A refined model of Quaternary valley downcutting emphasizing the interplay between tectonically triggered regressive erosion and climatic cyclicity

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While climatic models of Quaternary valley downcutting discuss the origin of terrace staircases in valleys of middle Europe within the frame of alternating cold and temperate periods, other models, starting from a base level fall imposed by a tectonic signal, describe the response of the drainage network mainly as the propagation of an erosion wave from the place of base level fall toward the headwaters, the two types of model being rarely confronted. In the Ardennes (W Europe), the tectonic and climatic influences combined to produce a complex spatio-temporal pattern of terrace development since the beginning of the middle Pleistocene, thus providing an opportunity for analyzing the interplay between tectonically triggered regressive erosion and cyclical incision of climatic origin.

Study area

We focus on the drainage system of the Ourthe River, the main tributary of the Meuse River in the Ardennes (Fig. 1). Its catchment extends over 3600 km^2 of central and NE Ardennes, with a 150-km-long main stem flowing from south to north (Fig. 3). The Ourthe River flows into the Meuse River at Liège, which, at 55 m asl, makes a regional base level located approximately at the border of the uplifted massif.

As a consequence of a middle Pleistocene increase in uplift rate, valleys in the Ardennes display a typical cross section that opposes a narrow, steep-sided young valley nested into a broader older valley with gently sloping valleysides (Fig. 2). Dated ~0.73 Ma north of the massif (Rixhon et al., 2011), the extended lower level of the Main Terrace Complex (YMT) clearly separates the two units and marks the beginning of the middle Pleistocene incision episode. Cosmogenic age data of the YMT and knickpoint data are used to decipher the incision history of the Ardennian valleys since 0.73 Ma.

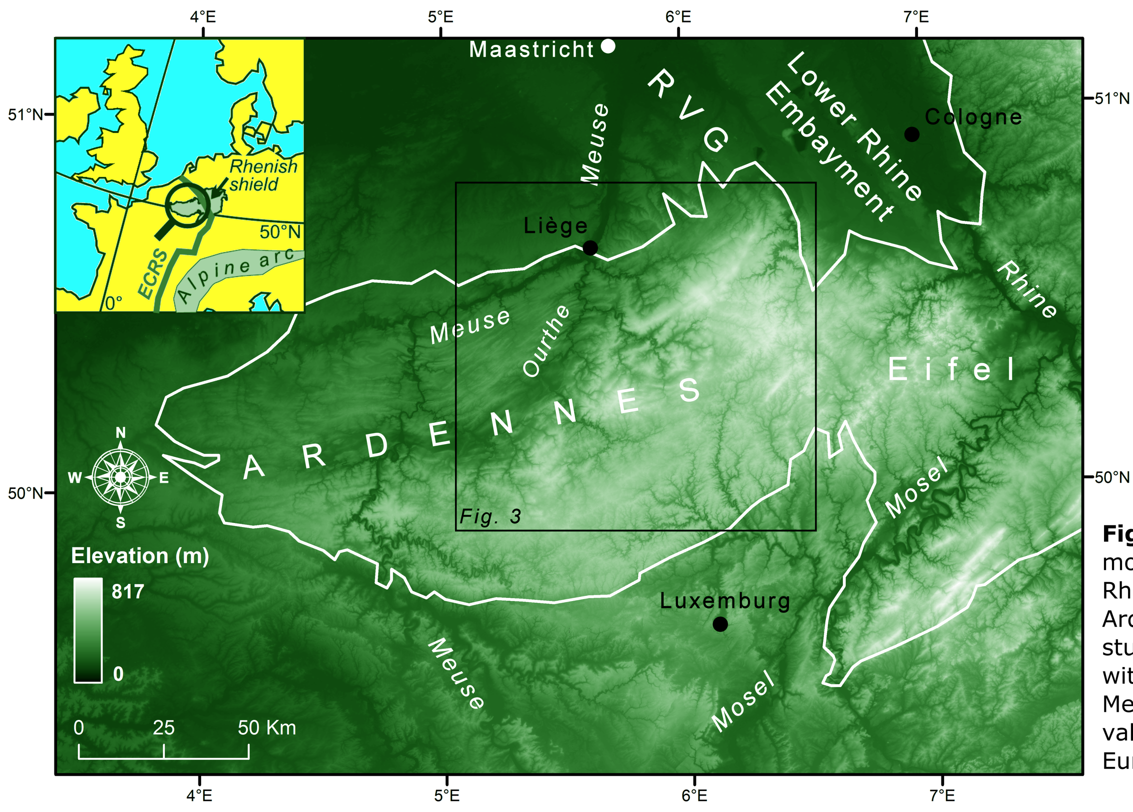


Figure 1. Digital elevation model of the western half of the Rhenish shield, centred on the Ardennes and locating the study area (frame of Fig. 3) within the Ardennian part of the Meuse catchment. RVG. Roer valley graben. ECRS (inset). European Cenozoic rift system.

