes (*i.e.*,  
631 mantle driven) at uplift rates of 65-150 m/Myr.

632 These simple calculations indicate two possible end-member scenarios for the topographic growth of  
633 the FMA during the last 5-7 Ma: 1) shortening was the main cause of surface uplift (730 m), which  
634 occurred at ~100 m/Myr, while dynamic uplift (470 m) took place at ~65 m/Myr; 2) shortening  
635 accounted for a smaller fraction of elevation gain (150 m) and led to uplift at ~20 m/Myr, while  
636 dynamic uplift (1050 m) took place at ~150 m/Myr (Table 2). In both cases magma addition may  
637 have also, at least locally, influenced to the topographic growth of the FMA, although it is not possible  
638 to isolate such a contribution. In any case, if we consider that the volcanic lavas younger than 4 Ma  
639 crossing major faults are undeformed, and that the marine deposits of the Skoura Basin are only  
640 slightly tilted ( $< 10^\circ$ ), the amount of shortening and thickening during the Plio-Quaternary should be  
641 marginal (El Azzouzi et al., 2010; Babault et al., 2008). Thus, the dynamic-supported scenario (option  
642 2) seems to be the most reliable possibility (Fig. 10c profile 2) for the topographic growth of the FMA  
643 (Babault et al., 2008).

644 Finally, the spatial pattern of surface and uplift rates over the last 5-7 Ma, document a large-scale  
645 topographic bulge (wavelength  $> 300$  km) centred in the FMA (Fig. 11). In this configuration, the  
646 WMM appears to represent the western shoulder of a bulge with uplift at rates that are 2.5 to 6 times  
647 lower than those inferred from the central bulge (Figs. 10c and 11b). This large wavelength signal  
648 can be explained as results of lithospheric delamination/dripping or upwelling of asthenospheric  
649 mantle associated with even deeper processes like the rise of plumes possibly sourced from the  
650 Canary hotspot, or a combination of both (Duggen et al., 2009; Miller and Becker, 2014; Miller et

651 al., 2015). Although a large number of geophysical studies robustly detected a shallow LAB and  
652 Moho beneath the Middle Atlas, the nature of the regional, deep dynamic processes is still under  
653 debate (*e.g.*, Missenard et al., 2006; Clementucci et al., 2023). Given the wavelength and the  
654 amplitude of the most recent uplift event and the characteristics of coeval volcanism, we tend to  
655 favour the plume hypothesis. Dynamic rising of asthenospheric mantle can reconcile the occurrence  
656 of large-scale surface uplift, non-isostatically compensated topography, anomalous thinning of the  
657 crust and lithospheric mantle and intermittent Mio-pliocene alkaline volcanism.

658 In essence, we conclude that the regional topographic evolution of the northern Atlas-Meseta system  
659 can result from the contribution of deep components (plume activity and mantle lithospheric  
660 delamination) coupled with smaller-scale processes such as possible injection of magmatic bodies  
661 within the crust and crustal shortening and thickening, at least for the structural domains characterized  
662 by contractional deformation (*e.g.*, Middle and High Atlas).

663

## 664 **6. Conclusion**

665 Our study allows the characterisation of the magnitude, timing, and rates of the long-term topographic  
666 evolution of the northern domains of the Atlas-Meseta system. The preserved relict landscape  
667 standing at a high elevation and the occurrence of deeply incised valleys downstream of major non-  
668 lithological knickpoints document a transience in topography and hence different stages of  
669 topographic evolution. Specifically, the ancient relict topography displays low relief, slope, and  $k_{sn}$   
670 values in association with low rates of denudation on both bedrock and watersheds (from 4 to 20  
671 m/Myr). Conversely, the downstream portion of the landscape exhibits higher topographic metrics  
672 and denudation rates (up to 40 m/Myr) in response to an increase in rock uplift rate that led to a  
673 topographic rejuvenation. Within this general trend a few exceptions emerge. In certain catchments  
674 of the Western Meseta, the granite massifs exposed on top of the relict landscape provide a higher

675 amount of quartz than the downstream metamorphics, resulting in a mixed signal of  $^{10}\text{Be}$   
676 concentration, giving lower denudation rates than expected. These findings highlight that the uneven  
677 distribution of quartz-bearing rocks in the sampled catchments and their relative location within the  
678 topographic sectors (*i.e.*, relict vs rejuvenated landscape) represent a critical point for deriving basin-  
679 wide denudation rates.

680 Combined with geological data, our river-profile inversion results suggest that the elevated relict  
681 surfaces of the WMM have been forming since the Eocene. Moreover, our inverted uplift rates  
682 indicate that surface uplift and associated knickpoints migrations started at ~22-20 Ma and reached  
683 peak values of ~55 m/Myr at ~15 Ma, while the relict portion of the WMM has been eroding steadily  
684 at an average of 15 m/Myr. These values agree with our basin-wide denudation and fluvial incision  
685 rates derived from 1-Myr-old lava flows for the relict landscape and the catchment area downstream  
686 of non-lithological knickpoints. This Miocene uplift (first uplift phase) of the WMM led to a  
687 cumulative surface uplift of ~400 m over an extent of ~ 130 x 260 km, and is interpreted to reflect  
688 crustal-scale processes such as igneous intrusion or magma underplating.

689 Subsequently, from 5-7 Ma, regional uplift occurred as documented by uplifted, Messinian marine  
690 deposits of the Skoura and Saiss basins and minor knickpoints over the WMM domain. Surface uplift  
691 inferred from the modern elevation of these marine deposits in the northern FMA (Skoura Basin) is  
692 ~1200 m, that agree also with estimates from the western FMA obtained from the river projections.  
693 The larger scale (wavelength > 200 km) and the higher magnitude of uplift suggest that mantle  
694 processes like upwelling of deep asthenospheric mantle (*i.e.*, plume) may have driven the topographic  
695 rejuvenation of the entire Atlas-Meseta system including the WMM (second uplift phase). Uplift  
696 occurred at rates ranging from of ~30 to ~170 m/Myr from the WMM to the FMA over a pattern  
697 describing a bulge centred in the FMA, where the Plio-Quaternary volcanisms is also centred. The  
698 WMM represents the western shoulder of this bulge. Finally, minor crustal thickening induced by  
699 shortening may have also contributed to the post 7-Ma topographic growth of the FMA. Overall,

700 these results suggest that uplift in the WMM may have occurred in two major steps at 22-20 and 5-6  
701 Ma, while in the FMA, at least in its northern and western sectors, the major uplift pulse occurred  
702 during the last 5-7 Ma.

