Tectonically- and climatically-driven mountain-hopping erosion in Central Guatemala from detrital 10Be and river profile analysis

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Abstract. The rise of a mountain range affects moisture circulation in the atmosphere and water runoff across the land surface, modifying the distribution of precipitation and ~~the shape of~~ drainage patterns~~.~~ in its vicinity. Water routing in turn affects erosion on hillslopes, and incision in river channels~~. The rise of a mountain range thereby alters the erosion of~~ on surrounding mountain ranges. ~~We document here such influence in~~In Central Guatemala, ~~where~~ two parallel, closely spaced mountain ranges formed during two consecutive pulses of ~~single-stepped~~ uplift, ~~one from~~the first between 12 ~~to~~and 7 Ma (Sierra de Chuacús-Sierra de las Minas), and the second ~~one~~ after 7 Ma (Altos de Cuchumatanes). We explore the climatic and tectonic processes ~~by~~through which the rise of the most recent range drove the slowing of river incision and hillslope erosion over the previously-uplifted range. 40Ar-39Ar dating of perched volcanic deposits documents the sequential rise and incision of ~~the two~~these mountain ranges. Terrestrial cosmogenic 10Be in river sediments ~~shows~~indicates that currently, hillslopes in the older range ~~today~~ erode more slowly than in the younger range (20-150 vs. 300 m·My-1~~), and that these~~). These differences mimic the current distribution of precipitation, with the younger range intercepting the atmospheric moisture before it reaches the older range. River channel steepness and deformation of paleovalleys in the new range further ~~show~~indicate that the younger has risen faster than the older range up to today. We review how atmospheric moisture interception and river long-profile adjustment to the rise of the new range ~~contribute~~have contributed to the ~~decrease in~~decline of erosion rates over the old range. We ~~then~~also explore ~~how~~ the ~~topography~~consequences of this decline and of aridification on the topographic evolution of the older range~~ has evolved in response to the decrease in erosion rates.~~. The ~~old~~older range undergoes a slow topographic decay, ~~owing to the stalling of river incision around its base. Aridification makes such decay very slow, and~~ dominated by backwearing,~~ rather than downwearing, marked~~ by the stacking of slowly-migrating erosion waves along the mountain flanks, and by the formation of pediments around its

base. The morphology of the old range is therefore transitioning from that of a front range to that of a dry interior range.

1. Introduction

~~The relief of~~A mountain ~~ranges~~range affects both the circulation of atmospheric moisture ~~in the atmosphere~~circulation around its relief, and the flow of precipitated water ~~across~~over the land surface~~.~~ on its slope and in the vicinity. Moisture rises and precipitates on ~~the~~its windward side ~~of mountains and~~ , while rain shadows ~~are~~tend to be cast over ~~their~~its lee-side~~,~~ and ~~beyond on~~over the land surface located downwind ~~reliefs~~ (e.g.Meijers et al., 2018; Galewsky, 2009). ~~Overland flow generates~~Once precipitated, the fraction of water than runs off as overland flow drives hillslope erosion and river incision. River drainages are dynamic systems that can transmit forcing along drainage lines in both the downstream ~~disturbances that affect their~~ and upstream directions. Changes in climate and vegetation modulate hillslope erosion, and these changes are then transmitted to rivers from the headwaters~~, and also transmit upstream disturbances affecting their~~ downstream . Conversely, changes affecting downstream river reaches, ~~in particular~~such as the adjustment of river ~~profiles~~gradient to the rise of mountain ranges, or to variations in sea level, can be transmitted upstream along river channels (Humphrey and Heller, 1995; Whittaker and Boulton, 2012). ~~Signals~~From there, they are ~~then~~ transmitted ~~from the rivers to the toe of valley slopes, and then~~ uphill along valley slopes (Harvey, 2002; Mudd and Furbish, 2007). ~~Through~~Mountain ranges affect the erosion of surrounding reliefs through this combination of top-down ~~(precipitation and runoff)~~ and bottom-up ~~(upstream-migrating signals)~~ processes~~, the rise of a mountain affects the erosion of surrounding reliefs.~~.

The growth of contractional orogens commonly involves the outward, sequential propagation of contraction~~.~~, and the formation of successive, in-sequence mountain ranges. Moisture, ~~on the other hand~~by contrast, is ~~often~~commonly advected in the opposite direction, from the ~~foreland toward~~forelands to the orogen ~~interior~~interiors. Precipitated water is then commonly returned to the foreland ~~along~~by river networks that flow from the ~~interior~~orogen interiors to the ~~foreland. In such setting, the in-sequence~~forelands. The rise of ~~frontal~~front ranges~~, at the margins of orogens, will~~ therefore ~~frequently occur~~commonly takes place both upwind and downstream of pre-existing ~~reliefs (Garcia-Castellanos, 2007). The rise of a new frontal range therefore leads to the~~ ranges, driving the aridification of previously uplifted ~~ones. In the meantime,~~ranges (Garcia-Castellanos, 2007). The new front ranges will also affect the ~~new frontal range rises across the course of~~ rivers that ~~flow from~~drain the ~~interior to~~previously uplifted ranges toward the ~~foreland. It~~forelands. These rivers will ~~impart~~adjust to enhanced rock uplift by enhanced incision, through the steepening of ~~rivers transverse to the range~~their gradient in areas of enhanced uplift (Leland et al., 1998~~), thereby promoting~~). This steepening is accompanied by a transient ~~decreases~~decrease in ~~river~~ incision ~~rates farther~~rate, upstream of the rising ranges (Champel et al., 2002). ~~It may spark the~~In some cases, the topography and underlying tectonic structure will respond fast enough to reach a new dynamic equilibrium between relief, climate, and tectonics (Willett and Brandon, 2002; Whipple and Meade, 2006) without any substantial alteration of the drainage network. In other cases, however, the range-transverse river networks will experience reorganization ~~of~~before the ~~range-transverse river network~~equilibrium is reached (Jackson et al., 2002; van der Beek et al., 2002; Brocard et al., 2012). In ~~some cases, topography and tectonic structure will adapt fast enough to re-establish a new equilibrium relief, equilibrium climate, and equilibrium tectonic structure (Willett and Brandon, 2002; Whipple and Meade, 2006). In other cases,~~ a few cases even, the slowing down of ~~the~~ landscape response~~, upstream and downwind or a rising range~~ time, as a result of aridification, upstream and downwind or the rising ranges will lead to the disintegration of river drainages, ~~following by~~and to the topographic decay of ~~the~~ interior ranges~~, an~~. This evolution ~~conducive to~~characterizes the nucleation and growth of orogenic plateaus formed by lateral accretion (Sobel et al., 2003; Garcia-Castellanos, 2007). These ~~two~~different evolutionary pathways have been explored at the scale of entire orogens~~, but they~~. They are ~~less frequently~~, however, seldom documented at the scale of individual mountain ranges, ~~where the hallmark of these evolutions interferes with~~ because their manifestation at that scale is harder to separate from more local signals ~~resulting from~~driven by spatial variations in bedrock erodibility, ~~topographic inheritances, or~~ stochastic processes ~~such as~~(e.g. landslides), and topographic inheritance.

We document here ~~the effects of~~how the rise of a recent mountain range (the 170 km-long Altos de Cuchumatanes, or AC range) ~~on~~affected the topographic evolution of ~~an~~a nearby, older range (the 220 km-long Sierra de Chuacús-Sierra de las Minas, or SC-SM range) in Guatemala (Fig.1). Sharp topographic, climatic, and tectonic gradients ~~affect~~in this region exert themselves over a relatively small (350 x 100 km) area, allowing ~~us to conduct~~a detailed investigation of the interactions between the two ranges. The SC-SM range ~~grew~~started to rise first~~;~~ in early late Miocene time, when its flanks were deeply eroded ~~in late Miocene time~~ (Brocard et al., 2011). The AC range, on the other hand, started to grow ~~at the end of~~in the ~~late~~latest Miocene, next to the SC-SM range. The rise of the AC range sparked widespread drainage rearrangement in front of the SC-SM~~, characterized by numerous river captures~~ range during the late Miocene (Brocard et al., 2011). ~~These~~ Numerous captures occurred during this event. Interestingly, these captures~~, however,~~ did not generate upstream-migrating waves of accelerated erosion. ~~Instead,~~On the contrary: river incision ~~almost completely~~ stalled upstream of the capture sites (Brocard et al., 2011). We ~~investigate here~~seek to identify the processes that arrested river incision, and retrieve, from the characteristics of ~~their~~ river long-profiles~~ some~~, insights on how arrested incision ~~affected~~influenced the topographic evolution of ~~these ranges~~the SC range.

New 40Ar/39Ar ages on volcanic rocks are used first ~~help us~~ to tighten the chronology of river incision and surface uplift ~~in~~of the SC-SM range. Detrital terrestrial 10Be erosion rates then provide a snapshot of current spatial variations ~~of~~in hillslope erosion rates ~~across~~in the ~~study area~~SC-SM and AC ranges. Profile linearization is implemented to study the complex long-profiles of the rivers that drain these ~~two~~ ranges. River knickpoints are extracted, and then ~~carefully~~ classified in order to ~~extract~~identify river knickpoints that ~~inform~~transmit the long-term landscape ~~dynamics and the~~ response ~~time~~ of ~~river incision~~ the drainage to the sequential uplift of the two ranges. We then discuss ~~successively~~ the respective contribution of topographically-controlled climate and of tectonically-controlled river profile adjustment to the ~~observed decrease in~~decline of incision ~~rates in~~over the SC range during the rise of the AC range. ~~We then discuss how both processes~~

~~contribute to the overall decrease in erosion over the SC range, and to the slowing down of migrating knickpoints.~~ We finally ~~present some~~review topographic characteristics ~~that appear as direct consequences~~ of the SC range directly related to the slowing down of erosion over the ~~older~~SC range.

2. Origin and evolution of the mountain ranges of Central Guatemala

2 .1. Tectonics and orogenesis

Left-lateral motion along the North American-Caribbean plate boundary in Central Guatemala has produced elongate ranges parallel to the plate boundary ~~in Central Guatemala~~ (Fig.1a). We investigate ~~here~~ the growth and erosion of two of these ranges~~(~~, namely the Sierra de Chuacús - Sierra de las Minas range (SM-SC range), and the Altos de Cuchumatanes range (AC range, Fig.1b). Rocks in the SC-SM range ~~display~~possess a deeply penetrative, sub-vertical tectonic fabric, imparted by 70 My of left-lateral wrenching along the Caribbean-North American plate boundary (Ratschbacher et al., 2009; Ortega-Gutierrez et al., 2004; Ortega-Obregón et al., 2008). Since Eocene ~~times~~time, left-lateral motion ~~between the Caribbean and North American plates~~ has been accommodated ~~mostly~~ by the Motagua fault, and, to a lesser extent, by the Polochic fault (Fig.2b). The Motagua fault is, with >1,100 km of total cumulative offset, the active subaerial fault with the largest cumulative offset on Earth. The Polochic fault has a total offset of 125 ± 5 km (Burkart, 1978~~). The Polochic fault~~); it probably branches out of the Motagua fault offshore, somewhere in the Caribbean Sea (Fig.1a), before running on land at an average distance of 50 km from the Motagua fault. Strain ~~along~~across the plate boundary is strongly partitioned between almost pure ~~-~~left-lateral slip on the Motagua and Polochic faults, and ~~boundary-normal~~ dip-slip on faults parallel to the Polochic and Motagua faults (Authemayou et al., 2011b; Brocard et al., 2012).

Figure 1. Shaded topography of the study area, showing the tectonic setting of Central Guatemala ~~in general~~ (a), and of the studied range ~~specifically~~ (b).Topographic features: CB: Chixóy River basin, CD: Central Depression of Chiapas, AC: Altos de Cuchumatanes (AC range), LI: Lake Izabal, SC: Sierra de Chuacús (SC range), SM: Sierra de las Minas (SM range), VA: Central American Volcanic Arc. MIS: δ18O Marine Isotopic Stage

Today, Central Guatemala is straddled by 3-4 km-high ranges ~~that separate~~separated by deep valleys ~~with~~. The floors of these valleys stand at elevations as low as 0.2-0.8 km (Fig.1b). In Middle Miocene times~~, however~~, the topography of Central Guatemala was much more subdued. Remnants of that past topography (referred to as the Maya surface (Brocard et al., 2011)) still cap numerous mountaintops across the study area (Fig.2). They are separated by regions where the Maya surface has been deeply incised (Fig.3). The ~~low Miocene relief~~Maya surface formed from the topographic decay of Eocene folds (Authemayou et al., 2011b; Brocard et al., 2011). It grades to the east and north into lowlands, near the Caribbean Sea, indicating that it formed near sea level. Its uplift started after the Middle Miocene, ~~then~~ affecting both the southern (Simon-Labric et al., 2013), and northern side of the Motagua fault, as far north as the Polochic fault (Brocard et al., 2011). ~~Uplift led~~This event saw the rise of the SC-SM range during the late Miocene. Valleys up to 1,000 m deep were incised within ~~its~~the northern flank of the SC-SM range between 12 ~~to~~and 7 Ma (Brocard et al., 2011).