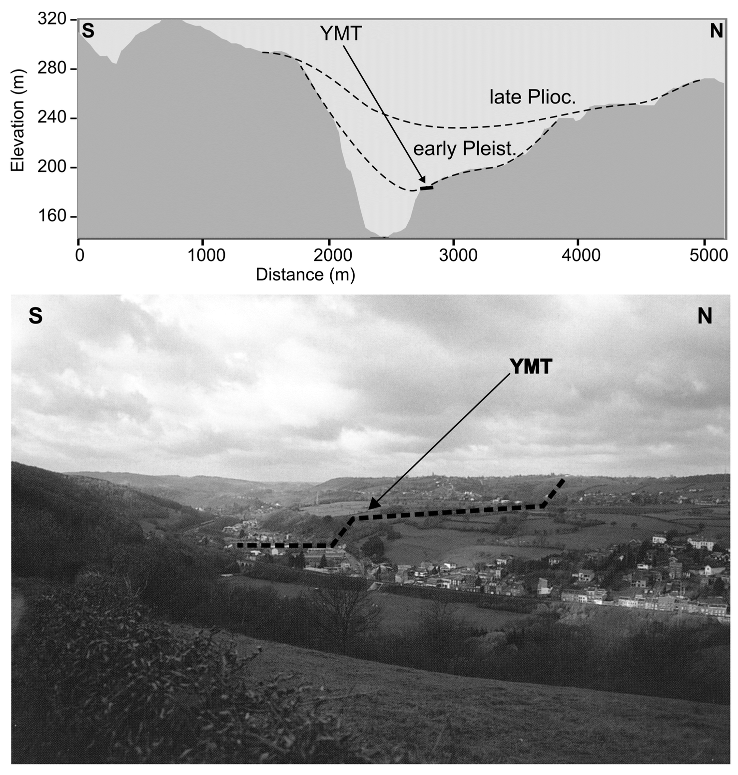


Figure 2. Cross-profile and photograph of the Vesdre valley, a typical Ardennian valley, downstream of Verviers (see location on Fig. 3), showing the nested late Pliocene, early Pleistocene, and narrow post-YMT valleys. The YMT represents the last floodplain developed within the broad early Pleistocene valley before abrupt incision and valley narrowing at 0.73 Ma.

New data

Cosmogenic $^{10}Be/^{26}Al$ ages have recently been calculated for the abandonment of the YMT (Rixhon et al., 2011) in the valleys of the lower Meuse, the lower Ourthe, and the Amblève (Fig. 3). These ages show that the terrace has been abandoned diachronically as the result of a migrating erosion wave that started at ~0.73 Ma in the Meuse catchment just north of the massif, soon entered the latter, and is still visible in the current long profiles of the Ardennian Ourthe tributaries as knickpoints disturbing their upper reaches (Beckers et al., submitted).

This diachronism is further confirmed by the identification of another stage of the erosion wave progression along the Eau Rouge River, a tributary of the Amblève. Until the end of the Eemian, the Eau Rouge valley was occupied by the Warche River, whose upstream half was then captured by a small tributary of the Amblève (Fig. 4). In the abandoned valley, the reconstructed long profile of the Paleowarche displays a prominent convexity (Pissart & Juvigné, 1982) that marks the place the post-YMT knickpoint had reached at 50-78 ka, the approximate time of the capture.

	River	Data	Distance from Maastricht (km)	Age (ka)	Drainage area (km^2)
Romont	lower Meuse	$^{10}Be + ^{26}Al$	6	725 (±120)	20976
Colonster	lower Ourthe	$^{10}Be + ^{26}Al$	30	390 (±35)	2914
Belle-Roche	lower Amblève	^{10}Be	55	223 (±31)	1072
Stavelot	middle Amblève	^{10}Be	101	135 (±6)	465
Lodomez	middle Amblève	^{10}Be	103	140 (±10)	264
Bernister	Paleowarche (Eau Rouge)	buried knickpoint	111-113	50 - 78	151
Robertville	Warche	knickpoint	120	0	106
Ligneuville	upper Amblève	knickpoint	116	0	115

Table 1. Time tags of the migrating erosion wave triggered by the pulse of uplift of the Ardennes at 0.73 Ma. The Romont - Maastricht area is located at the northern margin of the uplifted massif.