703

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717

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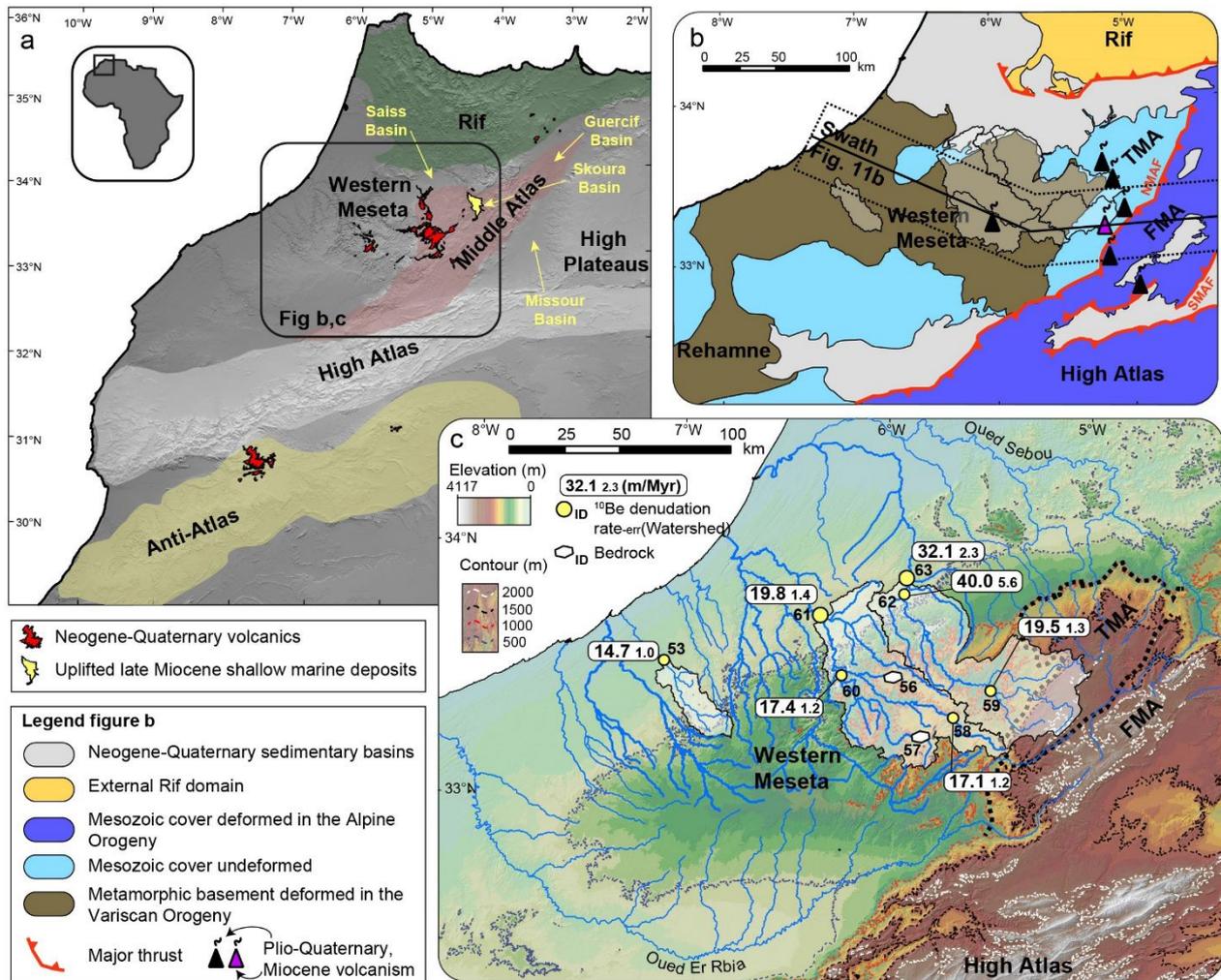
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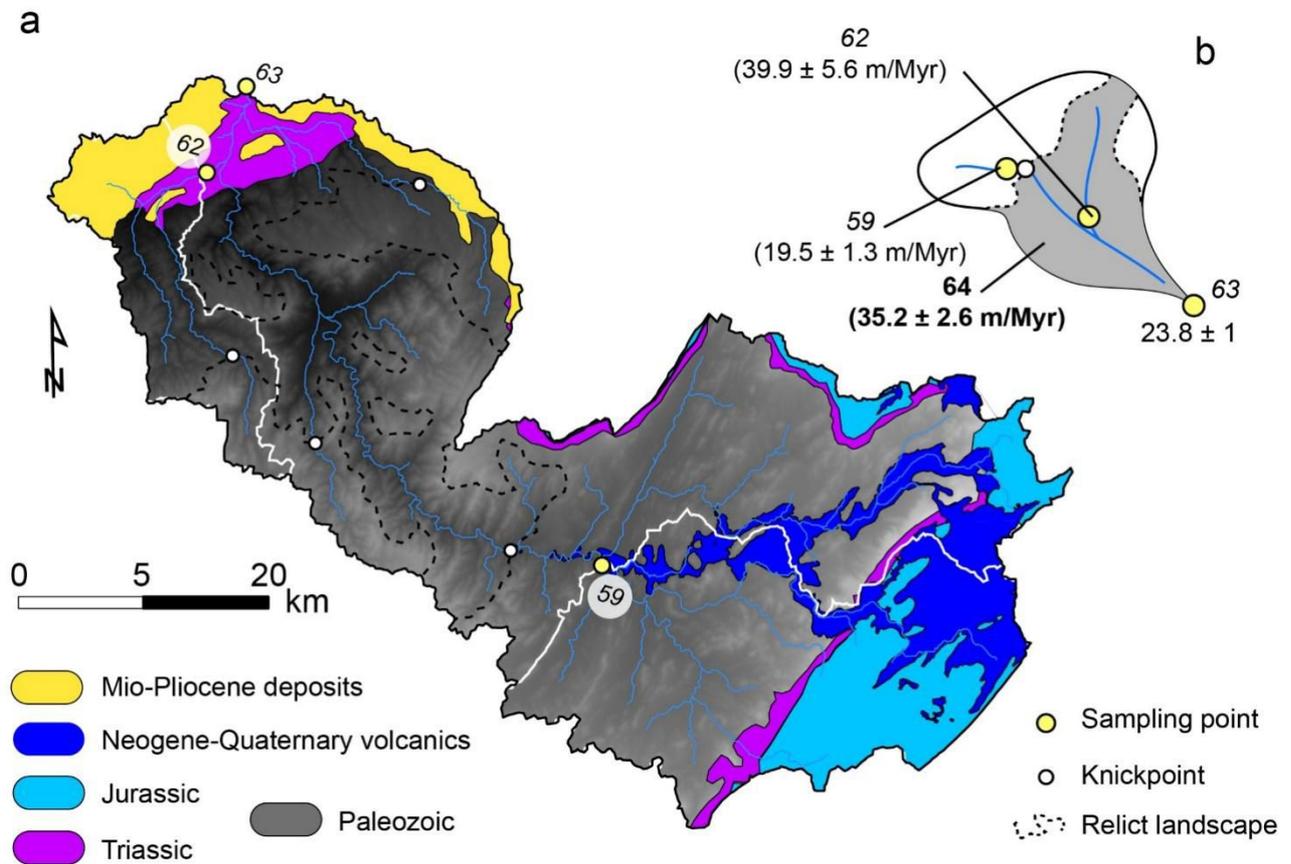
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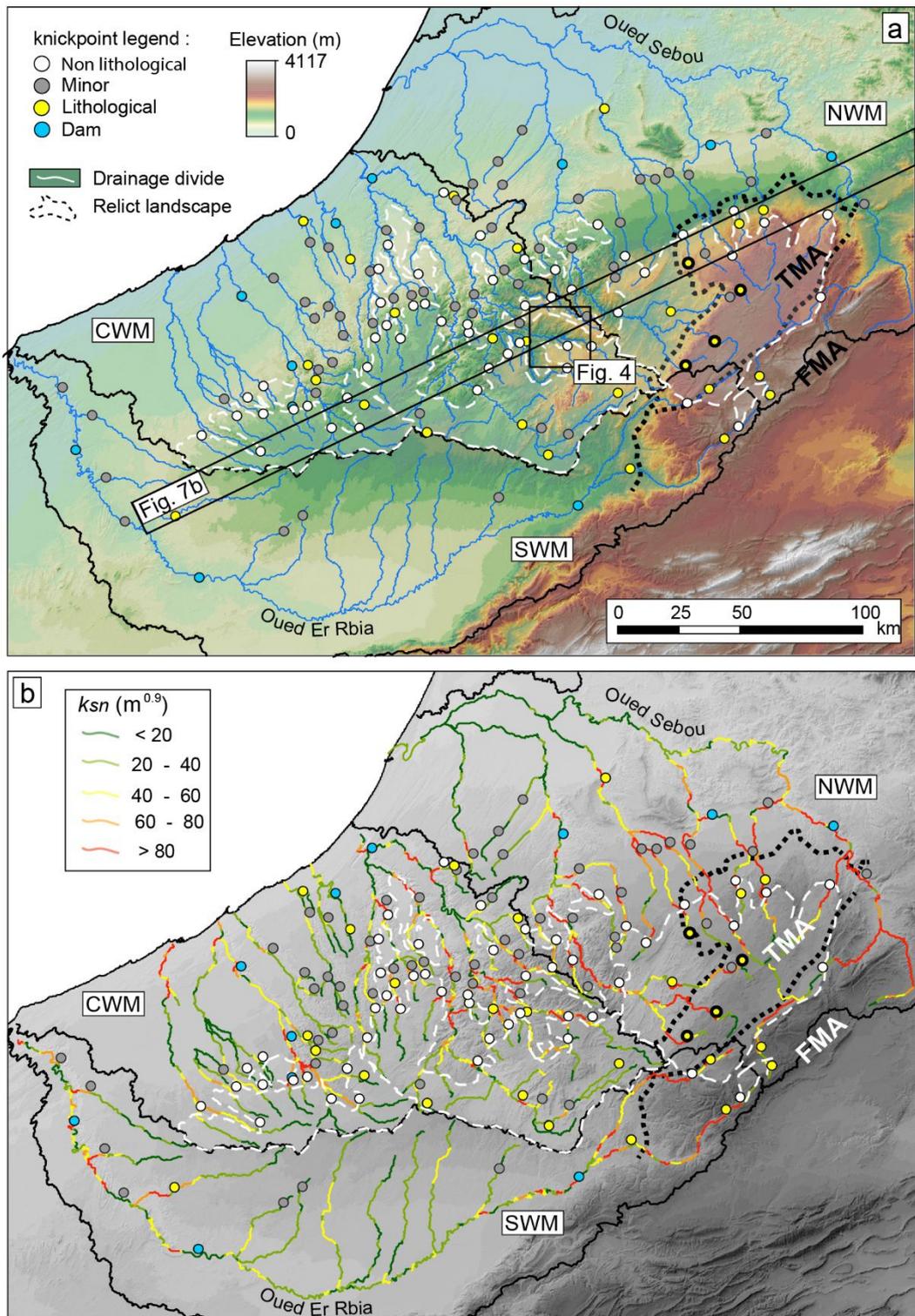
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**Figure 1. (a)** Topographic hillshade of the Rif, Atlas and Meseta domains. **(b)** Morpho-structural domains in the western central Morocco and selected. FMA: Folded Middle Atlas. TMA: Tabular Middle Atlas. NMAF: North Middle Atlas fault. SMAF: South Middle Atlas fault. **(c)** DEM of the Western Moroccan Meseta. The white transparent areas show the sampled catchments while the dots show the location of the sampling points. Note the occurrence of two major catchment and several sub-catchments. The white hexagons show the location of bedrock samples. The thick dashed line indicates the boundary between the TMA, the FMA and the Western Meseta.

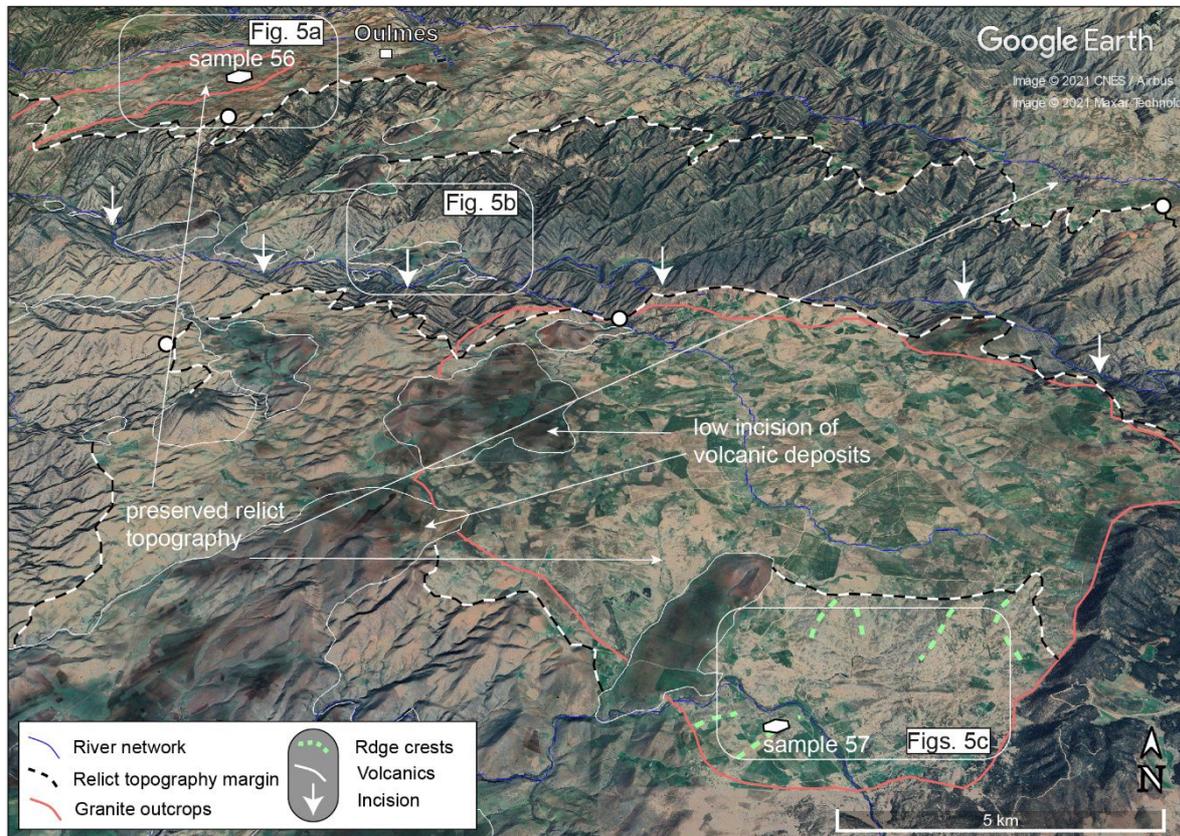


**Figure 2. (a)** Topographic and geological map of the sampled catchment 63. Note, sampling point 59 is located upstream the non-lithological knickpoint, 62 is downstream the non-lithological knickpoint and 63 represents the mixed rate of basin-wide denudation. **(b)** Schematic illustration of the catchment 63, showing the correction method to estimate the denudation rate of the downstream portion (64) of the catchment 63, by using drainage area and denudation rate of the basin 63 and 59, respectively. Note, basin-wide denudation derived from basin 62 is consistent with estimate value of the basin 64, both located in the downstream of non-lithological knickpoints.

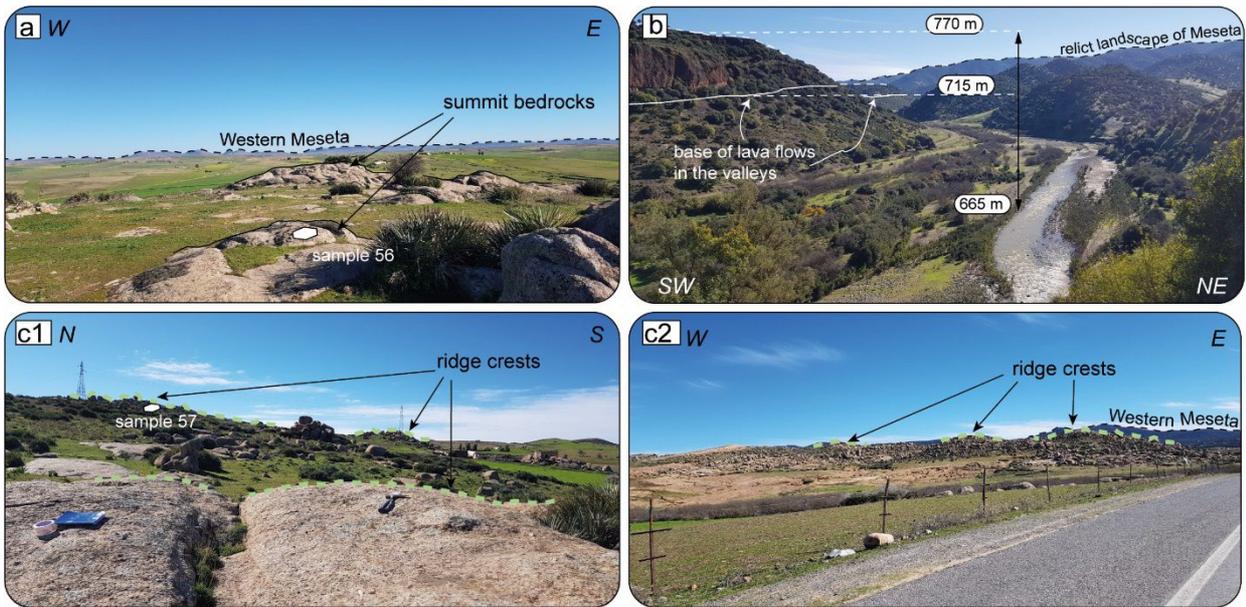


**Figure 3. (a) DEM (b)  $k_{sn}$  map with main knickpoints.** The bold knickpoints demark the escarpment between the TMA and Western Moroccan Meseta (WMM), while the thick dashed line indicates the boundary between the main morpho-structural domains. The solid lines demark the tributaries of the Oued El Rbia (South Western Meseta, SWM), of the Oued Sebou (North Western Meseta, NWM) and rivers draining directly from the