Figure 2. Age of geomorphic markers and drainage lines~~.~~ in Central Guatemala. Ages of Miocene valleys and Quaternary paleovalleys (V1-V12) ~~provided~~ in My. Data source: 1: (Brocard et al., 2011), 2: (Brocard et al., 2012), 3: (Tobisch, 1986), 4: Plio-Quaternary lacustrine deposits (Brocard et al., 2015a). Newly dated lavas: CJY: Chujuyúb, EJ: El Jute. Range names: AC: Altos de Cuchumatanes, SC: Sierra de Chuacús, SM: Sierra de las Minas, VA: volcanic arc. Faults: MF: Motagua, PF: Polochic. Background: shaded GTOPO 30 DEM.

Figure 3. Incision below the Middle Miocene Maya surface, based on the elevation of surface remnants (upland relict surface). Incision contour line spacing: 1km. Yellow dashed lines: range drainage divides .AC: Altos de Cuchumatanes, SC: Sierra de Chuacús, SM: Sierra de las Minas, VA: volcanic arc.

Uplift propagated north of the Polochic fault during the Late Miocene (Brocard et al., 2011~~). It~~) and was marked by the rise of the AC range in response to contraction ~~in~~within the North American plate (Authemayou et al., 2011a). The rise of the AC range drove widespread reorganization ~~of~~among the ~~river network~~rivers that ~~drains~~drain the northern flank of the SC-SM range (Fig. 2). Numerous river valleys were then abandoned and ~~were~~ left stranded on the rising AC range. Their deformation indicates that the AC range has risen >1-2 km relative to the SC range over the past 7 My (Brocard et al., 2011). Earthquake focal mechanisms further indicate that the tectonic structures bordering the AC range to the north still accommodates shortening today (Guzmán-Speziale, 2010; Authemayou et al., 2011b).

While contraction has defined the evolution of the western part of the study area, transtension has prevailed further east since ~~at least~~ the Late Miocene~~. Such~~ at least. The dominance of transtension in the east results chiefly from an eastward increase in the divergence angle between the strike of the plate boundary and the direction of plate motion (Rogers and Mann, 2007). Transtension led to ~~development~~growth of the Lake Izabal basin (Fig.1a~~) into~~), which is has been filled with ~5 km of terrigenous sediments ~~have accumulated~~ since the Middle Miocene (Carballo-Hernandez et al., 1988; Bartole et al., 2019). ~~Transtension also led the growth of another~~Another ≥1.4 km-deep, elongate (125x15 km) sedimentary basin formed over the same period at the eastern termination of the subaerial trace of the Motagua fault, next to the Caribbean Sea (Carballo-Hernandez et al., 1988) (Fig.1a)). Transtension spread further to the west during the Pliocene, generating~~ still-active~~ normal faults that disrupt the northern flank of the SM range (Authemayou et al., 2011b; Brocard et al., 2012).

2.2. Drainage evolution since the Middle Miocene

The rivers ~~that drain~~located along the northern flank of the SC range represent the headwaters of a network that, farther downstream, experienced widespread reorganization during the late Miocene (Fig.2). Reorganization led to the formation of range-parallel rivers halfway between the drainage divides of the SC-SM and the AC ranges~~ that ~~. These E-W-striking rivers collect the rivers that ~~drain~~flow north, down the northern flank of the SC-SM range, and funnel them into the Chixóy River, one of the few rivers~~ (~~, together with the Cahabón, Chixóy, Selegua, and Cuilco Rivers~~,~~ (Fig.2), that still ~~crosses the AC range. These rivers that ~~cross the AC range. These later rivers also ~~cross~~straddle the trace of left-lateral Polochic fault, before entering the AC range. The Polochic fault has deflected and lengthened ~~the~~their course ~~of the rivers that cross its trace ~~(Fig.2) since the late Miocene (Brocard et al., 2011). ~~Transtensional~~Plio-Quaternary transtensional faulting along the northern flank of the SM range ~~has ~~initiated a second (and still ongoing) pulse of drainage reorganization during the Quaternary (Fig.2) (Brocard et al., 2012).

~~Large~~Since the Pliocene, large volcanoclastic aprons have piled up along the NE ~~flank~~side of the Central American Volcanic arc~~ since the Pliocene.~~. They have buried the western end of the SC range, deranging its river network~~.~~ (Fig.2). This complex area is therefore excluded from the present study. Likewise, the karstic highlands of Central Guatemala, especially those located north of the Polochic fault, are also excluded from the analysis, because their dynamics is ~~mostly under~~strongly influenced by the ~~influence of the higher~~high-frequency opening and closure of subterranean karstic pathways (Brocard et al., 2015a; Brocard et al., 2016a).

2.3. Current pattern of precipitation

Moisture tracking from the Pacific Ocean and from the Caribbean Sea is intercepted by ~~the ~~slopes that face the western and eastern coasts of Guatemala, ~~as well as~~and the Petén lowlands in the north (Fig. 4). The AC range receives 4-6 m.yr-1 of mean annual precipitation (MAP) along its northern flank in the Zona Reina (Thattai et al., 2003). In the west, the Central American Volcanic Arc intercepts moisture rising from the Pacific Ocean. In the east, moisture from the Caribbean Sea is channeled along the Lake Izabal basin and then rises up along the northern flank of the SM range~~. Fog~~, where fog interception represents a substantial part of the annual precipitation above 2,000 m ~~in the SM range ~~(Holder, 2004). The volcanic arc, the SM range, and the AC range cast rain shadows over the Corridor Seco (Machorro, 2014), and in particular over the SC range, which receives little precipitation. Semi-arid climate ~~is reached on the floor of~~conditions are met in the valleys that surround the SC range.

Figure 4. Mean annual precipitation across the study (MARN, 2017) from dry (red) to wet (blue). Isohyet spacing: 100 mm, draped over the shadowed GTOPO 30 DEM. Yellow dashed lines: range drainage divides. Blue dot: location of the fossil forest of Sicaché, buried below a 7.4 My-old ignimbrite (Brocard et al., 2011). CD: Central Depression of Chiapas, AC: Altos de Cuchumatanes, PL: Petén lowlands, SC: Sierra de Chuacús, SM: Sierra de las Minas, VA: volcanic arc.

2.4. Bedrock lithology

Rock belts in Central Guatemala tend to follow the strike of the mountain ranges (Fig. 5). Late Cretaceous schists and gneisses of the Chuacús Fm. form the core of the SC-SM range. They are flanked by the late Cretaceous migmatites of the San Agustin Fm., and by ~~the~~ marbles and amphibolites of the Jones Fm. In the north, this metamorphic core is tectonically juxtaposed, across the Baja Verapaz shear zone, to the basement of North America, which ~~mostly~~is covered mostly by a Permian megasequence of terrigenous sediments and carbonates (Sacapulas, Tactic-Esperanza, and Chochal Fms.(Anderson et al., 1973)). ~~These units~~The basement and cover are intruded by ~~Ordovician~~Paleozoic (e.g. Rabinal), Triassic, and Jurassic (e.g. Matanzas) ~~granites~~plutons.

A megasequence of continental terrigenous sediments (the Todos Santos Fm.), Cretaceous carbonates, and Cretaceous evaporites (Cobán Fm., Campur Fm.) covers much of the AC range (Fig. 5). Ultramafic rocks obducted over the carbonates in Late Cretaceous (Campanian) time (Fourcade et al., 1994) are preserved within weakly metamorphic synformal klippes (Baja Verapaz, Santa Cruz, and Juan de Paz ophiolites). Higher grade serpentine mélanges crop out along the Motagua valley (Flores et al., 2013).

The southern base of the SC-SM range is incised into sediments deposited in ~~elongate~~narrow transtensional basins ~~that formed~~ along the Motagua fault (Ratschbacher et al., 2009). During Eocene times (Newcomb, 1975~~)~~), one such basin was filled by ~~the~~continental red beds of the Subinal Formation (Fig.5), which has an exposed thickness of ≥1,500 m (Hirschman, 1962). ~~Its~~Some of its detrital sediments ~~were provided by~~are derived from the current basement of the SC-SM range, ~~and by the more mature fluvial sediments of~~while others were brought by an axial river that prefigures the current Motagua River (Guttiérrez, 2008). ~~It~~The Subinal

Fm. now lies in tectonic contact against the SC-SM basement ~~rocks, usually~~ along high-angle reverse faults (Muller, 1979; Bosc, 1971a).

Figure 5. Geology and structure of Central Guatemala (Instituto Geográfico Nacional de Guatemala; Instituto Hondureño de Geología y Minas; Instituto Nacional de estadística y geografía de México), draped over the GTOPO 30 DEM. AC: Altos de Cuchumatanes, IXF: Ixcán fault, MF: Motagua fault, PF: Polochic fault, SC: Sierra de Chuacús, SM: Sierra de las Minas, VA: volcanic arc.

3. Methods

3.1. 40Ar-39Ar radiometric dating of volcanic rocks

The age of the low-relief Maya surface ~~has been~~ was previously constrained ~~previously using~~by bracketing age markers~~-~~, such as 14-15 Ma overlying ignimbrites on the Chortís Block, and a 10 Ma ignimbrite filling a paleovalley, incised into the Maya surface (Brocard et al., 2011). To improve the dating of the Maya surface we ~~dated~~ resorted to the 40Ar-39Ar dating of andesite boulders, embedded in a lahar deposit that ~~rests~~lies on the Maya surface~~,~~ at the western termination of the SC-range, near the locality of Chujuyúb (Fig. 2). To establish the chronology of incision of the Motagua valley, we used previously dated alkaline basalts ~~located~~that crop out on the floor of the Motagua valley (Tobisch, 1986~~), and~~). We also dated a basalt flow ~~located~~that hangs 500 m above the Motagua River, in the foothills of the Sierra de las Minas, near the town of El Jute (Bosc, 1971b) (Fig. 6). Two 40Ar/39Ar whole-rock ages were retrieved from the basalt of El Jute, and one whole-rock age was obtained on the basaltic andesite of Chujuyúb by the U.S. Geological Survey (USGS) in Denver, CO, USA (see Supplement 1).

3.2. Terrestrial 10Be erosion rates

We measured the concentration of 10Be in quartz grains extracted from soils and river sediments. We used ~~their~~the 10Be concentration to calculate hillslope erosion rates, integrated over the past 103-104 years (see Supplement 2). ~~The soil~~Soil and rock samples ~~were~~, collected along ridgelines in the SM range~~. They~~, provide erosion rates restricted to the ~~site~~sites of sampling (Table S2-1, Fig. S2-3c). Three ~~of these~~ samples consist of quartzose vein fragments exhumed from weathered orthogneiss, ~~while the~~and two ~~remaining~~other samples come from ~~a~~outcrops of highly weathered pegmatite ~~that crops out~~located on the monadnock of Cerro las Palomas, in the Montaña El Imposible (Fig. S2-3b).

The majority of the samples~~, however,~~ consist of riverborne quartz collected in ~~the bed of~~ 30 rivers ~~in~~that drain the SM, SC, and AC ranges (Fig. 6, Table S2-2, Fig. S2-3). They provide catchment-averaged hillslope erosion rates (Brown et al., 1995). ~~The quartz~~Quartz was extracted from the sand grain-size fraction (250-500 µm) of the river sediments. Because 10Be production increases rapidly with elevation~~. As a result~~, systematic altitudinal variations in the concentration of quartz ~~of~~in the source rocks may ~~distort~~skew the calculation of erosion rates. ~~Such layout in encountered in AC range (Fig. S2-3a), in which a~~A sensitivity analysis to this effect was conducted~~. The~~ in the AC range, where this situation in encountered, by weighting 10Be production ~~was weighted~~ according to ~~estimates of~~ the quartz concentration in the source rocks~~. Weathering is~~ (Fig. S2-3a). Besides, the intense ~~in~~ weathering of tropical mountains~~, promoting~~ promotes the concentration of quartz in the soils~~,~~ and ~~an~~to the underestimation of erosion rates ~~that increases with increasing weathering intensity.~~. An assessment of the effect of quartz enrichment on erosion rates was therefore conducted (Table S2-2), using quartz enrichment values from mountain tropical soils of Puerto Rico (Ferrier et al., 2010). ~~The~~River sampling was ~~further designed such as to document erosion rates within~~conducted in nested catchments (Fig. 6. Fig. S2-3a,b~~),~~) in order to capture along-stream variations in erosion rates, such as those produced by headward-migrating knickpoints (Willenbring et al., 2013b; Brocard et al., 2015b). ~~The samples~~Samples were prepared at the 10Be extraction laboratory of the Department of Geology and Geophysics at the University of Minnesota, ~~as well as~~and at the PennCIL lab of the Earth and Environmental Sciences department at the University of Pennsylvania (see Supplement 2).