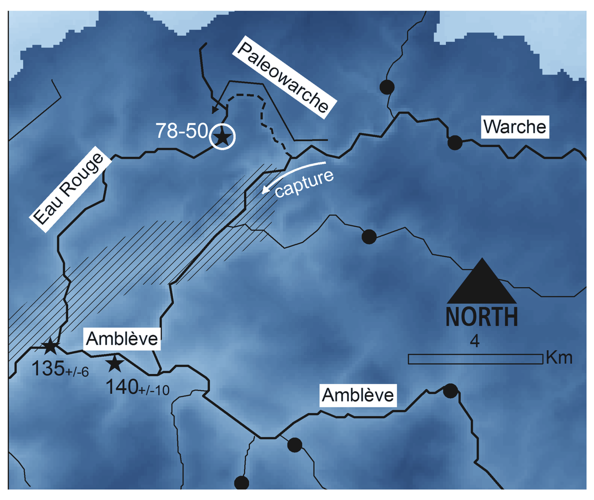


Figure 4. Sketch map illustrating the Warche capture (see location on Fig. 3). The dashed line marks the ancient course of the Warche, continued by the course of the present Eau Rouge. Stars indicate dated positions of the retreating post-YMT knickpoint (in ka, with 1σ uncertainty for the cosmogenic ages along the Amblève). The circled star locates the buried knickpoint of the Paleowarche in its pre-capture course. Black dots denote post-YMT knickpoints in the current river profiles.

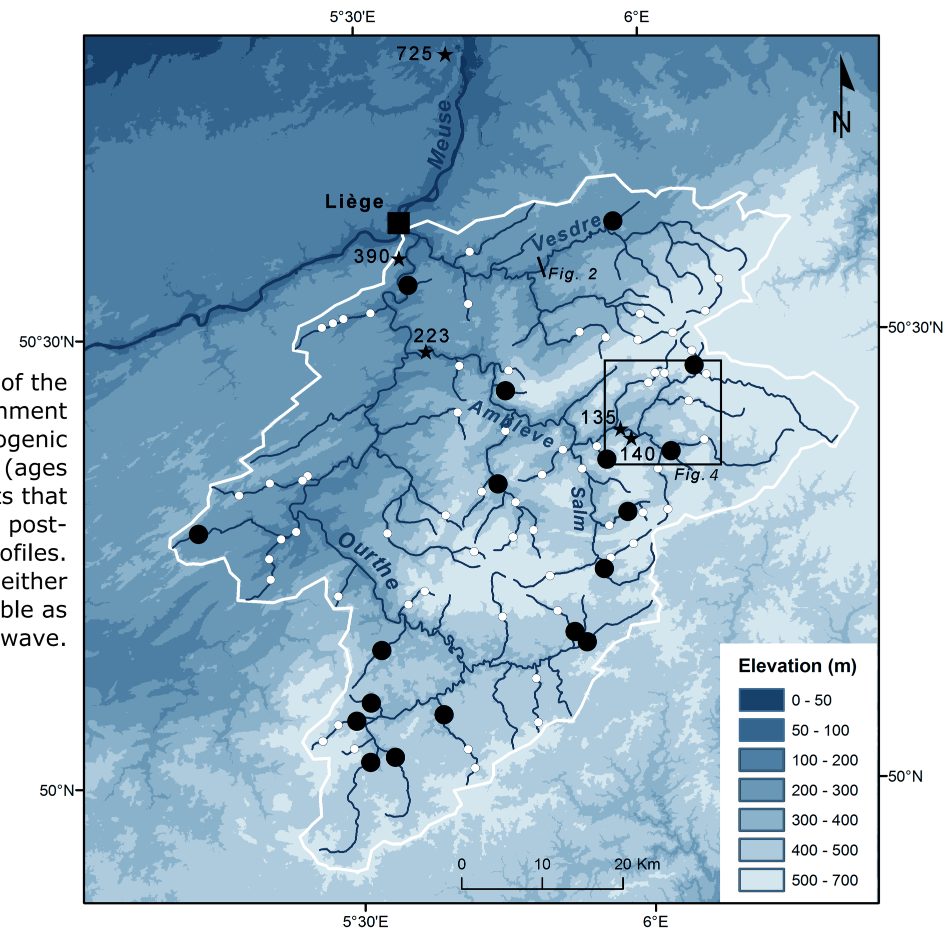


Figure 3. New data about the migration of the post-YMT erosion wave within the Ourthe catchment (outlined in white). Stars locate sites of cosmogenic $^{10}Be/^{26}Al$ dating of alluvial gravels of the YMT (ages in ka). Large black dots denote knickpoints that reliably locate the positions reached by the post-YMT erosion wave in the present-day river profiles. Smaller white dots are for other knickpoints, either of lithological origin or at least not fully reliable as indicators of the post-YMT erosion wave.