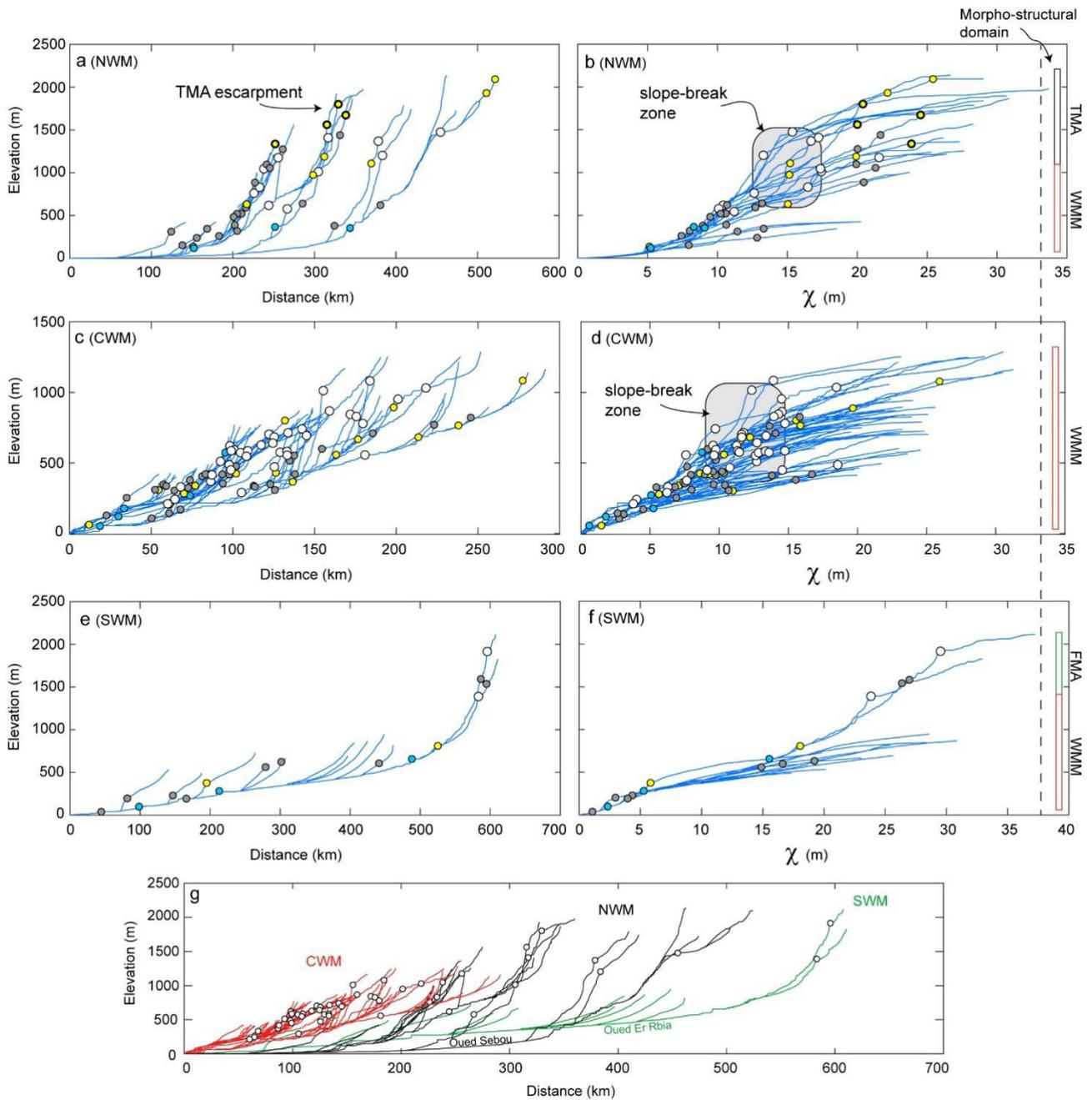
Western Meseta to the Atlantic ocean (CWM: Central Western Meseta). TMA and FMA indicate the Tabular Middle Atlas and the Folded Middle Atlas, respectively.



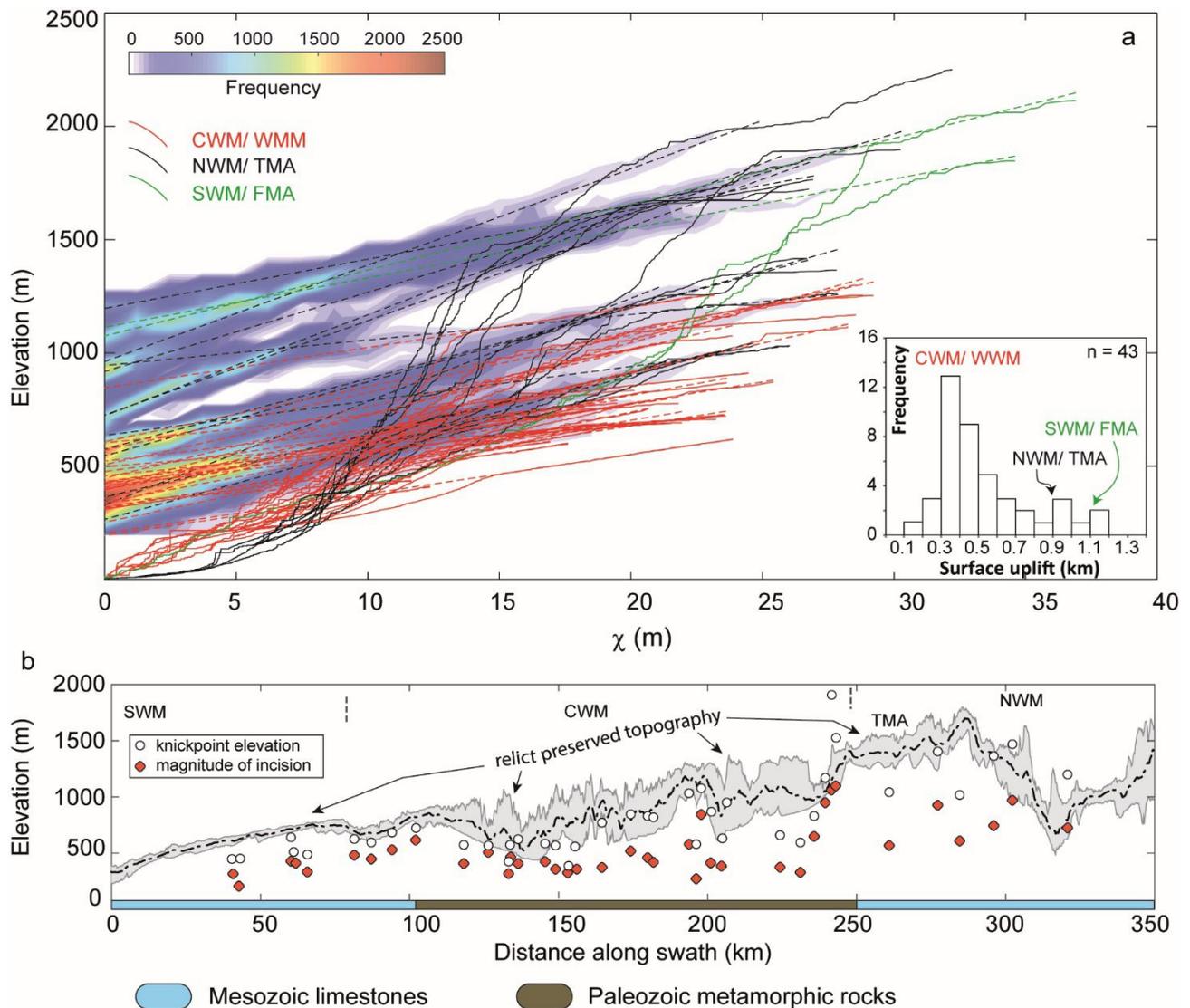
**Figure 4.** Prospective Google Earth view of the Western Moroccan Meseta. The granite rocks are red polygons and are located at the maximum topography over the summit erosional surface within the sampled catchments 60 and 61 (*i.e.*, relict landscape). The Pleistocene lava flows are deeply incised and well preserved in the deep incisions on the relict topography, respectively. The location of the picture is shown in figure 3.



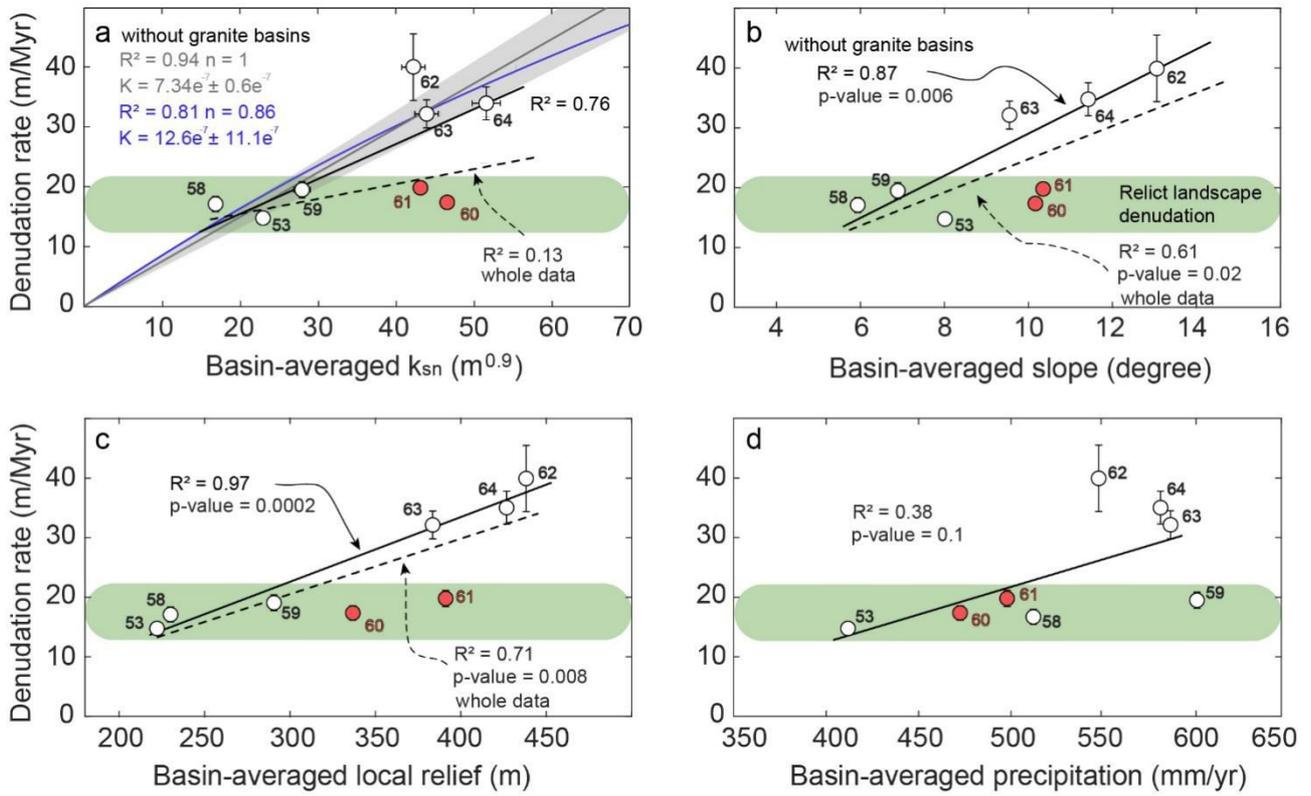
**Figure 5.** (a) View of the summit erosional surface of the Western Moroccan Meseta near the locality of Oulmes. The typical morphologies of the granite rocks lying at the maximum elevation are shown in the foreground (black lines). (b) View of the Aguenour River valley. Note the incision across the lava flow deposits ( $\sim 100$  and  $\sim 50$  m from the top and the base of the lava flow, respectively). (c1-c2) View of the granite outcrops close to the plateau margin. Note the rugged morphologies related to the granite incisions (green lines). The location of the pictures is shown in figure 4.