Figure 6. Catchments sampled for the 10Be analysis (AC: Altos de Cuchumatanes, SC: Sierra de Chuacús, SM: Sierra de las Minas), and 40Ar/39Ar dating (CJY: Chujuyúb, EJ: El Jute). Enlarged maps of the catchments and their lithologies are provided in Fig. S2-1). The arcuate line represents the axis used for plate boundary-parallel projections of Figs. 10 and 12.

3.3. Calculation of an erosion index

To test the influence of hillslope steepness and of precipitation on 10Be-derived erosion rates, we calculated a normalized erosion index (Montgomery and Stolar, 2006; Finnegan et al., 2008) over the study area~~, and averaged it over the extent of the sampled catchments. In its simplest form, the erosion index (EI) correlates the~~

~~entrainment of particles to hillslope steepness and annual rainfall. We used a formulation in which this entrainment~~. We used a formulation in which soil erosion is assumed to be proportional to shear stress: Eq. (1):

where Q is discharge (in m3·s-1) and S the along-slope gradient (m·m-1). Slope was extracted from the national Guatemalan IGN DEM at a resolution of 20 m, and discharge was calculated using ~~mean annual precipitations~~MAP provided in the MARN (2017) report. Rainfall values were corrected for evapotranspiration, using a map of vegetation from the MARN (2017) report, and evapotranspiration values from the Puerto Rico GAP project (Gould et al., 2008~~), which amount~~). It amounts to 10-82% of the total rainfall, for the different types of vegetation reported in the MARN report. EI values were normalized to the highest obtained EI value within the study area.

3.4. River profile segmentation

We extracted the long-profiles of 220 rivers located in the AC, SC, and SM ranges, using the Guatemala national 20 m-resolution DEM, released by the National Geographic Institute of Guatemala. The beds of these rivers were observed on stereoscopic couples of aerial photographs, provided by the National Geographic Institute of Guatemala (see next section for details). ~~These observations allowed us to~~We sieve out rivers along ~~the expression of longer~~which long-term ~~river~~ dynamics is ~~hidden~~mired by ~~shorter-term~~ adjustments to ~~karstic~~shorter-term disturbances, such as interactions with karst conduits, with debris flows, and with deep-seated landslides. A subset of ~~the~~ 110 rivers that best capture long-term trends was used in the final analysis (Fig.7).

Figure 7. Distribution and grouping of the streams used in the river long-profile analysis, and their grouping by geographic areas. AC: Altos de Cuchumatanes, LI: Lake Izabal, PF: Polochic fault, SC: Sierra de Chuacús, SM: Sierra de las Minas. Numbers (1-106) correspond to the numbers ascribed to the rivers, as listed in table S4-1. The corresponding river profiles are presented on Figs S4-2 to S4-7, and on Fig. 12. Boxes A-D: footprints of the maps displayed on Fig. 8.

~~To identify knickpoints along the river profiles, we resort~~We resorted to a linearization method that filters out the downstream increase in stream discharge to identify knickpoints along river profiles. We chose the integral method (Perron and Royden, 2013), in which elevation is plotted (on chi-plots or χ-plots) as a function of chi (or

χ), which is an upstream integral of incremental upstream distance, divided by a normalized local drainage area: Eq. (2):

where A and x are the drainage area (in m2) and upstream distance (in m), respectively; Ao (in m2) a reference drainage area and xo a reference upstream distance taken at the same point, m and n two exponents that encapsulate the influence of drainage area and of local slope on river incision rate, respectively. This method divides river profiles into a succession of linear to sublinear segments, separated by break-in-slopes that represent the knickpoints. The method overcomes ~~a lot~~much of the scatter that ~~plague~~plagues earlier linearization methods (Whipple and Tucker, 2002; Goldrick and Bishop, 1995). ~~One of its caveats~~It requires, however, ~~is that it requires~~ a foreknowledge of the intrinsic concavity~~, or~~ θ, defined as m/n. The value of θ can be determined by incrementally fitting river profiles to a straight line (Mudd et al., 2014). ~~Such approach is convenient on river profiles made up~~Most of ~~a small number of successive segments. Many~~the studied rivers ~~in the study area~~, however, have highly segmented profiles (see section 4.3), preventing ~~convergence toward a single value.~~the retrieval of well-defined θ values. Besides, ~~the value of θ may change~~θ might vary along-stream as a result of changes in climate (Murphy et al., 2016~~)~~), or changes in the dominant erosive processes operating on the streambed (Brocard and Van der Beek, 2006~~)~~), such as the alternation of detachment-limited (Howard, 1994) and transport-limited river incision (Whipple and Tucker, 2002), or such as the alternation of sediment-starved and overfed reaches (Sklar and Dietrich, 2006). ~~Therefore, instead of fitting θ~~ The method is here chiefly used to ~~each river profile, we applied~~ locate knickpoints. We therefore simply assessed whether the choice of θ would impact the location and number of break in slopes, when varied within the range (0.4- 0.6) over which the profiles appear well linearized. The segmentation being stable over this range (Supplement 3), a common normalizing concavity θ_n ~~value~~ of 0.5 was applied to all river profiles~~, after assessing best fit values on a subset of streams (see Supplement 3). This initial screening showed that most concavity values range between 0.4 and 0.6, as predicted by theoretical studies (Perron and Royden, 2013; Whipple, 2004), supporting the choice of a concavity of 0.5~~.

3.5. Classification of stream segments

~~The~~Streambed morphology ~~of the streambeds~~ was examined along each linearized segment using stereoscopic black-and-white 0.5-m resolution aerial photographs ~~taken~~shot in 2001, provided by the Guatemala National Institute of Geography (see Supplement 4). Observations were ~~punctually~~occasionally ground-proofed during field work campaigns stretching over 6 years. River beds were grouped into types according to the bed component that dominantly determines river gradient along each segment, namely: bedrock, bedrock and gravel bars, gravel bars over bedrock strath, gravel bars over thick alluvial fill, colluvium, large immobile boulders, boulders and gravel bars, boulders and bedrock (Table S4-1). Classification failed in many headwater channels ~~because their bed is~~, where beds are masked by overhanging riparian vegetation. The classification roughly reflects differences in the factors that determine stream incision. River incision is indeed likely detachment-limited along bedload-dominated reaches, and transport-limited along gravel- and cobble-dominated reaches, lying over bedrock straths (Tucker and Whipple, 2002; Brocard and Van der Beek, 2006). Boulder-armoured reaches are chocked by slowly- to non-moving boulders that act more like bedrock than bedload, and are therefore likely detachment-limited. However, unlike other types of bedrock channels, ~~these~~ boulder channels do not reflect the erodibility of the underlying bedrock, but rather that of surrounding hillslopes, because the majority of the boulders originate from ~~the~~ valley sides. Changes in streambed type from one segment to the next assisted the classification of river knickpoints (see following section).

3.6. Classification of river knickpoints

Convex-up breaks-in slope along river profiles are commonly referred to as river knickpoints. For convenience, we refer here to all breaks-in-slope, whether convex or concave, as knickpoints. Knickpoints were classified as lithogenic, alluvial, tectonic, migrating and miscellaneous (see supplement 4). Miscellaneous knickpoints represent adaptations or river profiles to local, stochastic disturbances (such as landslides and epigenies), and are usually short-lived. Most knickpoints in the study area ~~are~~reflect adaptations of river gradients to along-stream variations in rock uplift rate, bedrock erodibility, sediment flux, or sediment grain size. These knickpoints can be regarded as steady, inasmuch as their location only changes very slowly along the river profiles, tracking spatial changes in the distribution of rock types, rock uplift, sediment fluxes and bedload grain size. By contrast, knickpoints that spearhead step-increases or step-decreases in river incision rates migrate in the upstream direction along river profiles in the form of waves of accelerated (Rosenbloom and Anderson, 1994; Merritts et al., 1994) or decelerated ~~incision~~ (Howard, 1997~~).~~) incision. They are hereafter referred to as migrating knickpoints, for they usually migrate faster than the knickpoints previously described. Concave-up migrating knickpoints commonly mark the transition from detachment-limited to transport-limited river incision (Whipple and Tucker, 2002) are usually found at the apex of alluvial fans (Fig. 8c~~),~~) and pediments (Fig. 8b).

Theoretical geometric differences between migrating and steady knickpoints in linearized spaces have been used to discriminate unstable, migrating knickpoints from stable, equilibrium knickpoints (Goldrick and Bishop, 1995; Perron and Royden, 2013; Whipple and Tucker, 2002). In χ-space, upstream migrating knickpoints which celerity is controlled by the stream power law, and that propagate along various branches of a single drainage through a homogenous substrate affected by homogeneous rock uplift, should all share the same elevation and the same χ value (Royden and Taylor Perron, 2013). In the real world, however, variations in bedrock erodibility, climate, and rock uplift often scatter these values, challenging interpretations based on these sole geometric properties~~, in particular~~. This is especially the case in areas where environmental heterogeneities generate steady knickpoints which heights and wavelengths that are similar to that of the migrating knickpoints interspersed among them.

Figure 8. Examples of some knickpoint types presented in their geomorphic setting. Shaded and sloped ~~20~~30 m resolution ALOS DEM © JAXA. Location of maps a-d on Fig. 7. (a) valley of the Quilén Novillo-Chancol river (91-QNo, AC Range), showing the paleovalley V3 (fig.2~~)~~), shallowly incised into the Maya surface (Brocard et al., 2011), and two ~~imbricated~~imbricate waves of erosion migrating up the reversed (southward-directed) drainage of the valley. (b) ~~typical~~Typical stepped topography of the SC range, in the ~~valley~~catchment of the Rabinal river (69-Rab), showing three~~,~~ imbricate~~,~~ upstream-migrating erosive signals distributed along the mountain slope. The upper one is a wave of erosion that dissects the Maya surface, a second one is located half-way down the mountain flank ~~one finds a second wave of increased erosion, while~~, and the basal and final wave is ~~composed of pediment (PD) apexs that spearhead~~located at the ~~upstream growth~~base of the range, at the apex of pediments~~.~~ (PD). (c) Diffusive erosion in serpentinite mélanges, in the catchment of Río Hato (17-Lat, SM Range). (d) dissection of the Maya surface by prominent migrating knickpoints along the northern flank of the SM Range, from the Ribaco to the Chilasco Rivers (47-Rib to 50Sco). C3: 200 ky-old avulsion site (Brocard et al., 2012).

~~Under such circumstances, additional~~Additional discriminating elements must be used. ~~As a~~A first screening~~, we checked~~ consisted in checking whether the ~~observed~~ knickpoints coincide with marked variations in bedrock erodibility, rock uplift rates, or local anomalies, in which case they were ~~regarded~~classified as steady. To assess the effect of lithological variations we used ~~the~~ 1:50,000 and 1:250,000 geological quadrangles of Guatemala, and topical geologic maps from published papers (e.g. (Brocard et al., 2011; Bosc, 1971a). ~~The stereoscopic~~Stereoscopic black-and white 0.5-m aerial photographs of the Guatemala National Institute of Geography were used to refine the location of lithological contacts, and to assess the effects of bedrock fabric, fault damage zones, active faults, deep-seated landslides, and large debris flows on the location of ~~the~~ knickpoints. We used our foreknowledge of the ~~active~~ tectonics of the area (Authemayou et al., 2011a; Authemayou et al., 2012; Brocard et al., 2012) and of the Quaternary drainage reorganization (Brocard et al., 2012) to assist the identification of tectonic knickpoints and of ~~some~~ migrating knickpoints~~.~~ related to this recent reorganization. The remaining knickpoints were then considered as potentially migrating~~.~~, carrying the signal of the long-term evolution of the studied mountains. We ~~then~~ looked for supporting evidence~~, such as geomorphic markers~~ of knickpoint migration, in particular break-in-slopes running along valley flanks, tied to specific knickpoints (Fig. 8a,b) after verifying that such break-in-slopes were not ~~the result of~~ produced by lithological variations along ~~the~~ valley sides. Changes in erosion rates along hillslopes ~~produced by~~associated to the passage of ~~a~~ migrating ~~knickpoint~~knickpoints can ~~also be marked by changes in drainage density, which reflect changes in~~affect saprolite thickness (Brocard et al., 2015b~~).~~) and associated drainage density. In only a few cases ~~the passage of migrating knickpoints was marked by~~were abandoned river terraces and hanging pediments found in the wake of migrating knickpoints.

The method ~~above~~ has some limitations: first, local variations in bedrock erodibility maybe not be systematically detected, as a result of the imprecision of geologic ~~mapping~~maps, especially in the least accessible parts of the SM and AC ranges. Second, large intraformational changes in facies can generate variations in bedrock resistance as sharp as, or even sharper than erodibility differences between mapped geological units. These two effects may lead to the interpretation of stable knickpoints as migrating knickpoints. Conversely, some migrating knickpoints may be pinned to lithological contacts (Crosby and Whipple, 2006), and filtered out by the analysis. Nonetheless, we consider that, given the large number of analysed knickpoints, the analysis captures the most import aspects of the evolution of the landscape within the study area.