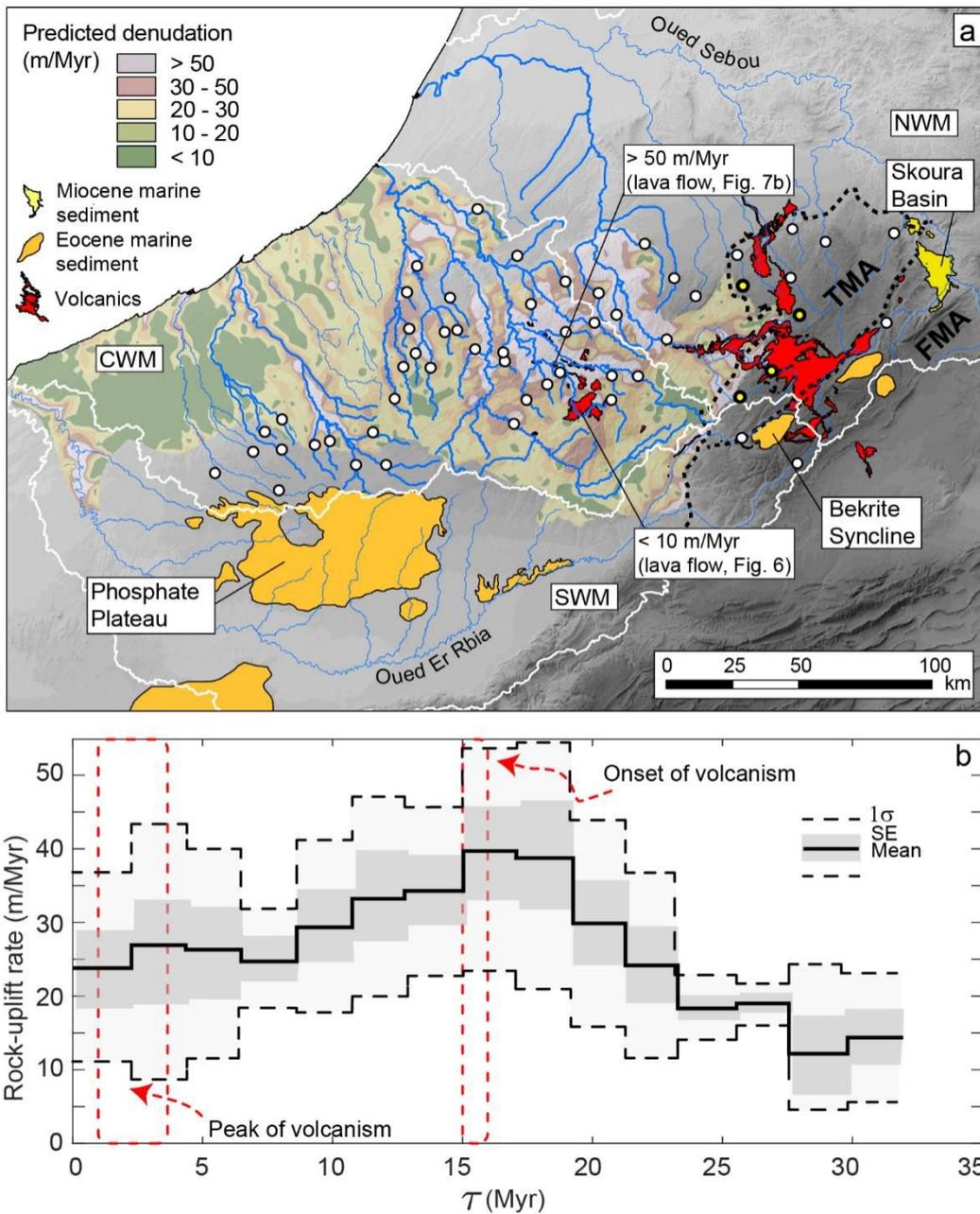
**Figure 6.** Longitudinal river profiles and  $\chi$ -z plots with knickpoints for the NWM (a-b), CWM (c-d), and SWM (e-f). The knickpoints legend is in figure 2a. The non-lithological knickpoints are located at the slope-break zone separating segments with different  $k_{sn}$  value. (g) Longitudinal river profiles with the major non-lithological knickpoints for the three morpho-structural domains. Red rivers: CWM sector; black rivers: NWM sector; green rivers: SWM sector. The non-lithological knickpoints mark the boundary between the downstream steep river profiles and the upstream low-gradient river segments, describing a paleo-surface margin. Note, the rivers of NWM and SWM sectors come mainly from the most elevated TMA and FMA domains, respectively.



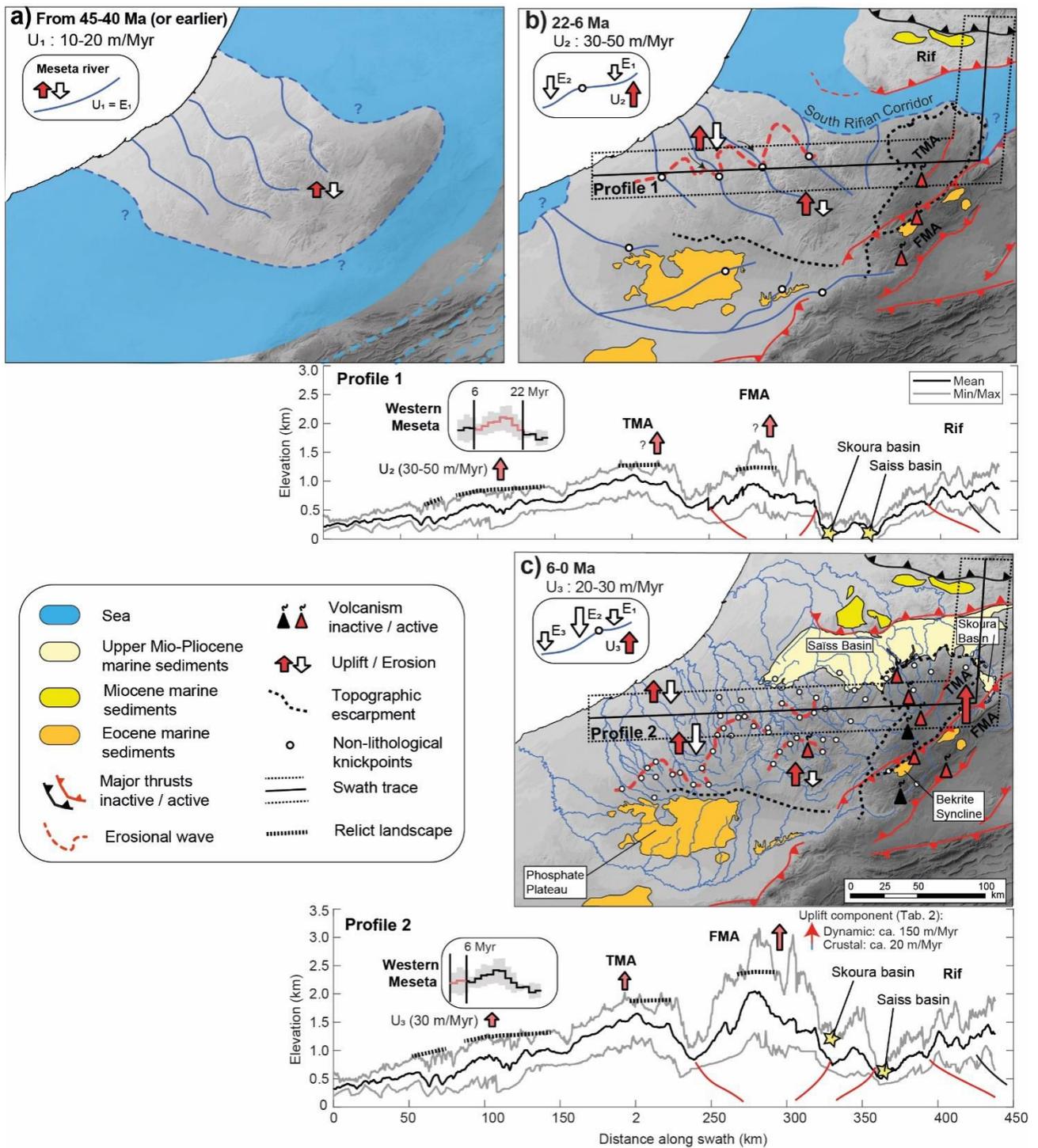
**Figure 7. (a)** Modern longitudinal profiles and projections of the relict landscape (black dashed segments) upstream of the highest knickpoints using  $\theta_{ref} = 0.45$  and the  $k_{sn}$  of the relict portion in the  $\chi$  plot. The main peaks of long-term fluvial incision are at  $\sim 400$  m and  $\sim 800$  m in the Western Moroccan Meseta and Tabular Middle Atlas domains, respectively (see details in Table S2). The density distribution legend is relative to the data point of the projected segments. Inset shows the frequency diagrams of the magnitude of long-term incision for the entire dataset (NWM, WMM, SWM). Note, the rivers of NWM and SWM sectors come mostly from the TMA and FMA domains, respectively. **(b)** Along-strike topographic swath profile, knickpoints elevation and magnitude of long-term incision obtained from the reconstructed river projections. SWM : South Western Meseta; CWM : Central Western Meseta; NWM : North Western Meseta; TMA : Tabular Middle Atlas. The location of the swath profile is shown in figure 3a.