4. Results

4.1. Rock uplift and stream incision chronology from 40Ar/39Ar dating

The Maya surface (Fig. 2,3) likely formed close to sea level, because it can be traced to the coast of the Caribbean Sea (Brocard et al., 2011). It was once covered by extensive fluvial deposits, especially south of the Motagua fault, where ~~these~~the fluvial deposits are preserved below extensive ignimbrites (Williams and McBirney, 1969). The lahar deposit of Chujuyúb rests directly onto a thick saprolite that blankets the Maya surface. Lahar emplacement predates the incision of a 450 m-deep valley. The lahar yielded a plateau age of 12.54 ± 0.04 Ma (Fig. S1-1, Table S1-2). It indicates that incision at ~~this site~~Chujuyúb started after 12 Ma. This is consistent with the ~~previously~~ proposed 12 Ma entrenchment of the Cuilco River valley into the Maya surface (Fig.7), 70 km to the NW of Chujuyúb (Brocard et al., 2011), as well as with ~~a~~the 10.3 Ma emplacement of an ignimbrite ~~emplaced in~~within the ~~shallowly-incised~~ Colotenango valley (Fig.2), 35 km to the NNW of Chujuyúb (Authemayou et al., 2012~~).~~), which is shallowly-incised into the Maya surface. It is also consistent with ~~a~~the 7.4 Ma deposition of an ignimbrite ~~deposited in a 1 km-deep~~ paleovalley, incised 1 km into the Maya surface (Fig.2), 10-30 km to the NE of Chujuyúb (Brocard et al., 2011). The depth reached by the late Miocene valleys prior to their abandonment implies that incision proceeded at >140-280 m·My-1 from 12 to 7 Ma, assuming that the dissection of the Maya surface started at 12 Ma (a, Fig. 9). Incision rates averaged over the length of the ~~valleys~~paleovalleys, between the SC and AC ranges, range from 145 to 205 m·My-1 (b, Fig. 9). Subsequent incision, from the base of the late Miocene valley fills, down to modern valley floors, only amounts to a few tens of meters, at rates of <30 m·My-1 (c, Fig. 9).

Figure 9. Evolution of incision rates in the studied ranges.

Letters a-j correspond to river incision rates inferred from 40Ar/39Ar dating (see text). Black double arrowed lines: range of calculated value for each of incision rate. Rectangles: range of calculated values and time span of each of incision rate. Curves: overall evolution of incision rates within each range, inferred from these discrete estimates. Shades of blue: Sierra de las Minas (SM~~). Shades of~~), red: Sierra de Chuacús (SC~~). Shades of~~), and green: Altos de Cuchumatanes (AC). ~~a-j: see main text.~~

The chronology of incision along the southern side of the SC range is documented by remnants of basalt flows scattered along the floor of the Motagua valley. These flows track from vents located south of the valley, ~~in~~on the Caribbean plate (Tobisch, 1986). The outcrop of El Jute represents the distal end of a lava flow which abutted the base of the SM range, backfilling the Huijo River valley with ≥ 70 m of basalt. The base of the flow lies >400 m above the Huijo River. Using the modern gradient of the transport-limited Huijo River as a proxy for its 6 My-old gradient, we find that the basalt flow crossed the Motagua River 360 m above the current elevation of the Motagua River. The basalt yields a plateau age of 6.88 ± 0.03 Ma, and a slightly less constrained total age of 6.46 ± 0.09 Ma (Fig. S1-1, Table S1-2). Assuming that incision of the Maya surface started 12 My ago, then the 2.6 km-deep Motagua valley would have been incised at ~350 m·My-1 between 12 and 7 Ma (d, Fig. 9). Incision would have continued until today at an average rate 79 ± 4 m·My-1. If the basalt dam was removed rapidly however, then incision would have instead proceeded more slowly, at 59 ± 9 m·My-1.

The chronology of incision can be refined by incorporating the ~~ages of the~~ previously dated basalts (Tobisch, 1986). The closest occurrence, located 6 km upstream along the Motagua River, is the 6.1 Ma Cerro lo de China flow. The flow was actually emplaced 120 km farther west at current plate-boundary slip rates, because it lies on the southern side of the Motagua fault. Conversely, the 3.1 ± 0.7 Ma Cerro Onanopa was emplaced on the same side of the plate boundary, 16 km upstream of El Jute. Its high vesicularity implies an emplacement at, or near the ground surface, rather than as a sill, deep within the Subinal Fm., followed by exhumation. Its base lies <10 m above the Motagua River. Strath terraces of the Motagua River have been cut in its flanks (Tobisch, 1986), indicating that the flow underwent some minor burial and exhumation. The accordance in elevation between its basal contact and the Motagua River suggests that the Motagua River has oscillated tightly around its current vertical position over the past 3 My.

Incision of the Motagua valley, from the elevation of the basalt of El Jute, down to the current valley floor, would thus have occurred between 6.1 and 3.1 Ma, at > 110 ± 40 m·My-1 (f, Fig. 9). If, after the emplacement of the basalt of El Jute, incision continued at the same ~350 m·My-1 rate as before (g, Fig. 9), then incision would have reached the current valley floor at ~5 Ma, no incision taking place afterwards (h, Fig. 9). The evolution of incision during the rise of the SC-SM range therefore looks similar on either side of the range: it is dominated by a single step of rapid incision, at 140-350 m·My-1, between 12 and 7-5 Ma, followed by an almost complete cessation of incision along the main trunk streams (the Motagua and Chixóy Rivers), which act as base levels of the streams located in the SC range.

~~Note that large~~ Large steeply-dipping faults bound the Eocene fill of the Motagua valley. Dip-slip on these faults could be responsible, in part or in whole, for the deepening of the Motagua valley, a possibility contemplated by Tobisch (1986). Various traits of the valley, however, rule out any substantial contribution of these faults. First, fluvial sediments have bypassed the Motagua valley since Eocene time, feeding a transtensional basin at the lowest eastern ~~d~~end of the Motagua valley~~.~~ (Fig.1b). Second, the alluvial fans that have grown astride these faults show no evidence of faulting, nor any anomaly in their catchment/fan surface ratios (Tobisch, 1986). Third, the faults encountered along the base of the SC-SM range exhibit only ancient, ductile to ductile-brittle left-lateral deformation (Bosc, 1971a; Roper, 1978). Last, the middle Miocene low-relief surfaces lie at about the same elevation north and south of the Motagua fault (Simon-Labric et al., 2013). Extension on antithetic boundary faults would need to remain well-balanced, despite hundreds of kilometers of left-lateral displacement along the Motagua fault since the middle Miocene, to avoid the development of significant offsets of these surfaces. The deepening of the Motagua valley therefore appears to have been achieved by erosion, through the removal of the erodible Eocene sediments that filled the Eocene fault basin, giving the valley the appearance of a recently active graben.

The incision chronology of the AC range is constrained by transverse paleovalleys that are shallowly incised into the Maya surface (e.g. Fig. 8a; i, Fig. 9). Uplift of the AC range since their abandonment ~~has allowed~~ provided space for the incision of 1,500- 2,600 m deep valleys along the northern flank of the range (Fig. 3) at 200-350 m·My-1 (j, Fig. 9). River incision of the AC range therefore started and developed while river incision in the SC-SM rang was stalling.

4.2. Spatial variations in 10Be-derived erosion rates

Catchment-averaged detrital 10Be erosion rates range from 11 m·My-1 within the catchments that drain the Maya surface on the SM range, up to 330 m·My-1 along the wet and steep northern flank of the AC range (Fig. 10). Most slowly-eroding catchments are located within the SC range. Weighting erosion rates by the relative concentration of quartz in quartz-feeding lithologies only marginally affects the calculated rates (by 3.4% on average in the SC range, 4.8% in the SM range, and < 7% in the AC range). Quartz enrichment corrections, on the other hand, increase erosion rates by up to 40% (Fig. 10, Table S2-2), but the amplitude of this effect remains speculative, in the absence of field measurements. However, because quartz enrichment increases with weathering intensity, its ~~effect is~~effects are probably smaller in the AC range, where soils erode the fastest. Quartz enrichment ~~corrections can be~~could therefore ~~expected~~act such as to reduce ~~the contrast~~contrasts in erosion rates between the SC-SM range and the AC range.

In the AC range, erosion rates (arrows, Fig. 10) show a marked increase from the drier, and less steep highlands, to the wet and steep frontal slopes (from CATA to CHEL to XAC). The SM range displays a similar trend of increasing erosion down the mountain flank, as entrenchment in the Maya surface increases (from COL to FRI to RAN), with one outlier (SLO). The magnitude of increase ~~is~~ in the SM range intermediate between ~~that observed~~the ones measured in the SC and CA ranges. In the SC range indeed, a downstream increase would be expected ~~initially~~to occur first, in the downstream direction, ~~from~~between the drainage divide ~~down~~and the mountain flanks, ~~from~~as a result of the decreasing contribution of slowly-eroding low-relief uplands with downstream distance (Willenbring et al., 2013b). ~~It would~~Increase should be followed by a decrease in erosion ~~rates~~rate as rivers start draining ~~the~~ pediments that floor the Chixóy River catchment. An increase in erosion rate, downstream of the paleosurface, is ~~observed~~measured (from PAS to PAE), but it is much less pronounced than in the AC range. The ~~following~~ decrease in erosion rate is also very subdued (from XEU to CUB). In one case (from SMS to SMM to SMI), no increase nor decrease ~~is~~are observed.

Figure 10. Variations in detrital 10Be ~~denudation~~hillslope erosion rates along the strike of the plate boundary, from the AC range in the west, to the SM range in the east. Data are projected along the strike of the plate boundary, on an arc displayed on Fig. 6. Arrows ~~shows~~show feeding ~~directions, from~~ relationship, between nested hillslope sites ~~to nested~~and catchments. ~~Low relief~~Some uplands drain remnants of the Middle Miocene Maya surface~~. Denudation~~ (green shaded areas). Detrital 10Be hillslope erosion rates are compared to river incision rates along the northern (salmon-colored shaded area, SC-N) and southern (blue-shaded area, SM-S) base of the SC-SM range, over the past 7 My. XAC: peak incision rates in the AC range along Río Xacbal, ~~where incision~~ below the Maya surface ~~along the river course is maximum~~ (Fig. 3).

4.3. Distribution of streambed types

9% of the rivers retained in the analysis do not host any knickpoint, 16% host one knickpoint, 51% host 2 to 5 knickpoints, and 25% host 5-12 knickpoints (Fig. 11~~). This distribution highlights~~), reflecting the high degree of segmentation of many rivers ~~in the AC~~, and ~~SC-SM ranges, and the~~ high ~~concentration~~density of knickpoints ~~within these ranges. These~~. The knickpoints ~~separate~~delimitate 452 river segments, of which 92% are well linearized, 6% are concave, and 2% are convex, for an applied intrinsic concavity θ = 0.5. ~~The river~~River segments were grouped ~~by~~according to streambed types. ~~Their~~The distribution of streambed types according to elevation is projected along the strike of the studied ranges ~~is displayed~~ on Figure 12 and Figure S4-7, and their distribution ~~between north- and south-facing flanks is displayed~~across the strike of the ranges on Figures S4-2 to S4-6.

Figure 11. Distribution of rivers according to the number of segments identified in each river

The distribution of alluvial reaches is bimodal in the SC-SM range (Fig. 12a1-b2): alluvial reaches tend to be found either at the base of the mountains, or at high elevation, over the remnants of the Maya surface (e.g. Fig. 8 a,d). High-elevation alluvial reaches tend to transport a rather fine-grained bedload, composed of sand derived from the weathering of micaschist, gneiss and granite, and of gravel derived from quartzose veins and silicified pegmatites (Brocard et al., 2012). Intermediate-elevation alluvial reaches occur upstream of obstructions, most notably landslides in the SM-SC range, over extremely erodible fault damage zones, and within localized areas of tectonic subsidence (especially along the Polochic fault corridor, on the southern flank of the AC range).

Boulder reaches are found mostly on crystalline rocks. ~~They~~There, they are ~~then~~ more frequent on the wet slopes SM range than on the dry slopes of the SC range. In the SM range, many ~~of these~~ boulder-strewn reaches ~~have formed out of debris flows deposits, by~~ form after the winnowing of ~~their~~the fine-grained matrix~~.~~ of debris flows. The SM range is the first range hit by ~~Atlantic~~ tropical depressions tracking from the Caribbean Sea. They ~~frequently~~ trigger numerous landslides along ~~its~~the wettest slopes of the SM range (Ramos Scharrón et al., 2012; Bucknam et al., 2001). Because ~~it~~SM range soils are more ~~often~~frequently close to water-saturation, ~~it is also~~they are more likely to be affected by ~~numerous~~ landslides when earthquakes strike the range (Harp et al., 1981). ~~Boulder~~In the SM range, boulder armoring is ~~also~~ common ~~in the SM range over~~on the serpentinite mélanges that ~~locally~~ crop out up to high elevations along its southern flank, owing to the presence of knockers ~~embedded within~~in the mélanges (e.g. Fig. 8c). Boulder-strewn reaches in the AC range ~~are observed~~form over phyllites. There, ~~the~~ boulders are made of the most resistant beds of ~~the~~ Pennsylvanian phyllites, and of sandstone and limestone blocks ~~of~~derived from overlying formations that ~~have sled~~slid along ~~the~~ valley flanks down to the streambeds.