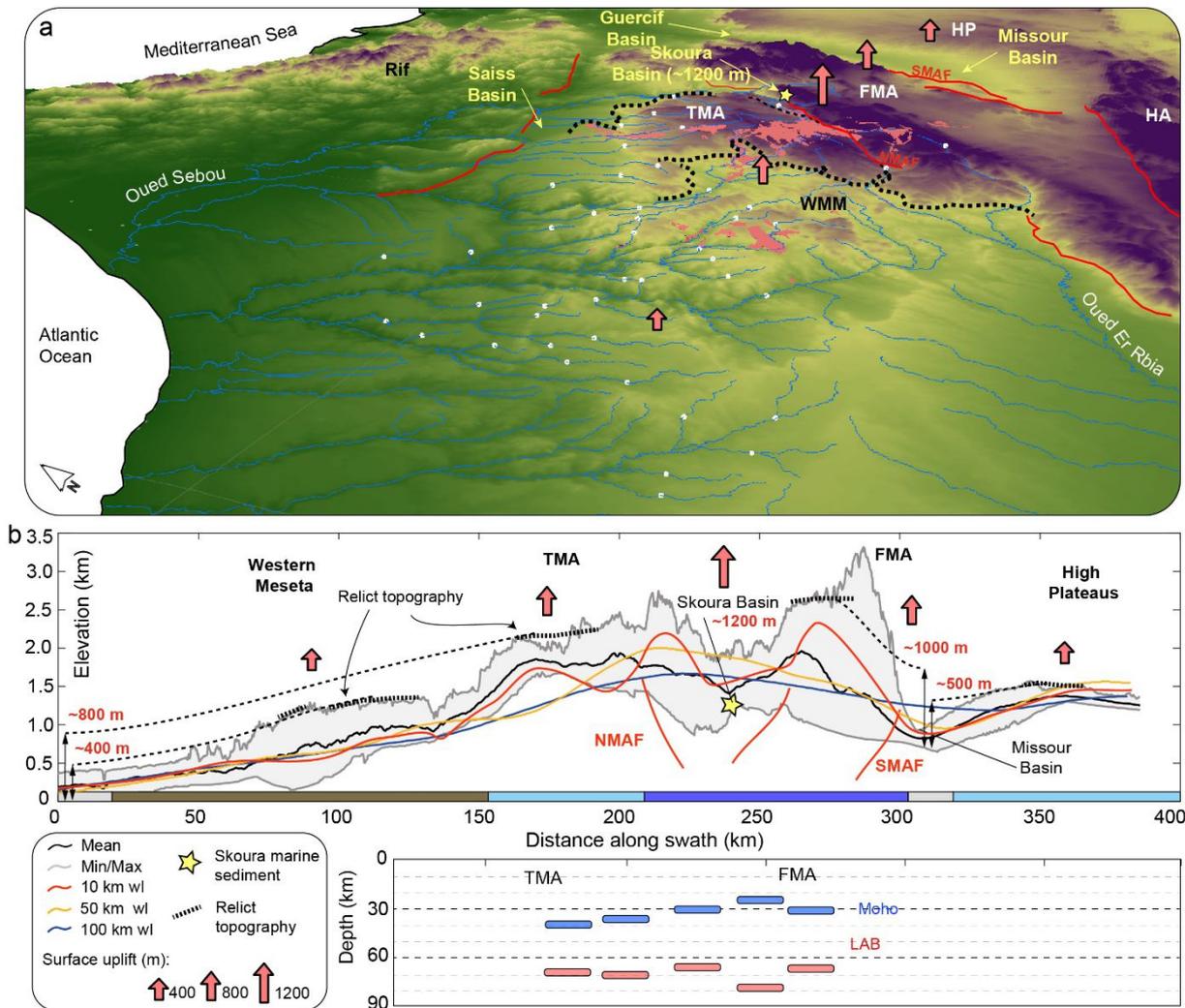
**Figure 8.** Basin-wide denudation rate vs basin-averaged a)  $k_{sn}$ , b) slope, c) local relief (2.5 km radius), and d) precipitation rate for the sampled basins. The black and grey solid lines show the bootstrap linear best-fit, and forced linear best-fit without considering basins with exposed granite rocks. The blue trend is the power best-fit. The dashed black lines denote the best-fit considering all sampled basins. The red circles indicate catchments characterized by the contribution of quartz from granite massifs (details in fig. 4).



**Figure 9.** a) Predicted denudation rates based on the distribution of normalized channel steepness in the basement rocks. b) Rock-uplift history for selected rivers (bold blue rivers in figure 9a). Mean and standard deviation and error results from the river-profile inversion of six basins of the Western Meseta (details in Figs. S5 and S6 in supplementary material).



**Figure 10.** Schematic evolution of the Western Meseta and the Middle Atlas domains since the Lutetian (45-40 Ma). **a)** Erosional steady-state topography of the Western Meseta with marine conditions in the Middle Atlas and surrounding regions. **b)** Miocene topographic rejuvenation associated with volcanism and upstream migration of an erosional wave in response to the increase in rock-uplift rates at 22-20 Ma. Note also the southward propagation of the frontal thrusts of the Rif orogenic system with subsidence and marine deposition in the Saiss and the Skoura basins. **c)** Second slight increase in rock-uplift rates in the Western Meseta. Abrupt increase in uplift rates in the Middle Atlas as testified by uplifted marine Messinian deposits at rates of  $\sim 170 \text{ m/Myr}$ . Inset in figures **b** and **c** show the river profiles and the inverse modelling results of the rivers flowing through the Western Meseta.



**Figure 11. a)** Tridimensional view of the northern Atlas-Meseta system. **b)** Swath profile (details and location are shown in Fig. 1b) with filtered topography at 10 – 50 – 100 km wavelengths and data of long-term surface uplift of WMM, TMA, FMA and HP (this work and Pastor et al., 2015). WMM: Western Moroccan Meseta; TMA and FMA: Tabular and Folded Middle Atlas; HP: High Plateaus; SMAF: South Middle Atlas Fault; NMAF: North Middle Atlas Fault (after Gomez et al., 1996). The bottom panel indicates the projected position of Moho and lithosphere-asthenosphere boundary (LAB) beneath the Atlas-Meseta system from S-received functions (data from Miller and Becker, 2014).

**Table 1.** Denudation rates from cosmogenic  $^{10}\text{Be}$  in river borne sand and bedrock samples.

ID	Geomorphic position	Long.	Lat.	Elev. <sup>a</sup>	Quarz mass <sup>b</sup>	Carrier mass ( $^9\text{Be}$ )	$^{10}\text{Be}/^9\text{Be}^c$		$[^{10}\text{Be}]^d$ $10^3$ (at./g)		Production rate <sup>e</sup>			Denudation (m/Myr)		Integration time <sup>f</sup> (yr)	
							Value ( $10^{-15}$ )	Error (%)	Value	Error	Neutrons	Slow muons	Fast muons	Value	Error	Value	Error
53	Watershed	7.1500	33.5364	455	20.70	0.151	195.1	3.4	284.7	9.8	5.08	0.015	0.04	14.76	1.02	48081	3330.1
58	Watershed	5.7512	33.2640	1173	21.82	0.150	292.6	4.3	406.0	17.6	8.69	0.02	0.05	17.11	1.27	41624	3080.5
59	Watershed	5.5714	33.3807	1083	21.68	0.151	241.6	3.4	338.5	11.7	8.16	0.02	0.05	19.49	1.35	36639	2535.6
60	Watershed	6.2790	33.4496	914	21.20	0.150	238.8	3.4	339.4	11.8	7.28	0.02	0.05	17.36	1.20	41023	2845.5
62	Watershed	5.9743	33.7520	721	21.12	0.151	95.5	12.3	135.0	17.0	6.32	0.02	0.05	39.94	5.57	18044	2514.7
Blank							0.45	51.3									
61	Watershed	6.365	33.698	928	21.47	0.152	211.5	3.3	302.7	10.3	7.35	0.02	0.05	19.80	1.37	36076	2488.0
63	Watershed	5.931	33.829	1049	21.74	0.151	146.6	4.1	204.8	8.5	7.95	0.02	0.05	32.15	2.34	22369	1630.0
56A	Summit	6.0535	33.4123	1124	21.84	0.150	1055.6	3.1	1467.4	46.0	8.43	0.02	0.05	3.46	0.23	163446	11064.1
56B	Summit	6.0535	33.4123	1124	21.59	0.150	900.1	2.5	1259.7	31.2	8.43	0.02	0.05	4.11	0.27	139446	9053.0
57A	Ridge crest	5.8906	33.1922	1098	19.45	0.150	251.2	3.3	389.0	12.9	8.23	0.02	0.05	14.36	0.98	41958	2874.7
57B	Ridge crest	5.8913	33.1919	1099	17.24	0.151	239.1	3.5	423.6	14.9	8.24	0.02	0.05	13.13	0.91	45808	3185.9
Blank							0.788	23.05									

<sup>a</sup> Basin mean elevation.

<sup>b</sup> Mass of pure quartz dissolved.

<sup>c</sup> Isotopic ratio uncertainties include statistical error on counted  $^{10}\text{Be}$  events (N) and analytical error correction.

<sup>d</sup> Uncertainties on  $^{10}\text{Be}$  concentrations are calculated using the standard error propagation method using the quadratic sum of the relative errors associated to the counting statistics, AMS internal error (0.5% for ASTER), and error associated to the process blank.

<sup>e</sup> Production rate is the spatially averaged production rate over the river basin, scaled for elevation, latitude (Stone, 2000) and geomorphic shielding (Dunne et al., 1999). The values, relative to watersheds, are calculated for a non-uniform distribution of quartz-lithologies in the sample basins (e.g., Carretier et al., 2015; Clementucci et al., 2022).

<sup>f</sup> Integration times are calculated after Lal (1991) while their uncertainties are calculated propagating the error of the uncertainties associated with denudation rates.

**Table 2.** Structural topographic relief and lithospheric thickening of the Folded Middle Atlas based on the equation of Garzione et al., (2006):  $dh/dt = (\rho_m - \rho_c) / \rho_c * (UH/W)$ , assuming that Airy isostasy is maintained during shortening and for crustal ( $\rho_c$ ) and asthenospheric mantle ( $\rho_m$ ) densities of 2.8 and 3.23 kg/m<sup>3</sup>, respectively. Shortening produces thickening and surface uplift at a rate of  $dh/dt$  (assuming no surface erosion and subsidence with deposition). The parameters  $H$  (crustal thickness) and  $W$  (orogen width) at 7 Ma and the inferred thickness after 7 Ma of shortening at rates of 0.5 to 1.5 mm/yr are consistent with modern crustal thickness data reported by Miller and Becker, (2014).

$W^a$ min (km)	$W^a$ max (km)	$H^b$ min (km)	$H^b$ max (km)	$U^c$ min (mm/yr)	$U^c$ max (mm/yr)	$dh/dt^d$ min (mm/yr)	$dh/dt^d$ max (mm/yr)
70	100	28	32	0.5	1.5	0.021	0.105

<b>Since 7 Ma</b>					
Elevation gain, min (km)	Elevation gain, max (km)	Crustal root <sup>e</sup> min (km)	Crustal root <sup>e</sup> max (km)	Mean thickness of crust <sup>f</sup> min (km)	Mean thickness of crust <sup>f</sup> max (km)
0.15	0.73	0.81	3.96	28.96	36.7

<sup>a</sup> Width of the deforming Middle Atlas range.

<sup>b</sup> Initial crustal thickness

<sup>c</sup> Shortening rate (data from Vernant et al., 2010 and Gomez et al., 1999).

<sup>d</sup> Surface uplift rate assuming lithospheric ( $\rho_c$ ) and mantle ( $\rho_m$ ) density of 2.8 and 3.23 kg/m<sup>3</sup> (after Garzione et al., 2006).

<sup>e</sup> Expected crustal root of the thickened crust according to Airy isostatic model (Mean gain elevation\*  $\rho_c$ )/(  $\rho_c$ \*  $\rho_m$ ).

<sup>f</sup> Expected crustal thickness of the thickened crust (H + Elevation gain + Crustal root)

## Supplementary materials

### S1. Topographic, stream analysis

A Shuttle Radar Topography Mission Digital Elevation Model (SRTM DEM, pixel size of 30 m) was used to extract the drainage network. Hillslope metrics, such as slope and local relief with a circular sampling window of 2.5 km radius, as well as basin and channel morphometric characteristics were extracted using ArcGIS and the MATLAB software packages TopoToolbox (Schwanghart and Scherler, 2014) and Topographic Analysis Kit (TAK, Forte and Whipple, 2019), together with additional MATLAB functions (*e.g.*, Gallen, 2017).

Regions characterized by recent changes in base level retain a topographic signal in the upstream river network that provides the opportunity to evaluate the magnitude and the spatial variation of such perturbations.

The relationships between channel steepness and erosion/uplift rates have been demonstrated in various geological settings (Kirby and Whipple, 2012; Miller et al., 2013; Adams et al., 2020). In detachment-limited conditions, these relationships are modulated by the stream-power model (Howard, 1994; Whipple and Tucker, 1999). Under steady-state conditions, erosion and rock uplift rates are balanced and  $dz/dt$  is equal to zero, therefore the power-law can be solved as (Flint et al., 1974):

$$S = \left(\frac{E}{K}\right)^{\frac{1}{n}} A^{-\left(\frac{m}{n}\right)} \quad (1)$$

where  $E$  is the erosion rate (*i.e.*, change in elevation ( $z$ ) of a stream with respect to time ( $t$ )),  $A$  is the upstream contributing drainage area,  $S$  is the local channel slope,  $K$  is the erosional efficiency (which is function of lithology and climate), and  $m$  and  $n$  are constant values (which depend on basin hydrology, channel geometry and erosional processes). Equation (1) predicts a power relation between slope and drainage area and can be integrated, assuming  $E$  and  $K$  as spatially invariant (Perron and Royden, 2013):

$$z(x) = z(x_b) + \left(\frac{U}{KA_0^m}\right)^{\frac{1}{n}} \int_{x_b}^x \left(\frac{A_0}{A(x')}\right)^{\frac{m}{n}} dx = z(x_b) + k_s A_0^{-\left(\frac{m}{n}\right)} \chi \quad (2)$$

where:

$$\chi = \int_{x_b}^x \left(\frac{A_0}{A(x')}\right)^{\frac{m}{n}} dx' \quad (3)$$

where  $x_b$  is the base level and  $\chi$  is an integral quantity,  $A_0$  is the reference drainage area, and  $m/n$  describes the concavity of the stream. Equation (2) allows transforming river longitudinal profiles to  $\chi$  versus elevation plots (here and thereafter defined as  $\chi$  -  $z$  plot, where  $z$  and  $\chi$  are the dependent and independent variable, respectively). Consequently,  $(U/K)^{1/n}$  is the slope in the  $\chi$  space, where the slope is defined as steepness index ( $k_s$ ) by imposing  $A_0$  equal to 1. The steepness index ( $k_s$ ) and the concavity ( $m/n$ ) can be determined through the integral approach proposed by Perron and Royden, (2013). To compare  $k_s$  values of longitudinal profiles, a typical reference concavity index ( $\theta_{ref}$ ) of 0.45, is applied to derive normalized channel steepness indices ( $k_{sn}$ ; Snyder et al., 2000; Wobus et al., 2006). This value represents the best-fit concavity for all rivers draining the study area that minimizes the scatter in the  $\chi$  space (Perron and Royden, 2013; Goren et al., 2014; Fig. 3h).

Knickpoints were identified and discretized along the stream network based on the shape of the streams in the longitudinal profiles, the  $\chi$  -  $z$  plots and using available geological maps (Service Géologique du Maroc) and satellite imagery (Google Earth). Importantly, non-lithological, transient knickpoints cluster around similar  $\chi$  values (Perron and Royden, 2013) and separate stream segments with different  $k_{sn}$  values (Kirby and Whipple, 2012; Olivetti et al., 2016; Clementucci et al., 2022). Conversely, knickpoints associated with heterogeneities along the profile and lithological contrasts are usually anchored in space and do not show a significant break in  $\chi$  space (Fig. S1; Kirby and Whipple, 2012). Using this approach, the knickpoints were divided into four categories: non-lithological knickpoints, minor, lithological and dam related.

## **S2. $^{10}\text{Be}$ concentration measurements and denudation rates calculations**

Samples were analyzed following a protocol including: (1) crushing (only for bedrock samples) and sieving of sand to extract the 250 – 1000  $\mu\text{m}$  fraction. (2) Magnetic separation with the Frantz magnetic separator

(three steps: 0.5 - 1 - 1.5 Ampere). (3) Decarbonation of carbonate-rich samples through the reaction with HCl. (4) Leaching with HCl and H<sub>2</sub>SiF<sub>6</sub> solution to remove all remaining minerals except quartz. (5) Decontamination from atmospheric <sup>10</sup>Be in the quartz grains by means of a three sequential leaching in HF. (6) Total dissolution of quartz grains, after addition of 150 µl spike of an in-house carrier of <sup>9</sup>Be carrier solution (3025 ±9 µg/g), from deep-mined phenakite crystal (Merchel et al., 2008). (7) Extraction of the final amount of Be using hydrofluoric and perchloric fuming to remove fluorides; cation and anion exchange chromatography was used to eliminate iron, aluminum, manganese, and other elements. (8) Mixing of beryllium oxide with a 325-mesh niobium powder. Measurements of in situ-produced <sup>10</sup>Be concentrations were performed at the French Accelerator mass spectrometry (AMS) national facility ASTER (Aix-en-Provence). The obtained <sup>10</sup>Be/<sup>9</sup>Be ratios were corrected for procedural blanks and calibrated directly against the in-house STD-11 standard (<sup>10</sup>Be/<sup>9</sup>Be = (1.191±0.013) × 10<sup>-11</sup>; Braucher et al., 2015). Analytical uncertainties (1σ) are related to external uncertainties, variation of isotopic ratios of standards during the runs, and AMS counting statistics, and were propagated into the uncertainty of the calculated denudation rates. Finally, the basin-wide denudation rates were calculated considering the three different categories of particles responsible for the in situ production of <sup>10</sup>Be (Braucher et al., 2011), solving analytically:

$$C(x, t) = \frac{P_n}{\lambda + \frac{\rho \cdot \varepsilon}{\Lambda_n}} \cdot e^{\frac{\rho \cdot x}{\Lambda_n}} \cdot \left(1 - e^{-\left(\lambda + \frac{\rho \cdot \varepsilon}{\Lambda_n}\right)t}\right) + \frac{P_{\mu s}}{\lambda + \frac{\rho \cdot \varepsilon}{\Lambda_{\mu s}}} \cdot e^{\frac{\rho \cdot x}{\Lambda_{\mu s}}} \cdot \left(1 - e^{-\left(\lambda + \frac{\rho \cdot \varepsilon}{\Lambda_{\mu s}}\right)t}\right) + \frac{P_{\mu f}}{\lambda + \frac{\rho \cdot \varepsilon}{\Lambda_{\mu f}}} \cdot e^{\frac{\rho \cdot x}{\Lambda_{\mu f}}} \cdot \left(1 - e^{-\left(\lambda + \frac{\rho \cdot \varepsilon}{\Lambda_{\mu f}}\right)t}\right) \quad (4)$$

where  $C(x, t)$  corresponds to the nuclide concentration as a function of depth  $x$  (g/cm<sup>2</sup>),  $\varepsilon$  (g/cm<sup>2</sup>/yr) represents the denudation rate and  $t$  (yr) the exposure time.  $P_n$ ,  $P_{\mu s}$ ,  $P_{\mu f}$  and  $\Lambda_n$ ,  $\Lambda_{\mu s}$ ,  $\Lambda_{\mu f}$  are the production rates and effective apparent attenuation lengths of neutrons, slow muons and fast muons, respectively.  $\Lambda_n$ ,  $\Lambda_{\mu s}$ ,  $\Lambda_{\mu f}$  values used in this paper are 160, 1500 and 4320 g/cm<sup>2</sup>, respectively (Braucher et al., 2011),  $\lambda$  is the radioactive decay constant of <sup>10</sup>Be and  $\rho$  is the rock density.

**Table S1.** Averaged denudation rate, channel steepness, topographic slope, local relief, precipitation rate of the quartz-bearing areas exposed in the sampled basins

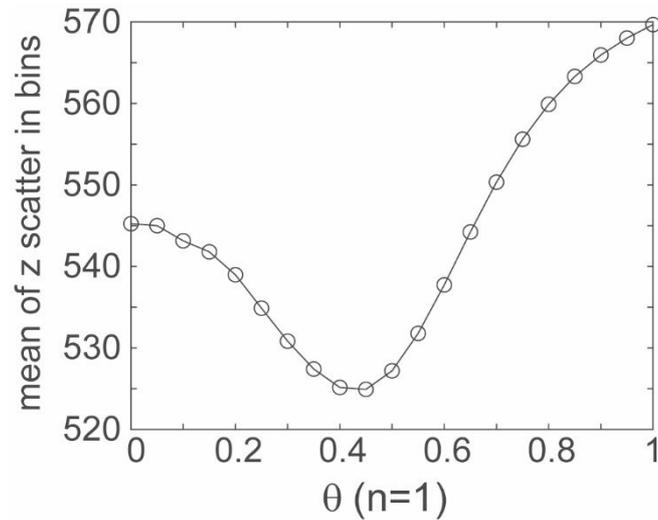
Sample	Basin area	Quartz-bearing area	Quartz-bearing area	Denudation rate (m/ Myr)		$k_{sn}$ ( $m^{0.9}$ ) <sup>a</sup>		Slope <sup>b</sup>	Local Relief <sup>c</sup>	Precipitation rate <sup>d</sup>
ID	( $km^2$ )	( $km^2$ )	(%)	Value	Error	Value	Error	( $^\circ$ )	(m)	(m/ yr)
53	535.5	228.0	42.6	14.76	1.02	22.7	0.5	8.01	222.2	411.5
58	339.3	339.3	100.0	16.66	1.23	16.7	0.6	5.9	228.4	517.9
59	970.1	496.2	51.1	19.49	1.35	27.6	0.7	6.9	288.4	599.8
60	1007.2	1007.2	100.0	17.60	1.22	46.4	0.8	10.0	337.8	472.1
61	3195.8	2775.8	86.9	19.80	1.37	43.6	1.0	10.1	381.9	495.2
62	354.5	238.9	67.4	39.94	5.57	42.4	0.9	12.9	439.9	549.6
63	3456.3	2591.5	75.0	32.15	2.34	44.4	1.0	9.8	377.4	586.3
64	-	1646.2	-	35.15	2.58	53.5	1.5	11.5	426.7	579.3

<sup>a</sup> Basin-averaged  $k_{sn}$  of quartz-bearing lithologies in the sampled basins.

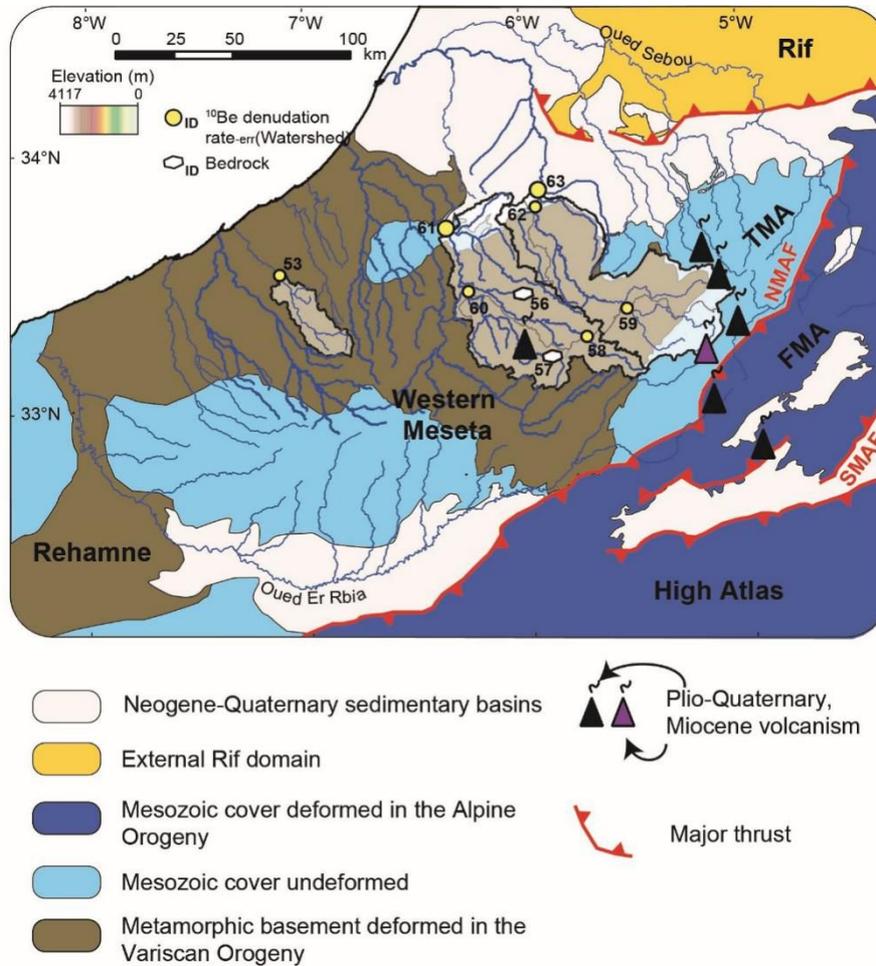
<sup>b</sup> Basin-averaged slope of quartz-bearing lithologies in the sampled basins.