Bedrock river reaches are most commonly found downstream of convex migrating knickpoints, the distribution of which is ~~present~~presented in the following section.

4.5. Distribution of steady and migrating knickpoints

Among the 350 identified knickpoints, 40% can be tied to variations in bedrock erodibility, 6% to temporary obstructions, 8% to active tectonics, 21% to upstream-migrating waves of accelerated erosion, and 14% to upstream-migrating waves of decelerated incision. 11% are composite and result from some combination of the above.

Details about the significance of the distribution of steady knickpoints ~~is~~are provided in Suppl~~.,~~.4, as well as a more systematic review of the origin of ~~various~~all identified clusters of migrating knickpoints. ~~The origin of some~~Some migrating knickpoints can be tied to well-identified and well-dated river Quaternary diversions (e.g. S3-1 to S3-3, Fig. 12a2, (Brocard et al., 2012)). Most migrating knickpoints dot the ~~margins~~brim of upland low-relief surface remnants (Fig. 12 a1 and a2; Fig. 8d). They may have therefore initiated ~~farther down their drainage networks,~~ when the Maya surface started being incised, at ~12 Ma, on the sides of the rising SM-SC range. Other clusters of migrating knickpoints are found halfway down ~~the~~mountain flanks ~~of the ranges.~~. The most conspicuous of these clusters is restricted to the northern flank of the SC range, within the watershed of the Chixóy River. It hangs above a ~~series~~cluster of concave-up migrating knickpoints ~~dotting~~located at the apexes of pediments~~, which extend is also~~ restricted to the drainage of the Chixóy River. The significance of these concave-up knickpoints and their genetic relationship with the ~~cluster~~clusters of convex knickpoints located ~~above them~~upstream is discussed in section 5.3.2.

Figure 12. Distribution of linearized stream segments and knickpoints along the SC-SM and AC ranges. Mountain ranges are projected on the plate boundary, according to a small circle defined on Fig. 6. (a) and (b) southern and northern flanks of the SC-SM range, (c) and (d): southern and northern flanks of the AC range. Key to abbreviated stream names is provided in Table S4-1 and in the captions of figures S4-2 to S4-7. Water gap names: CUI: Cuilco, SEL: Selegua, CHX: Chixóy. Paleovalley numbering from Brocard et al. (2011), river capture numbering from Brocard et al. (2012). LA: city of Los Amates.

5. Discussion

The decline of river incision rates in the SC-SM range was coeval to the rise of ~~incision rates~~ in the AC range~~, suggesting that the~~ (Fig.9). This can reflect a complete transfer of rock uplift from the SC-SM range to the AC range, but it remains surprising that river incision rates declined so sharply, considering the range had not undergone any substantial topographic decay. Likewise, very low current hillslope erosion rates are maintained on steep slopes within the SC-SM range today. A genetic relationship can therefore exist in the rise of the AC range ~~was instrumental in~~and the decline of river incision ~~rates~~ and hillslope erosion in the SC-~~SM~~SMA range. The rise of the AC range may have affected incision rates in the SC-SM range in two ways. First, by decreasing moisture delivery to the SC-SM range, it may have reduced hillslope erosion rates and the delivery of water and sediment to the streams, thereby decreasing river incision rates. Second, by forcing the drainage of the northern side of the SC range to adjust to ~~a new~~ rock uplift ~~field~~in the AC range, it promoted a decrease in river incision rates, upstream of the AC, among the rivers of the SC range that still cross the AC range. After reviewing the ~~potential~~respective contributions of ~~the~~these top-down and bottom-up processes, we analyse ~~their effects on~~how they combined to affect the present-day morphological evolution of the SC-SM range.

5.1. Effect of the rise of the AC range on climate-driven hillslope erosion

5.1.1. Climate and hillslope erosion in modern times

Silicate weathering ~~has been found to be~~is three times faster on the wet (1,800-3,000 mm·y1, Fig.4) side of the SM range than along its drier (1,000-2,400-mm·y-1) side (McAdams et al., 2015). Using detrital cosmogenic 10Be we find that ~~the~~ the wet (1,900-3,700 mm·y-1) side of the the AC range erodes on average distinctively faster (with a 92 % probability, based on a Welch's t-test, with t = 2.246, p = 0.08) than the drier (900-1,300 mm·y-1) SC range. Individual catchments document a sixfold increase in erosion (50 to 300 m·My-1), from the SC range to the AC range (Fig.10, Fig. 13b,c). The spatial distribution of erosion rates predicted by the Erosion Index (Fig.13a), which combines the effects of slope and precipitation on erosion, is consistent with the spatial distribution of measured detrital 10Be erosion rates. 10Be-~~source~~feeding slopes in the AC range receive three times more precipitation (MAP = 3.2 ± 0.7 m·y-1) than their counterparts ~~of~~in the SC and SM ranges (MAP= 0.9 ± 0.4 and 1.2± 0.3 m·y-1, respectively, Fig.13b~~).~~). Comparatively, 10Be-feeding slopes in the AC range are also marginally (1.2 times) steeper (26 ± 4°) than in the SC and SM ranges (22±3 and 22 ± 2°, respectively, Fig.13c). In the AC range, a linear relationship is observed between erosion rate~~ and both~~, precipitation (r2= 0.83~~)~~), and slope (r2=0.95). ~~This correlation is not as strong when~~When all ranges are considered together, however, the correlation is weaker (r2= 0.61 for precipitation and 0.52 for slope), and very weak ~~within~~if the SC and SM range ~~datasets~~are considered individually (-0.1<r2<0.4). The ~~stronger~~strong correlation ~~observed~~ in the AC range ~~reflects~~stems foremost from the greater homogeneity in bedrock erodibility among the measured catchments. ~~Slope~~In the AC range, slope gradient and MAP are good predictors of hillslope erosion rates at precipitation ~~is~~ > 2 m·y-1 (Fig. 13b~~), but a~~). However, this linear relationship predicts that erosion ceases for MAP <2 m·y-1 and slopes < 15°. ~~It~~By contrast, if the entire dataset is considered, the linear regression predicts that erosion tends toward zero as MAP decline toward zero, while hillslope erosion ceases on slopes that are still steep (≥ 19 °, Fig.13c). Globally, erosion rates < 50 m·My-1 are generally observed at slope values < 10° (Willenbring et al., 2013a). They are here measured in many catchments of the the SC and SM ranges that still maintain average slope values of 18-25°, pointing for a significant contribution of aridification to the limitation of erosion. The overall decrease in the steepness in relationship between erosion and MAP curve from the AC range to the overall dataset may imply that the relationship is ~~probable~~nonlinear, and that the curve flattens for MAP < 2 m·y-1, a trend observed elsewhere~~,~~ (for example~~ for~~, at MAP < 2 m·y-1 on Kauai (Ferrier et al., 2013~~). Low erosion rates (< 50 m·My-1) are observed in many catchments of the the SC and SM ranges that still all maintain average slopes ≥ 19 °(Fig.13c), when such low erosion rates are rather observed at slope values < 10° globally (Willenbring et al., 2013a).~~)).

For MAP < 2 m·y-1, MAP is a poor predictor of erosion rates, likely because storminess and rainfall intensity ~~increasingly~~ become better predictors of hillslope erosion (Liang et al., 2019). The~~ strong~~ correlation between slope and erosion rates in the AC range ~~suggests~~implies that slopes have not~~, on average,~~ reached the critical threshold ~~of~~for slope stability (Clarke and Burbank, 2010~~). At low precipitation rates, within~~) in the AC range. In the SC range, slope steepness only faintly captures ~~some of the~~ variations in erosion rates (r2= 0.41~~). Comparison~~) under low MAP: comparison between nested ~~individual~~ catchments ~~show~~indeed shows that, in 4 out of 6 instances, decreases ~~of~~and increases in EI values are not ~~echoed by~~associated with significant changes in erosion rates.

It seems, therefore, that the most arid ~~regions~~parts of ~~the study area~~these ranges erode slowly to very slowly, despite maintaining steep slopes~~,~~. Besides, slope steepness and ~~that slopes, like~~ MAP~~,~~ become poor ~~predictor~~predictors of~~ the~~ short-term (103-104y) hillslope erosion rates at low MAP. The pattern of catchment-averaged 10Be erosion rates ~~points to a role of climate in~~therefore that aridification limits the erosion ~~of the ranges, in particular in the limitation of erosion~~ on steep slopes. Fluctuations of climate, over millions of years, ~~could~~can therefore ~~affect~~be expected to impact the long-term evolution of these ranges. This aspect is explored in the following section, and in particular the ~~role~~interplay of mountain building ~~on the~~and climate ~~of~~evolution in Central Guatemala.

Figure 13. (a) Map showing the spatial distribution of normalized catchment-wide 10Be erosion rates superposed to the predicted spatial distribution of erosion according to the normalized erosion index. (b) catchment-wide 10Be erosion rates as a function of catchment-averaged precipitation. (c) catchment-wide 10Be erosion rates as a function of catchment-averaged slope (from quartz-contributing slopes) Arrows:

downstream connections between nested catchment within the AC range. Dashed line: linear correlation within AC range data, with correlation coefficient (r2) reported next to the line.

The sequential rise of the SC-SM and AC range generated an evolving pattern of hillslope steepness and of precipitation which may have contributed to the decline of incision in the SC range since the Middle Miocene. We review hereafter evidence for changes in climate and tectonics, susceptible to have impacted hillslope steepness and erosion over time.

5.1.2. Evolution of climate ~~driven by~~over the SC range since the rise of the AC~~ range, and expected consequences on the erosion of the SC~~ range

The distribution of precipitation (Fig.2) shows that the AC range currently prevents the ingress of ~~Caribbean~~ moisture tracking from the Yucatán and Petén lowlands~~. It can be expected,~~ toward the SC range. Moisture was therefore~~, that moisture was~~ likely able to reach the SC range before the rise of the AC range ~~started to rise~~. Such a deeper ~~inland~~ penetration of ~~the~~ moisture is ~~confirmed~~supported by paleo-precipitation estimates obtained from the ~~study~~analysis of tree species and of paleosols in the 7.4 Ma forest of Sicaché (Fig. 2). ~~The~~This subtropical forest ~~grew~~was growing on the floor of ~~one of the abandoned~~ a late Miocene ~~paleovalleys~~paleovalley. The geochemical characteristics of ~~the~~its paleosols ~~preserved below the forest~~ suggest mean annual precipitation ~~in the~~between 950~~-~~ and 1,300 mm·yr-1 ~~range~~ (Brocard et al., 2011). ~~The area where~~Today, the fossil forest ~~crops out~~ is located in a drier ~~today and~~area covered by xerophytic vegetation. ~~The fossil forest is located on the southern side of the AC range; it documents~~ The SC range therefore ~~a deeper penetration of Caribbean moisture toward the SC range at 7 Ma. It therefore suggests that precipitation was~~ likely received higher ~~on the SC range~~ precipitation between 12 and 7 Ma, and ~~that it decreased with~~its aridification was coeval to the rise of the AC range. ~~Drying of the SC range, in turn, can be expected to have contributed to the~~ Aridification likely led to the decrease in hillslope erosion rates~~ over the SC range. Aridification may have changed the balance between water and sediment discharge (Sklar and Dietrich, 2006; Beaumont et al., 1992; Whipple and Tucker, 1999), but if, in the process, streams were left not exceedingly overfed nor underfed with sediment, one can expect river incision to have scaled with stream discharge (Sklar and Dietrich, 2006). In that case the decrease in river incision rates observed at the base of the SC range (see section 4.1) could be, in part, due to the aridification of the SC range. The rise of the AC range could have affected hillslope erosion and river incision over the SC range by such a top-down process, from precipitation to hillslopes to streambeds. However, the AC range also altered the routing of water away from the SC range. In doing so, it sparked a massive adaptation of the drainage to the new tectonic field, to such extend that it also~~

~~contributed to the decrease in incision rates. This aspect is explored in the following section.~~, down to the values that are measured today.