<sup>c</sup> Basin-averaged local relief (2.5 km radius) of quartz-bearing lithologies in the sampled basins.

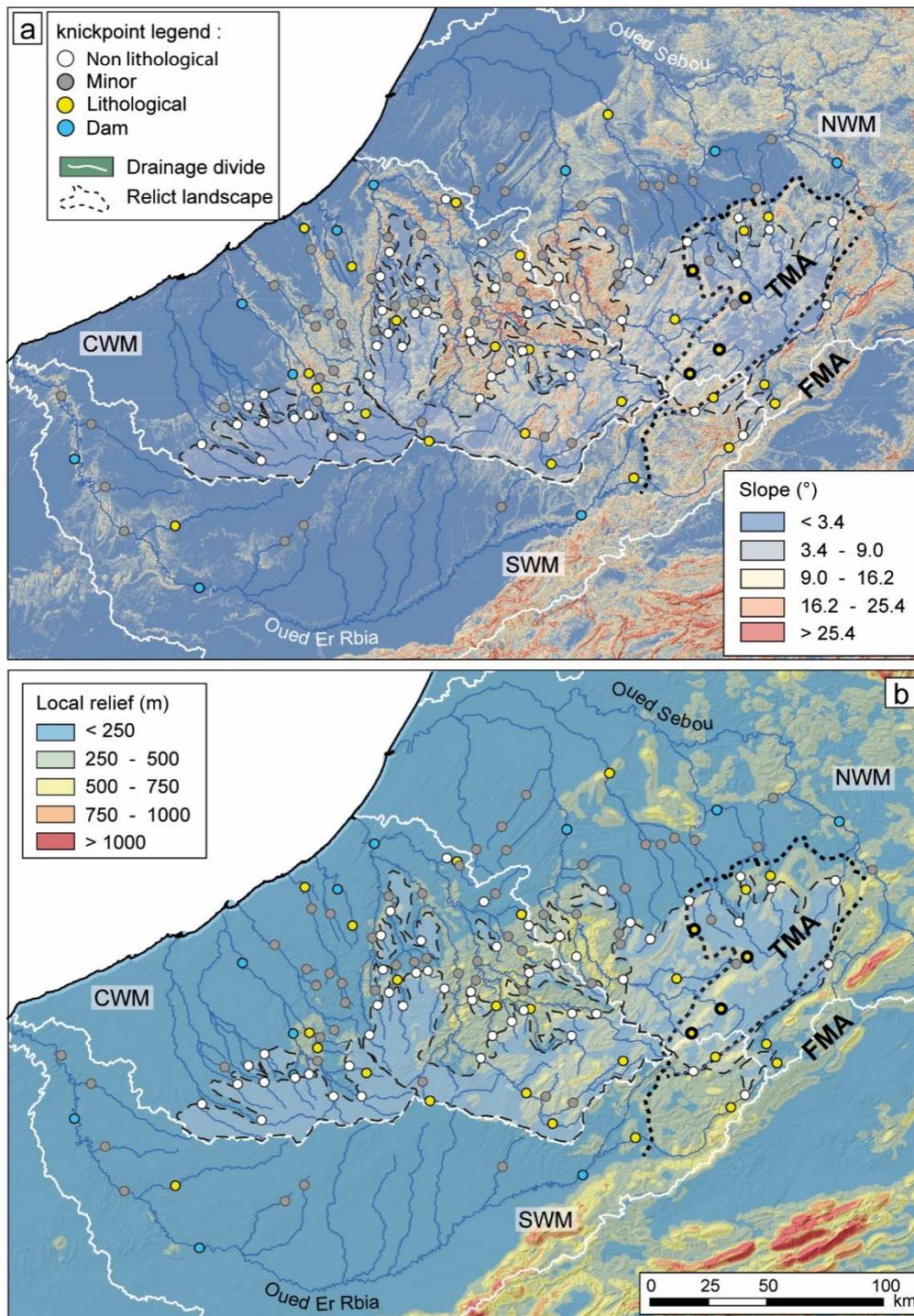
<sup>d</sup> Averaged precipitation rate for the quartz-bearing lithologies areas exposed in the sampled basins.



**Figure S1.** Plot showing the best-fit concavity index for the rivers of the study area, which is  $\sim 0.45$ .



**Figure S2.** Morpho-structural domains in the northwestern central Morocco and selected . FMA: Folded Middle Atlas. TMA: Tabular Middle Atlas. NMAF: North Middle Atlas fault. SMAF: South Middle Atlas fault. The white polygons are the sampling catchments. The bold blue rivers are the selected streams to perform the linear inversion.



**Figure S3.** The slope (**a**) and local relief (2.5 km radius; **b**) maps with main knickpoints. The bold knickpoints describe the escarpment between the TMA and Moroccan Meseta, while the thick dashed line indicates the boundary between the main morpho-structural domains. The white solid lines demark the tributaries of the Oued El Rbia (South Western Meseta, SWM), of the Oued Sebou (North Western Meseta, NWM) and rivers draining directly from the Western Meseta to the Atlantic ocean (CWM: Central Western Meseta). TMA and FMA indicate the Tabular Middle Atlas and the Folded Middle Atlas, respectively.

**Table S2.** Non-lithological knickpoints and river profile data

Stream <sup>a</sup>	Long.	Lat.	Elevation	DFM <sup>b</sup>	DFD <sup>c</sup>	Drainage area	Location <sup>d</sup>
	°W	°N	(m)	(km)	(km)	(km <sup>2</sup> )	
cwm1	798790.6	3686682.0	952	201.10	53.50	402.6	Meseta
cwm2	789008.6	3686828.0	1080	183.89	13.15	23.1	Meseta
cwm3	782292.6	3707195.0	870	158.74	34.06	130.0	Meseta
cwm4	771342.6	3723036.0	579	133.13	9.46	10.1	Meseta
cwm5	788862.6	3677776.0	1036	218.14	23.20	91.6	Meseta
cwm6	769298.6	3688215.0	829	175.38	13.76	22.8	Meseta
cwm7	764407.6	3683616.0	846	171.84	9.94	19.5	Meseta
cwm8	756596.6	3677849.0	780	179.56	12.64	34.1	Meseta
cwm9	788643.6	3651058.0	821	245.55	48.31	420.5	Meseta
cwm 10	737178.6	3697121.0	558	180.84	113.02	1659.8	Meseta
cwm 11	720242.6	3689894.0	624	117.30	30.97	151.4	Meseta
cwm 12	725571.6	3703691.0	587	99.21	13.76	24.6	Meseta
cwm 13	730316.6	3704348.0	570	104.67	10.10	31.1	Meseta
cwm 14	727615.6	3716685.0	372	86.58	16.31	64.2	Meseta
cwm 15	714694.6	3695588.0	575	109.39	16.58	32.6	Meseta
cwm 16	709949.6	3690259.0	550	108.05	19.47	68.3	Meseta
cwm 17	711993.6	3704932.0	417	87.22	10.62	16.5	Meseta
cwm 18	711190.6	3718875.0	380	68.00	10.91	16.9	Meseta
cwm 19	706737.6	3678141.0	573	128.93	28.52	197.5	Meseta
cwm 20	699656.6	3723255.0	309	64.17	14.03	28.9	Meseta
cwm 21	703379.6	3652810.0	715	133.85	27.29	177.1	Meseta
cwm 22	691918.6	3652883.0	683	125.31	18.69	110.4	Meseta
cwm 23	682063.6	3662008.0	594	100.79	15.43	48.6	Meseta
cwm 24	676369.6	3660548.0	625	98.17	20.55	84.8	Meseta
cwm 25	664032.6	3670330.0	450	98.74	37.46	187.6	Meseta
cwm 26	657389.6	3665585.0	486	97.54	8.08	9.7	Meseta
cwm 27	652936.6	3657920.0	510	92.40	23.13	69.1	Meseta
cwm 28	662791.6	3643247.0	641	124.46	30.87	215.0	Meseta
cwm 29	638628.6	3649817.0	450	97.60	14.43	42.9	Meseta
cwm 30	663813.6	3658869.0	586	109.10	17.52	84.7	Meseta
cwm 31	698415.6	3665439.0	702	122.12	20.19	65.5	Meseta
cwm 32	715059.6	3728876.0	208	60.65	87.61	766.1	Meseta
cwm 33	748347.6	3692522.0	742	142.19	9.29	18.5	Meseta
cwm 34	737178.6	3697121.0	558	133.22	28.75	124.6	Meseta
cwm 35	747836.6	3695880.0	695	145.04	9.45	16.7	Meseta
cwm 36	771561.6	3703691.0	1012	155.34	15.27	33.6	Meseta
cwm 37	753092.6	3732745.0	290	105.40	33.15	175.7	Meseta
cwm 38	742945.6	3747564.0	331	72.90	14.93	42.9	Meseta
Mean wmm			621 ± 121				
nwm1	800323.6	3705808.0	618	243.97	118.61	2097.4	Meseta
nwm2	892887.6	3707268.0	1475	454.62	84.77	1351.2	TMA
nwm3	895734.6	3741505.0	1202	383.38	48.15	290.2	TMA
nwm4	869965.6	3738074.0	1369	378.39	33.77	198.9	TMA
nwm5	857336.6	3743038.0	1013	304.82	20.06	76.4	TMA
nwm6	856752.6	3724350.0	1408	316.88	31.22	148.9	TMA
nwm7	820544.6	3717415.0	1175	255.61	10.79	35.3	TMA
nwm8	836385.6	3733110.0	1045	237.99	19.01	59.4	TMA
nwm9	783898.6	3718510.0	632	217.02	15.62	45.1	Meseta
nwm10	928949.6	3707560.0	1348	441.63	49.22	410.3	TMA
nwm11	812514.6	3724131.0	830	232.77	19.43	105.9	Meseta
nwm12	801272.6	3737344.0	545	201.53	31.10	103.6	Meseta
nwm13	790687.6	3710261.0	761	225.87	21.69	64.6	Meseta
Mean nwm			1032 ± 188				

swm1	859161.6	3653467.0	1915	595.72	13.29	57.7	FMA
swm2	847262.6	3670914.0	1532	595.71	19.90	84.9	FMA
Mean swm	798790.6	3686682.0	1724 ± 135				
Mean Meseta			627 ± 116				
Mean TMA			1255 ± 86				
Mean FMA			1724 ± 135				

<sup>a</sup> cwm : river draining directly to the ocean; nwm : river draining into the Oued Sebou; swm : river draining into the Oued Er Rbia.

<sup>b</sup> Distance from divide.

<sup>c</sup> Distance from river mouth

<sup>d</sup> Meseta : rivers draining the Western Moroccan Meseta sectors (WMM); TMA: rivers draining the Tabular Middle Atlas (NWM sector). FMA: rivers draining the Folded Middle Atlas (SWM sector).

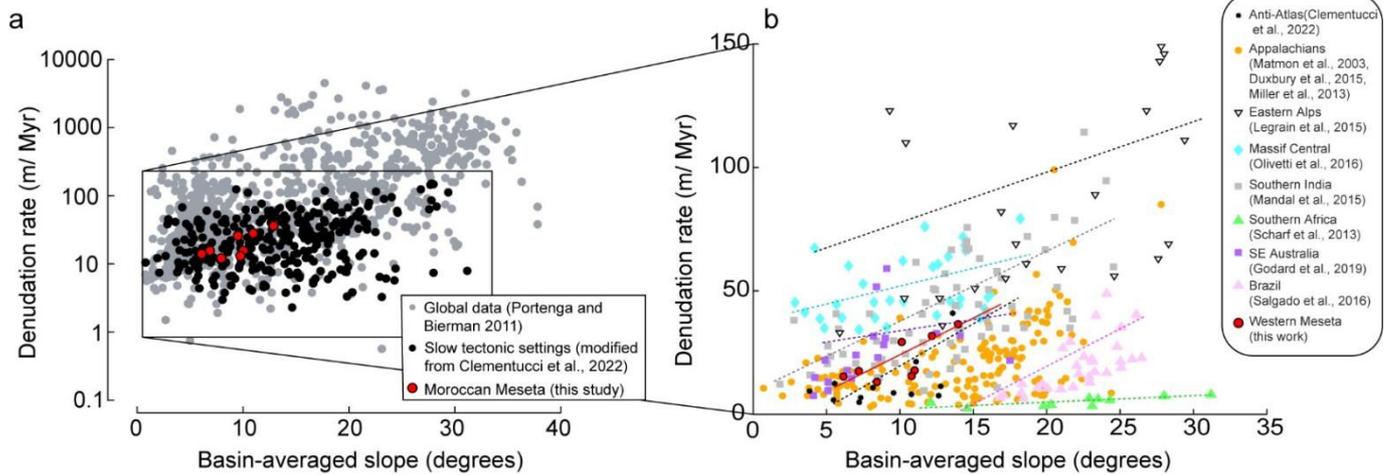
**Table S3.** Reconstructed relict stream profile and 95% confidence interval

Stream <sup>a</sup>	m/n	Elevation knickpoint	$\Delta Z^b$	Error ( $2\sigma$ )	Location <sup>b</sup>
		(m)	(m)	(m)	
cwm1	0.45	952	608.2	10.1	Meseta
cwm2	0.45	1080	845.3	2.7	Meseta
cwm3	0.45	870	404.8	6.3	Meseta
cwm4	0.45	579	252.3	11.8	Meseta
cwm5	0.45	1036	570.8	14.2	Meseta
cwm6	0.45	829	447.0	15.7	Meseta
cwm7	0.45	846	506.5	6.9	Meseta
cwm8	0.45	780	356.8	9.5	Meseta
cwm9	0.45	821	396.7	3.8	Meseta
cwm 10	0.45	558	332.5	6.5	Meseta
cwm 11	0.45	624	396.6	4.1	Meseta
cwm 12	0.45	587	423.5	4.7	Meseta
cwm 13	0.45	570	341.5	13.1	Meseta
cwm 14	0.45	372	310.7	14.1	Meseta
cwm 15	0.45	575	457.8	4.1	Meseta
cwm 16	0.45	550	497.4	7.0	Meseta
cwm 17	0.45	417	309.5	13.9	Meseta
cwm 18	0.45	380	341.4	4.1	Meseta
cwm 19	0.45	573	399.0	22.0	Meseta
cwm 20	0.45	309	193.7	14.8	Meseta
cwm 21	0.45	715	602.0	1.1	Meseta
cwm 22	0.45	683	521.9	1.3	Meseta
cwm 23	0.45	594	430.3	6.8	Meseta
cwm 24	0.45	625	475.9	2.5	Meseta
cwm 25	0.45	450	203.9	1.4	Meseta
cwm 26	0.45	486	319.2	9.0	Meseta
cwm 27	0.45	510	413.5	8.7	Meseta
cwm 28	0.45	641	428.1	4.6	Meseta
cwm 29	0.45	450	313.6	4.9	Meseta
Mean wmm			417.3	54.9	
nwm1	0.45	618	328.4	17.8	Meseta
nwm2	0.45	1475	961.3	26.9	TMA
nwm3	0.45	1202	722.4	22.6	TMA
nwm4	0.45	1369	725.1	23.8	TMA
nwm5	0.45	1013	574.3	41.3	TMA
nwm6	0.45	1408	917.7	23.3	TMA
nwm7	0.45	1175	944.3	12.6	TMA
nwm8	0.45	1045	544.8	28.1	TMA
nwm9	0.45	632	363.1	24.6	Meseta
nwm10	0.45	1348	1196.1	17.6	TMA
nwm11	0.45	830	635.6	24.1	Meseta
nwm12	0.45	545	265.1	27.1	Meseta
Mean nwm			681.5	86.4	
swm1	0.45	1915	1067.0	37.8	FMA
swm2	0.45	1532	1105.4	89.6	FMA
Mean swm			1086.2	63.7	
Mean Meseta			414.9	54.9	
Mean TMA			823.2	66.5	
Mean FMA			1086.2	63.7	

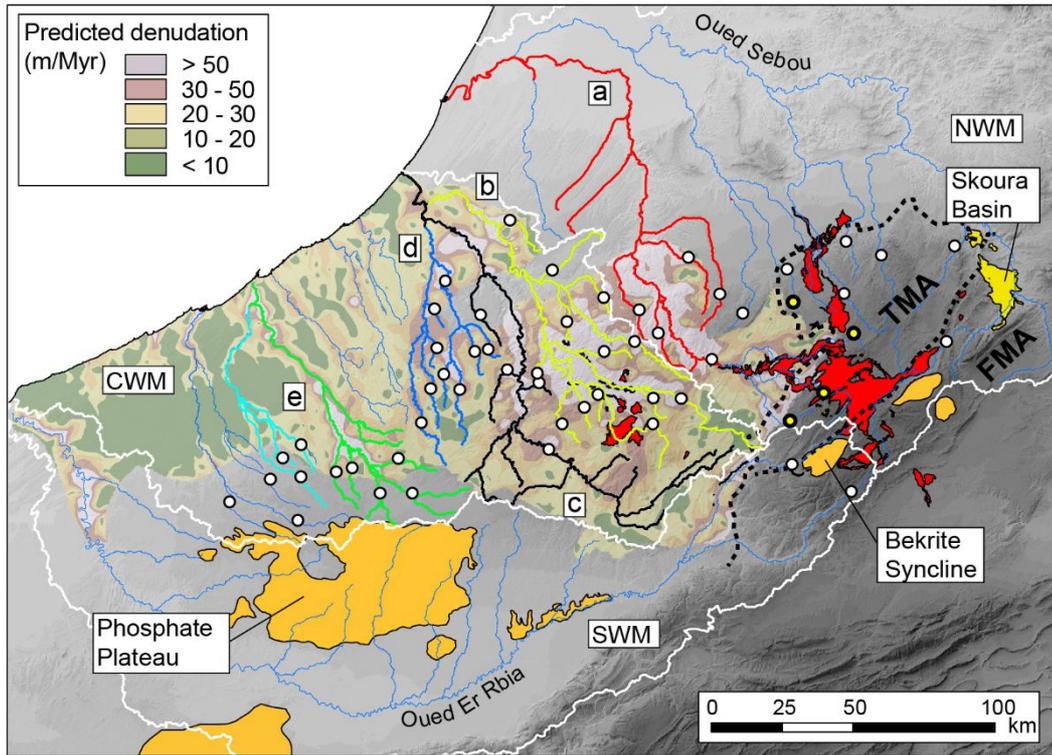
<sup>a</sup> cwm : river draining directly to the ocean; nwm : river draining into the Oued Sebou; swm : river draining into the Oued Er Rbia.

<sup>b</sup> Estimated long-term fluvial incision from reconstructed relict stream profiles.

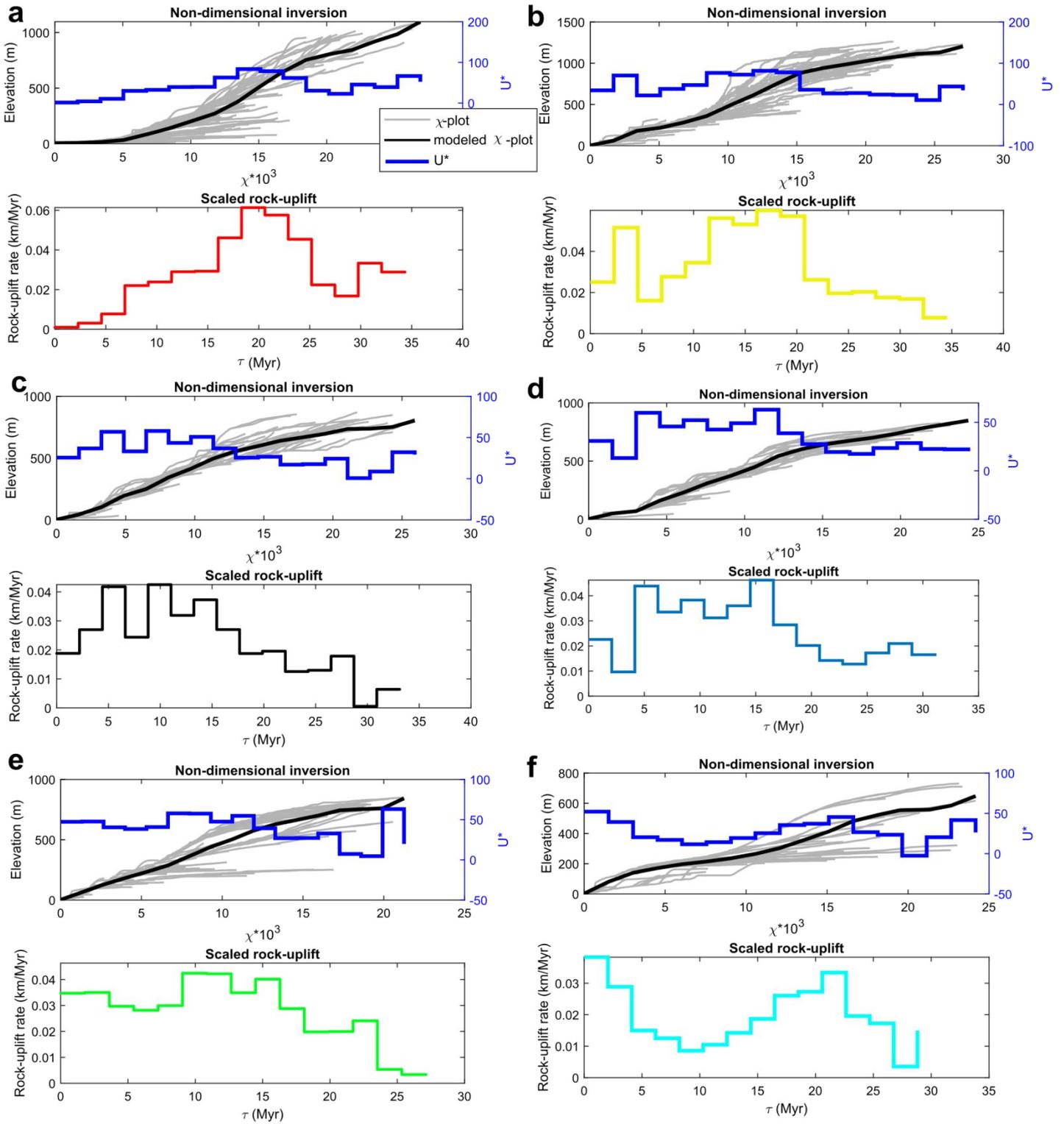
<sup>c</sup> Meseta domains : rivers draining the Western Moroccan Meseta domain (mostly from cwm and nwm sector); TMA: rivers draining the Tabular Middle Atlas (mostly nwm sectors); FMA: rivers draining the Folded Middle Atlas (from swm sector).



**Figure S4.** Global compilation of basin-averaged slope versus basin-wide denudation rates for slow tectonic settings (modified from Olivetti et al., 2016; Clementucci et al., 2022).



**Figure S5.** Predicted denudation rates based on the distribution of normalized channel steepness in the basement rocks. The colored rivers represent the catchments selected for the linear inversion (details in fig. S6).



**Figure S6.** River-profile inversion of six basins of the Western Meseta. The river inversions are constrained using the mean erodibility value of basement rocks,  $n = 1$  and  $m/n = 0.45$ . In the bottom  $\tau$ -plots, the thick transparent trends represent the river inversion results from  $K \pm 1\sigma$  ( $7.34 \pm 0.58 \times 10^{-7} \text{ m}^{0.1}/\text{yr}$ ). Location of selected rivers is shown in figure S5 through the colour scale.

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