5.2. Effect of the rise of the AC range on tectonically-driven river incision in the SC range

The rise of the AC range ~~results~~ sparked widespread reorganization of the range-transverse drainage (Brocard et al., 2011), ~~leading to the tectonic defeat of~~tectonically defeating many rivers that used to cross the AC range. ~~The~~Some rivers ~~that~~ maintained a course transverse to the rising structure ~~adapted~~by steepening their gradient ~~to the new crustal strain field.~~. We review ~~first~~hereafter the evidence for faster rock uplift in the AC range than in the SC range, ~~then analyse the consequences of this faster uplift on incision rates long the rivers that cross the AC range, upstream of the AC range, within the SC range. We also analyse the contribution of the rise of the AC range to~~for river course lengthening along the Polochic fault, ~~analyse how this affected~~and for decreased rock uplift rates in the SC range. We review the contribution of each of these tectonic processes to the decline of river incision in the SC range.

5.2.1. Fast, ongoing rise of the AC range from river channel steepness

The deformation of paleovalleys abandoned during the uplift of the AC range documents >1-2 km of rock uplift in the AC range relative to the SC range since the late Miocene (Brocard et al., 2011~~). Such deformation implies~~), implying on average faster rock uplift ~~rates~~ in the AC range than in the SC range over ~~the past~~ 7 My. Whether such difference ~~remains~~continues today is important ~~for~~to establish before analysing river profile dynamics. Glacial and fluvial landforms ~~of the AC range do suggest that that~~in the AC range suggest that the AC range still rises faster than the SC range~~. Glacial landforms provide some indirect clues.~~ today. A 20 x 30 km ice cap ~~spread over~~was established on the summit plateau of the AC range (Fig. 1) during the last glaciation (Anderson et al., 1973; Lachniet and Vazquez-Selem, 2005). On other neotropical mountains~~ the moraines of the~~, last glaciation moraine arcs are set in ~~older tracts of moraines, left~~moraine arcs deposited by ~~previous,~~ more extensive ~~ice-caps and~~ glaciers during earlier glaciations (Lachniet and Vazquez-Selem, 2005). In the AC range, however, ~~they~~older moraine arcs are not observed. Their absence implies that earlier ice caps were smaller than the one that ~~developed~~occupied the plateau during the last glaciation~~, and that their~~. Their deposits ~~have been~~were eroded away by the ~~most recent~~last glaciation ice cap. ~~Considering that there~~There is no particular reason why climatic forcing would have affected Central Guatemala in a different manner~~, the~~ that other neotropical areas. The most straightforward explanation therefore is that the ~~part~~fraction of the range located above the equilibrium line of accumulation (ELA~~),~~) has increased steadily from one glacial cycle to the next, as a result of sustained surface uplift~~, and that this uplift has been significant~~. Uplift was fast enough to overcome differences in the intensity ~~between~~of glacial cycles~~.~~, from one cycle to the next. The effect of surface uplift ~~is made easier~~on ELA was enhanced by the fact that the top of the range is a plateau, such that small increments of uplift bring large areas of the range above the ELA. The current driver of surface uplift is still contraction (Guzmán-Speziale, 2010; Authemayou et al., 2011b), just as ~~in~~it was during the early stages of mountain growth~~, to which erosional~~. Erosional unloading ~~may now contribute more than in the early stages,~~ driven by ~~the~~ deep dissection ~~of~~along the northern flank of the AC range may now contribute substantially to surface uplift of the summit plateau.

The steepness of river profiles in the AC range further support the hypothesis that the range still ~~lifts up~~rises faster than the SC range. The projection of river profiles in χ space (Figs. S4-2 to S4-7) shows that, in each of the analysed areas (AC, SC, and SM ranges), linearized segments ~~that share~~with similar streambed conditions (alluvial, boulder-armoured, bedrock) tend form share similar θ_n-normalized steepness (Fig. 14a). Rivers that flow over bedrock are steeper than rivers that flow over immobile boulders, which in turn are steeper than rivers that flow over alternations of gravel bars, or bedrock and boulder, which in turn are steeper than alluvial rivers. Each category, however, exhibit steepness values that change from one range to the next (Fig. 14 b,c,d). It is expected that ~~the~~ bedrock rivers conform to the predictions of the stream power law, because their incision is detachment-limited. At dynamic equilibrium, their steepness should therefore scale with rock uplift, bedrock erodibility and precipitation (Whipple and Tucker, 1999). The progressive increase in steepness from the SC range to the the AC range does not result from an increase in bedrock erodibility, because erodibility is higher in the AC range than in the SC and SM ranges. It does not result either from the observed increase in precipitation from the SC to the AC range, as ~~the increase would~~increased precipitation instead ~~decrease~~decreases river gradient. The steeper reaches of the AC range are therefore best explained by faster incision in the AC range, driven by faster rock uplift. This is consistent with the higher 10Be hillslope erosion rates measured in the AC range, assuming that slopes and channels are well coupled ~~there~~ (Callahan et al., 2019).

Boulder-armoured and alluvial channels are also steeper in the AC range (Fig. 14b,c). Boulders act as bedrock, and boulder-armoured ~~reaches could~~channels can therefore be expected to ~~evolve~~behave like ~~other~~ detachment-limited channels. ~~However, alluvial~~ Alluvial channels are likely transport-limited, and ~~the slope of transport-limited reaches~~therefore their gradient is less sensitive to rock uplift (Whipple and Tucker, 2002; Cowie et al., 2008). The observed increase in alluvial channel gradient therefore most likely reflects an increase in bedload grain size with increasing erosion rate, resulting from shorter residence ~~times~~time and ~~more~~ limited comminution of bedrock blocks in hillslope soils (Riebe et al., 2015; Neely and DiBiase, 2020).

Figure 14. Box plots of stream segment normalized steepness as a function of streambed type and location.

(a) Comparison of steepness by streambed environment; (b), (c), and (c): spatial variations in channel steepness across the study area, according to ~~the~~ regions defined on Fig.7, for the three main types of streambed environment: (b): boulder, (c): alluvial, (d): bedrock. Numbers above box plots: number of segments~~.~~ in each category. Oblique hatches: ~~mean defined by~~average over the total number of segments. Vertical hatches: ~~actively~~rapidly uplifting AC range.

5.2.2. Tectonic steepening of rivers transverse the AC range

The four rivers that still cross the AC range are the Cuilco, Selegua, Chixóy, and Cahabón Rivers (Fig. 7). ~~The~~ Of these, the Cahabón River is the smallest ~~these~~. It is affected by an ongoing pulse of drainage rearrangement ~~that started at~~which over the past ~1 ~~Ma that led to~~My has drastically reduced the ~~shrinking~~size of ~~its headwaters,~~ the Cahabón River catchment south of the Polochic fault~~, a process that will soon lead to its complete beheading south of the fault~~ (Brocard et al., 2012). To analyse the ~~effect~~impact of the AC range on ~~the~~ transverse ~~river~~rivers, we therefore focus on the three other rivers. ~~Of~~Two of these, ~~two~~the Chixóy and Selegua Rivers, exhibit steeper profiles as they cross the AC range~~, namely the Chixóy and Selegua Rivers~~ (Fig. 15). ~~As they cross the AC range~~Along these steepened reaches, the rivers incise rock formations that they ~~already~~ incise farther upstream~~,~~ without displaying ~~any~~ similar steepening~~, from which it can be concluded that the~~. The steepening is therefore not caused by ~~the present for~~ more resistant rocks~~,~~ but ~~instead~~ by faster uplift ~~of~~in the AC range (Leland et al., 1998; Kirby, 2003), consistent with the ~~interpretation of the~~ steepening of ~~shorter~~ rivers ~~draining only~~in the AC range ~~(see~~described in the previous section~~)~~.. The ~~lack of substantial~~ limited steepening ~~along~~of the Cuilco River could imply that ~~there~~, in the area crossed by the Cuilco River, the AC range ~~no longer rises~~does not rise faster than ~~the~~ areas located farther upstream. ~~This~~Such an interpretation, however, is at odds with documented ongoing contractional deformation ~~nearby~~in the area (Authemayou et al., 2012). Instead, the lack of steepening ~~may rather stem from~~is better explained by the fact that the Cuilco River ~~being a~~is transport-limited ~~river~~ over its entire length, as evidenced by ~~its~~a continuous cover of alluvium~~, in contrast to the~~. The Selegua and Chixóy ~~that~~ display ~~an alternation~~alternations of bedrock and alluvial reaches~~,~~ typical of detachment-limited rivers. Transport-limited conditions ~~indeed~~tend to generate less steepening than detachment-limited conditions in response to enhanced rock uplift (Cowie et al., 2008; Whipple and Tucker, 2002). ~~A~~Transport-limited conditions along the Cuilco River result from the profuse delivery of volcanic gravel in ~~the~~its headwaters ~~of the Cuilco River~~, where ~~the~~ river drains the Central American volcanic arc~~, probably explains this behaviour.~~. The Chixóy River also drains the volcanic arc ~~in its headwaters~~, but volcanic gravel sources in the Chixóy River catchment are located farther away from the AC range, such that, by the time the Chixóy River reaches the AC range, ~~the petrological composition of~~ most of this gravel has been trapped or comminuted and its bedload ~~reflect that of the most~~is dominated by proximal gravel sources (Deaton and Burkart, 1984~~), the gravel produced in the arc being comminuted or/and trapped upstream.~~).

Figure 15. Long profiles of rivers transverse to the AC range: Chixóy, Selegua, and Cuilco, with indications of reaches affected by vertical rock uplift (grey area), and those affected by horizontal lengthening along the Polochic fault (hatched area). S and L: contributions of steepening and lengthening to the uplift of river profiles, upstream of the AC range. River knickpoint nomenclature: see Fig. 12.

5.2.3. Transient slowing of incision in the SC range in response to river steepening in the AC range

The steepening of ~~rivers~~river profiles across the AC range ~~represents the~~ occurs in response ~~of rivers~~ to the rise of the AC range, in an area previously characterized by a foreland~~, crossed by~~ trough which flowed shallow-gradient rivers. The phase of steepening~~, from~~ that converted these shallow-gradient rivers to steep-gradient ~~ones,~~ transverse rivers should ~~end with the achievement of an equilibrium state whereby~~have ended when the gradient of the transverse rivers ~~is~~became steep enough for river incision to counterbalance rock uplift in the AC range. ~~For such steepening to occur,~~ Steepening requires the headwaters ~~must~~to rise with respect to the foreland. ~~This results in surface uplift in the SC range. Surface uplift~~Such rise requires a transient imbalance, upstream of the AC range, ~~with~~during which incision rates are lower than rock uplift rates. The sharp drop in incision rates in the SC range from 145-205 m·My-1 to <30 m·My-1 after ~7 Ma (see section 4.1) ~~can be viewed, therefore, as~~could have been driven by the steepening of the Chixóy River in response to the rise of the AC range, because the Chixóy River is the ~~post-7 Ma~~ outlet of most rivers draining the northern flank of the SC range~~ rivers~~.

Using the river ~~profiles~~profile of the Chixóy River (Fig.15), it can be assessed that, ~190 m of surface uplift along the Chixóy River can be ascribed to river steepening~~ resulting from the rise of the AC range~~, at ~27 m·My-1. If, before 7 Ma, rock uplift rates in the SC range matched its incision rates of 145-205 m·My-1 (Fig.9), then, if such uplift rates were sustained ~~in the SC range~~ after 7 Ma, ~~then~~ 1.5 to 2 My would be necessary to lift up the Chixóy River ~~and~~to its ~~tributaries to their~~ current elevation, upstream of the AC range. Incision would resume afterwards. ~~Such estimates have various~~This estimate has limitations, in particular because~~ both~~ the Chixóy and Selegua Rivers experienced large changes in drainage area upstream of the AC range during the 7 Ma reorganization event~~,~~ (Brocard et al., 2011), which affected their gradient across the AC range~~ (Brocard et al., 2011).~~. The Chixóy River was initially smaller, and therefore probably steeper~~, before receiving water and sediment contributions from of all surrounding streams at 7 Ma.~~. Conversely, the Río Selegua lost some of its headwaters, and ~~such~~this loss may have contributed to its steepening. The calculation, however, suggest that the timescale of equilibration should be much shorter than the 7 My that have elapsed since the AC range started to rise. Ever increasing rock uplift rate in the AC range would promote continuous steepening, and therefore could prevent the return of incision, upstream of the AC range. Although plausible, such an evolution remains speculative, because available data lack the resolution necessary to test it. We identified, however, other processes that can delay the resumption of incision along the northern flank of the SC range.

5.2.4. Slowing of incision in the SC range in response to river lengthening along the Polochic fault

~~One such process is the lengthening of rivers as they cross the Polochic fault, before flowing across the AC range. Their course is~~ River courses are progressively ~~set off~~offset by felt-lateral slip on the Polochic fault, leading to the development ~~left-lateral~~of ever-lengthening tectonic deflections ~~that lengthen their course. Rivers maintain a gradient sufficiently steep~~above the fault. Maintaining gradients along these deflections ~~such as~~ sufficiently steep to allow ~~at least~~ the ~~bypass~~downstream transport of ~~their~~the bedload~~. This results in the~~ requires uplift of ~~the streambeds~~river channels upstream of the tectonic deflections, commensurate to the amount of river lengthening. Before the rise of the AC range, ~~such~~left-lateral deflections ~~where located in~~formed at the ~~foothills of~~contact between the SC range~~, at the entrance of~~ and the northern foreland. Streambed uplift~~, at a place~~ along the deflections happened in an area where streambeds ~~are~~were shallowly incised, ~~allowed for repeated~~allowing frequent avulsions toward the foreland~~, periodically annealing~~ that annealed deflections (Sieh and Jahns, 1984~~).~~) and limited river lengthening. The rise of the AC range ~~led to~~promoted deeper entrenchment of the tectonic deflections along the Polochic fault, preventing the annealing of deflections~~,~~ and ~~ensuring that all~~converting slip on the Polochic fault ~~results in~~into permanent, cumulative river lengthening~~ and uplift~~. The courses of the Chixóy, Selegua, and Chilco Rivers have thus been lengthened by 25~~-~~ to 40 km (Fig.7~~), and the~~). The westward increase in the length of ~~deflection~~these deflections, in a context of westward decrease ~~of~~in total slip on the Polochic fault (Authemayou et al., 2011b~~),~~) was interpreted as the result of an earlier entrenchment of the rivers in the west (Brocard et al., 2011). River lengthening drove 500, 600 m, and 150 m of surface uplift along the Cuilco, Selegua, and Chixóy Rivers, respectively (Fig.15). Because left-lateral slip ~~rate of~~on the Polochic fault has been fairly steady over the past 7 Ma, at 2.9 ± 0.4 mm·y-1 along the ~~tectonic deflection of the~~ Chixóy River deflection (Authemayou et al., 2012; Bartole et al., 2019), river lengthening and uplift, likewise, must have steadily ~~uplifted~~contributed to surface uplift in the upstream parts of the Cuilco, Selegua, and Chixóy River, at 15 ± 2 m·My-1 along the Chixóy River. In contrast to river steepening, ~~the effect of such uplift on incision rates, upstream of the AC range, is permanent.~~ which generated 1.5 to 2 My of transient uplift, river lengthening has generated a constant uplift roughly proportional to slip rate on the Polochic fault.

5.2.5. ~~Respective contributions~~Slowing of ~~tectonics and climate to the stalling of river~~ incision in the SC range in response to decreased in rock uplift rates in the SC range

With estimated surface uplift rates of ~27 m·My-1 and 15 ± 2 m·My-1, tectonic steepening and river lengthening are the two bottom-up processes ~~that we could identify that contributed~~, driven by the rise of the AC range, ~~and~~ that contributed to ~~some decrease~~ the decline in ~~river~~ incision rates~~. Still, they~~ in the SC range. They only represent a fraction of the ~~drop in river incision rates~~measured decline, which went from 145-205 m·My-1 before 7 Ma, down to <30 m·My-1 after ~7 Ma~~. Such evolution implies therefore either~~ (Fig.9). The decrease may also result from a substantial decrease in rock uplift ~~rates in the SC range after 7 Ma, or/and a strong effect of the aridification of the SC range on river incision rates~~rate in the SC range.

A decrease in rock uplift rates in the SC range is ~~supported~~documented by the difference in elevation between the paleovalleys located in the AC range, such as V3 (Fig. 2, Fig.8a), which underwent 2.8 km of uplift since ~7 Ma (assuming an initial foreland elevation of 0.3 km), and the Chixóy River, which ~~only~~ underwent only 0.35 km of uplift in the meantime. If the ~~Chixóy River~~SC range had ~~lifted up since~~continued to rise after 7 Ma at the rate at which river incision ~~occurred~~was taking place in the SC range before 7 Ma (145-205 m·My-1), then the resulting difference in elevation between V3 and the Chixóy River (0.9 km) would be only 1/3rd of ~~its present-day value. Their~~the actual difference ~~in elevation is~~. It would be even ~~slightly~~ smaller than the 1 km of back-tilting ~~of~~measured along paleovalleys V4-V5, south of the Polochic fault (Fig.2 ~~(~~in Brocard et al~~.,~~. (2011)). The observed difference therefore requires a substantial decrease in rock uplift in the SC range after 7 Ma.

~~Fluvial~~Between 50 and 300 m of fluvial and volcanoclastic aggradation ~~in the range of 50-300 m~~ occurred along the rivers that used to drain the northern flank of the SC range prior to 7 Ma~~, as documented by the sedimentary fills~~ (Brocard et al., 2011). This phase of ~~the paleovalleys, upstream of the AC range. They support the view of a strong imbalance in uplift rates between the two ranges from the start. Such~~ aggradation can be viewed as ~~the~~a transient response ~~of these rivers to increased uplift farther downstream~~ (van der Beek et al., 2002; Attal et al., 2008~~), due in these case,~~) to the rise of AC range (Brocard et al., ~~2011). A similar aggradation is observed along the northern drainage in Plio-Quaternary times, along the northern flank of the SM range, in response to the rise of transtensional horsts and tilted blocks (Brocard et al., 2012). The return~~ 2011). It suggests that the AC range was already undergoing faster rock uplift than the SC range early during its growth. Rivers have since then incised down to pre-aggradation levels ~~would mark the return to~~. If river incision in the SC range is now in dynamic equilibrium, ~~characterized by a~~then the lack of ~~rock uplift, of~~incision over the past 7 My implies that the SC range ~~with respect~~has not undergone any rock uplift relative to the foreland~~, hence the lack of river incision. In this view, the few 10s of meter of incision~~ since 7 Ma ~~would represent a fine balance between river incision and~~. More precisely, rock uplift in the SC range~~, with rock uplift providing quite precisely~~ would exactly match the 350 m of surface uplift ~~needed~~necessary to ~~counterbalance~~accommodate river steepening in the AC range and river lengthening above the Polochic fault. ~~There is, however, no~~We could not identify any obvious tectonic process whereby such a fine balance ~~of rock uplift rates~~ would be achieved.

~~Alternately, instead of an equilibrium response, the~~

5.3. Contribution of aridification to the decline of river incision in the SC range

The absence of incision in the SC range could also be viewed also as ~~an absence~~a lack of response to tectonic ~~processes~~forcing, in a landscape subjected to aridification ~~after~~since 7 Ma. By decreasing water discharge, aridification would reduce stream power. ~~This would initially reduce incision in the SC range, while promoting river steepening in both the SC and AC ranges (along rivers which mostly drain the AC range), furthering surface uplift. Second, it may have altered~~Besides, aridification could alter the balance between water and sediment ~~discharge in~~discharges such~~ a way~~ as to reduce sediment transport capacity and river incision (Beaumont et al., 1992~~), or limited~~). It could also dampen the ~~availability~~delivery of tools ~~for eroding~~to erode the bedrock (Sklar and Dietrich, 2006). A contribution of climate to the slowing down of incision is ~~also suggested~~further supported by the evolution of the southern flank of the SC and SM ranges~~, which, although~~. These flanks, albeit exposed to a different tectonic forcing than the northern side of the SC range, underwent a similar ~~evolution of incision rates as the northern flank of the range. There, the ~~decline in incision. The only possible contribution of bottom-up processes to the slowing down of incision along these flanks is the lengthening of the Motagua River ~~to the stalling of incision would be through a considerable lengthening of its course ~~at its downstream end, into the Caribbean Sea~~, requiring~~. Such lengthening would promote surface uplift farther upstream, in order to maintain the downstream dispersal of sediments. Some lengthening probably occurred ~~as a result of~~during the emergence, at the ~~its ~~downstream end of the river, of a transtensional basin (Fig. 1b) that has been filled with terrigenous sediments ~~that marine middle Miocene sediments~~since the Mio-Pliocene (Carballo-Hernandez et al., 1988). This lengthening of >180 km ~~currently involves~~involved <75 m of surface uplift~~. A stalling~~ (elevation of ~~incision along ~~the ~~southern flank of the range, would,~~river at ~~equilibrium, involve southward tilting~~the upstream end of the ~~range, such as to accommodate~~basin). This amount of uplift does not match the ~~difference in~~amount of surface uplift affecting the northern side of the range. It seems highly unlikely that independent tectonic phenomena~~,~~ such as the uplift of the AC range ~~in~~and the lengthening of river courses along the Polochic fault to the north, the ~~lengthening of rivers on the Polochic fault, the~~ decrease in rock uplift rates within the SC range, and the lengthening of the Motagua River ~~in~~to the west, ~~would converge such as to~~could produce ~~the~~a similar ~~stalling~~decline of incision on either side of the SC range. The aridification of the range, which is well documented on either side (Machorro, 2014), appears therefore ~~as an import factor,~~to significantly contribute to the slowing down of river incision on both sides.

~~Figure 16. Development of the central ranges of Guatemala. Along profiles A-A* and B-B* (see Fig. 13a for location).~~

Figure 16. Development of the central ranges of Guatemala. Along profiles A-A* and B-B* (see Fig. 13a for location). Red arrows: rock uplift/subsidence (arrow thickness proportional to rate). Thick blue arrows: moisture fluxes. Thin blue arrows: river incision (length proportional to rate). Yellow triangles and arrows: migrating

knickpoints with direction of migration. Atmosphere depicted as blue to yellow from wet to dry. Red stars: dated lavas, green star: fossil forest of Sicaché (SIC). Solid ground surface lines: black: topography along transects, blue: nearby river profiles. Dashed lines: blue: former river profile, red: Maya surface. Mo.F: Motagua fault, Po.F: Polochic fault. Pink, brown, and yellow sediment fills next to the Mo.F: Eocene Subinal Fm., Middle Miocene Padre Miguel Fm., and younger alluvium.

5.3. Topographic evolution of the SC range in response to the uplift of the AC range

5.3.1. Slowing down of hillslope erosion, topographic decay, and backwearing

Modern 10Be-derived hillslope erosion rates in the SC are higher (> 50 m·My-1) than the <30 m·My-1 long-term river incision rates measured around the SC range (Fig.10~~). This suggest~~), suggesting that the relief of the SC range has been slowing decaying ~~over the past~~since 7 ~~My~~Ma. Hillslope degradation during the decay could ~~possibly~~ account for the lower ~~average~~ steepness of the quartz-feeding slopes in the SC range (22±3°) compared to those in the AC range (26 ± 4°). Hillslope ~~steepness~~ degradation should ~~be associated with a~~ ultimately lead to the decrease ~~in~~of the local relief of the SC range. The preservation of the Maya surface on many summits, ~~combined with~~ and the absence of ~~substantial~~ incision ~~around~~at the base of the SC range however imply that the height of the SC range has not been ~~been~~ significantly reduced over the past 7 My. Instead, decay appears to have proceeded ~~through the~~by backwearing of the ~~slopes~~mountain flanks, from the base of the range ~~towards~~inward, toward its divide. This is manifested by the development of pediments ~~that expand towards~~at the base of the range~~ interior~~, and by the presence of upstream-migrating river knickpoints ~~within these~~on the backwearing slopes.

5.3.2. Origin of migrating river knickpoints within the SC range

Three clusters of migrating knickpoints are found at different elevations along the northern flank of the SC range (Fig. 8b and 12a2). The uppermost cluster consists of convex knickpoints that dissect the middle Miocene Maya surface. They represent the front of an erosion wave that formed in response to the initial uplift of the SC range, at 12 Ma. These knickpoints may have nucleated near the base of the range, along the Polochic fault, which, back then, represented the boundary between the SC range and the northern foreland ~~from 12 to 7 Ma~~ (Fig. 16a). The second cluster of knickpoints consists of convex knickpoints located 500 m farther ~~down~~downslope, along the northern flank of the SC range (Fig. 8b and 12a2). These knickpoints have heights of

200-300 m (Fig. S4-3). ~~Assuming that this~~If their height represents the amount of ~~stream~~ incision associated to their passage, ~~the this~~then their passage must predate 7 Ma, because these rivers have only incised 20-90 m ~~over the past~~since 7 ~~My~~Ma between ~~these~~the knickpoints and the ~~northern front of the SC range~~Polochic fault (Brocard et al., 2011). Like the ~~upper~~ knickpoints~~, therefore, they~~ of the upper cluster, the middle cluster knickpoints could have nucleated ~~on~~above the Polochic fault~~.~~, but at a later time.

10Be hillslope erosion rates ~~however~~ suggest that today, these two generations of migrating knickpoints ~~migrate very slowly today~~are almost immobile. Indeed, hillslope erosion rates ~~should~~ are expected to increase ~~across upstream-migrating knickpoints~~ in the downstream direction~~. Faster~~ across actively migrating knickpoints ~~should geometrically promote larger differences in hillslope erosion between upstream and downstream areas (Brocard et al., 2016b). Either~~. Yet, only marginal (e.g. catchments XEU to Cub) to negligible (e.g. SMS to SMM) ~~increase~~increases in erosion rate ~~is~~are documented across ~~these~~the knickpoints (see section 4.2~~), suggesting that they have stalled.~~). Knickpoint celerity is influenced by top-down processes, such as the amount of water runoff and sediment discharge delivered from upslope (Crosby and Whipple, 2006; Brocard et al., 2016b~~).,~~), and, under certain circumstances,~~ it can be influenced~~ by bottom-up processes, such as the rate of base level fall (Whittaker and Boulton, 2012). Therefore, both the stability of the base level around the SC range over the past 7 My~~,~~ and the reduction in rainfall resulting from the rise of the AC range may have contributed, together with decreasing upstream drainage area~~,~~ (Crosby and Whipple, 2006), to the slowing down of migrating knickpoints within the SC range (Fig. ~~16a,b). Their migration considerably slowed down over time, through a combination of (Crosby and Whipple, 2006), and of aridification in the SC range (Fig.16b~~16a,b).

The third cluster ~~of knickpoints~~ is located ~~along~~at the base of the mountain. It consists of concave-up knickpoints ~~located at~~dotting the apex of ~~the~~ pediments that have ~~developed~~formed along the range (Fig. 8b and 12a2). ~~These~~The pediments are currently extensively buried under pumice, deposited during a large, late Pleistocene eruption (Brocard and Morán, 2014; Rose et al., 1987). Pediments usually form under semi-arid climates, along drainages with stable base levels~~; they~~. They grow by extending their apex~~, in~~ into the ~~upstream direction~~ range (Pelletier, 2010; Strudley et al., 2006; Thomas, 1989). The ~~pediment~~pediments of the SC range have developed in an area that has been incising slowly over the past 7 My (<30 m·My-1~~) in an area~~), and where climate is among the driest ~~in~~of Guatemala (Machorro, 2014~~), over slate, schists, gneisses, and granite.~~). The concave-up ~~migrating knickpoint located at the apexes of these pediments~~ knickpoints can be regarded as knickpoints ~~that spearhead~~spearheading a wave of decreased incision (Baldwin, 2003). Streambed analysis further shows that these knickpoints are located at the transition between detachment-limited and transport-limited reaches downstream (Fig. S4-3~~)~~), as predicted by theory (Whipple and Tucker, 2002). Lateral planation ~~tend~~tends to dominate over vertical incision, downstream of that transition (Brocard and Van der Beek, 2006), which is ~~also~~ consistent with pediment development~~ downstream.~~ .

The ~~fact that these concave-up knickpoints~~steepest reaches along the northern flank of the SC range are located ~~downstream of the steepest river reaches, downstream of the~~between the intermediate cluster of convex-up ~~knickpoint located halfway the mountain side~~knickpoints, and basal cluster of concave-up knickpoints. The close association of the middle and lower clusters may not be coincidental~~, and could in fact imply that~~. An alternate hypothesis for the ~~second~~formation of the intermediate cluster ~~of knickpoints~~is that it did not nucleate, as hypothesized above, at the front of the range~~. Rather, they has formed and grown in height and steepness progressively inside the range~~, ~~ahead of the pediment apexes, rather than through nucleation along the Polochic fault. They would grow due to~~but on site, by faster backwearing of the lower slopes than downwearing of the upper slopes, ~~thus generating the steepest river reaches~~ immediately ~~upstream~~ahead of the lower cluster. They would have since grown in height and steepness as the pediments~~. From a conceptual point of view, the river reaches located between the mid-flank convex knickpoints~~ extend into the range. The intermediate cluster and ~~the~~ basal ~~concave knickpoints~~cluster can be viewed as the lips and toes of large knickzones (or knickpoint faces (Gardner, 1983)). Models predict that, if water discharge has a larger influence than river gradient on stream incision, such knickpoint faces tend to steepen and amplify over time, during backwearing (Weissel and Seidl, 1998; Tucker and Whipple, 2002~~). This~~), which is consistent with the observed topography. The intermediate ~~cluster is~~ and basal clusters are not ~~found~~present farther east, along the wet flank of the SM range~~, where no pediments have formed at the base of the range~~ (Fig. 12d, 16c). ~~There, only~~Only one cluster of large migrating knickpoints separates the very flat uplands of the SM range from its deeply incised, wet lower flank (Fig. 8d). ~~The aridification~~Aridification, therefore, appears to be responsible ~~to~~for the development of the highly stepped topography of the SC range.

5.3.3. Range-hopping erosion and the development of dry orogen interiors

The evolution of the study area can be summarized as follows. Orogenesis started with the rise and coeval incision of the SC-SM range, from 12 to 7 Ma (Fig.16a). After 7 Ma, rock uplift decreased in the SC range ~~while~~ and picked up in the AC range~~ started to rise in its northern foreland.~~. Fast uplift in the ~~SC~~AC range led to the tectonic defeat of many rivers which, upon exiting the SC range, flowed across the foreland. Most of the defeated rivers were rerouted into the drainage of the Chixóy River, one the four rivers that maintained a course across the AC range. Transient steepening of ~~these range-transverse~~ rivers in response to the fast rise of the AC range and the lengthening of these same rivers ~~along~~by the Polochic fault promoted surface uplift within the SC range. The complete cessation of river incision along the northern side of the range may therefore result from a combination of river steepening, river lengthening, and ~~from the~~ decrease in rock uplift ~~rates within~~in the SC range. However, the fact the stalling of incision is as complete along the southern side of the range as along the northern side ~~suggest~~suggests that tectonics was not the only cause, but that the aridification of the SC range, resulting from the rise of the AC range, was also instrumental in the stalling of river incision. The decrease in precipitation over the SC range reduced erosion on its hillslopes, decreased river discharge, and therefore contributed to the stalling of river incision on both sides of the range. Precipitation and erosion concentrated on the northern flanks of the AC and SM ranges, while the SC range ~~was becoming~~became almost passively uplifted.

The high erosion rates and wet slopes that characterize the AC range today are ~~therefore~~ reminiscent of the SC range ~~from~~between 12 ~~to~~and 7 Ma. The AC range ~~has become~~became the front range~~ that intercepts~~, intercepting the moisture ~~rising~~that tracks from the foreland, while the SC ~~has become a~~ became an inner range ~~located~~, upstream~~, in~~ of the front range, and within its rain shadow. ~~As such, it~~A decrease in rock uplift rate alone cannot account for the sharp decline of erosion in the SC range after 7 Ma, because the relief and steepness of the range did suddenly decreased. Aridification, within the rain shadow of the AC range, contributed to the overall decline in erosion in the SC range. The SC range displays ~~traits~~characteristics of dry orogen interior ranges and of orogenic plateaus: it ~~erodes slowly and undergoes a~~ has entered a stage of progressive topographic decay, marked ~~here~~ by the development of pediments~~ along its base.~~. Pediment ~~development is promoted by a combination~~formation occurs in a context of aridity and ~~of~~ very low incision rates. ~~Low~~Such low incision rates~~ that result from a combination of~~, driven by aridification in the rain shadow of ~~frontal~~front ranges, and ~~of tectonic~~by river steepening ~~of river gradients~~ across the front ranges, ~~is expected to characterized~~characterize the ~~growth of~~evolution orogenic plateaus ~~forming~~formed by ~~lateral~~tectonic accretion (Sobel et al., 2003; Garcia-Castellanos, 2007). ~~In the case of~~On orogenic plateaus, ~~however, the combination of decreased precipitation and rise of new frontal ranges achieve~~ this evolution ultimately leads to the disintegration of river drainages, isolating dry interior drainages from the ~~drainage of front ranges. River incision along~~forelands. Along interior ~~drainage is reduced by the~~ drainages incision then further decreases, the rivers being graded to high-elevation base ~~level maintained in the endohreic catchments. The reduction~~levels. Reduction in local relief ~~over then combines a continuation of pre-existing trends in topographic decay and pedimentation, and an~~ then receives the added contribution of ~~progressive~~the sediment infilling of the now closed catchments (Sobel et al., 2003). ~~The~~If the drying of the SC range was more severe it could ~~evolve –or not- toward full~~ultimately lead to drainage disintegration.

Continued ~~extension~~growth of the pediment~~ and their coalescence~~ could lead to the formation of an intramontane pediplain (Baulig, 1957), at elevations of 0.9-1.2 km, halfway between the high-standing remnants of the middle Miocene Maya surface, and the Petén-Yucatán lowlands. The Central American Dry Corridor, which straddle the SC range, continues to the NW over the Central Depression of Chiapas (Fig.1a), where ~~more~~ extensive pediments have developed over the basement rocks of the Sierra Madre de Chiapas (Authemayou et al., 2011a), in an area isolated from the Pacific moisture by the Sierra Madre de Chiapas to the

SE, and from Caribbean moisture by the Sierra de Chiapas in the NW (Fig.1a). These pediments are in a more advanced ~~process~~stage of coalescence and ~~pediplain. The formation of such pediplains,~~pediplanation. Pediplanation in a context of active orogenesis may explain the great abundance of low-relief perched surfaces that appear to ~~have~~ form quickly in many orogens~~,~~ without significant pauses in mountain building (Calvet et al., 2015; Pain and Ollier, 1995; Babault et al., 2005).

6. Conclusions

- Radiometric 39Ar-40Ar dating on volcanic rocks confirms our earlier finding that the ~~mountains~~mountain range the closest to the plate boundary (the SM-SC range) was ~~mostly~~ incised during the late Miocene, from 12 to 7 Ma. Incision almost completely stalled afterwards, during the formation of the Altos de Cuchumatanes (AC ~~r ange),~~range) farther north.

- The deformation of paleovalleys indicates that the AC range experienced > 1,000 m of uplift relative to the SC range over the past 7 My. Today the range is highly dissected. High river profile steepness and ever-expanding ice-caps indicate that the AC range still undergo fast rock and surface uplift.

- The concentration of detrital terrestrial 10Be in the sediments of rivers that drain these ranges show that hillslope ~~y reach~~erosion reaches 300 m·My-1 in the AC range, but ~~are~~is commonly <100 ·My-1 in the SC-SM range. The patterns of hillslope erosion rates ~~therefore~~ mimic ~~the~~ spatial patterns of precipitation and stream incision.

- Precipitation is strongly controlled by topographic obstructions resulting from the rise of the AC range, which intercepts Caribbean moisture. Precipitation is high along the northern flanks of the AC range, but low over the SC range, which lies within rain shadows. Fossil vegetation preserved at the base of the SC range indicates a wetter climate at 7 Ma, when the AC range started to grow.

- In this context, the slow current hillslope erosion rates in the SC range appear to be contributed in part by the rise of the AC and by the development of rain shadows. It can be hypothesized, therefore, that hillslope erosion rates in the SC range were higher before the uplift of the AC range. ~~Aridification may have also contributed to the decrease in river incision rates over the SC range.~~

- The rise of the AC range led to the steepening of river profiles along the rivers that maintained a course across the rising range. The steepening of river profiles triggered a transient decrease in river incision rates upstream of the AC range. The lack of resumption of river incision upstream of the AC range implies either that these rivers have not re-established equilibrium profiles, or that other factors prevent the return of incision. ~~Aridification and river lengthening are the most likely contributors.~~

- The rise of the AC range ~~indeed~~ led to the entrenchment of range-transverse rivers along the Polochic strike-slip fault. Fault slip has driven continuous lengthening of river courses on top of the fault over the past 7 My. Lengthening contributes to the rise of river profiles upstream of the Polochic fault, and therefore to the slowing down of river incision in the SC range.

- The difference in elevation between paleovalley in the AC range and the SC range imply rock uplift rates have declined in the SC range. This decrease in rock uplift rates may have also contributed to the decline in incision in the SC range

-The fact that incision decreased equally on either sides of the SC range, despite widely different tectonic forcing, implies however that aridification of the SC range contributed significantly to the decrease of river incision over the SC range.

- In the SC range hillslope erosion slightly outpaces base level lowering, implying an overall trend to slow topographic decay, despite continuing surface uplift. The persistence of Middle Miocene low-relief surfaces on mountain tops in the SC range however implies no net reduction in the range height, and a decay that proceeds by backwearing rather than downwearing.

- The slowing down or erosion rates over the SC range has resulted in a slowing down and stacking of upstream-migrating knickpoints and erosion waves over the SC range and of the development of pediments at its base.

Author contribution

Gilles Brocard: project design, river 10Be sampling (AC and SM ranges), 10Be sample processing (AC and SM ranges), river segment analysis, manuscript preparation, with contributions from all authors. Jane Willenbring: 10Be sample processing (SM-SC range). Tristan Salles: river profile segmentation. Mickael Cosca: 40Ar/39Ar dating. Axel Guttiérez-Orrego and Noé Cacao-Chiquín: 10Be stream sampling (SM-SC range). Sergio Morán-Ical: field work coordination. Christian Teyssier: project design and coordination.

Competing interests : ~~The~~the authors declare that they have no conflict of interest.

Code/Data availability : all in supplements

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