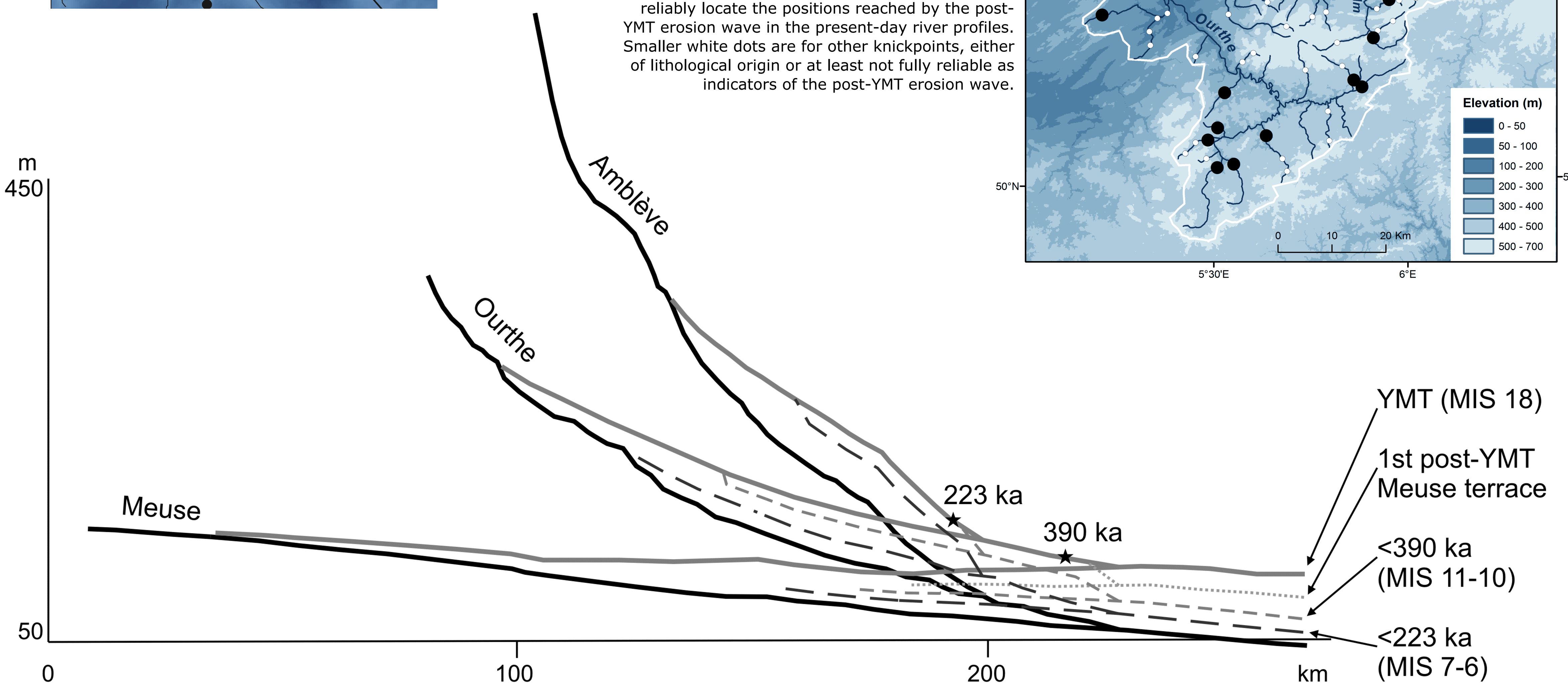


Figure 5. Long profiles of the Meuse-Ourthe-Amblève drainage system at 725 (starting time of the YMT formation in the Maastricht-Romont area), ~620 (= MIS 16, time of the first post-YMT Meuse terrace between Maastricht and Liège), 390, 223 and 0 ka, showing the progressive knickpoint retreat towards and within the smaller tributaries. Current long profiles in black. The stars locate and give the age of the sites dated by cosmogenic nuclides in the Ourthe and the lower Amblève. Not all post-YMT terrace levels are drawn in this schematic illustration, which however evidences that these levels are less numerous in tributaries than in trunk streams.

Discussion

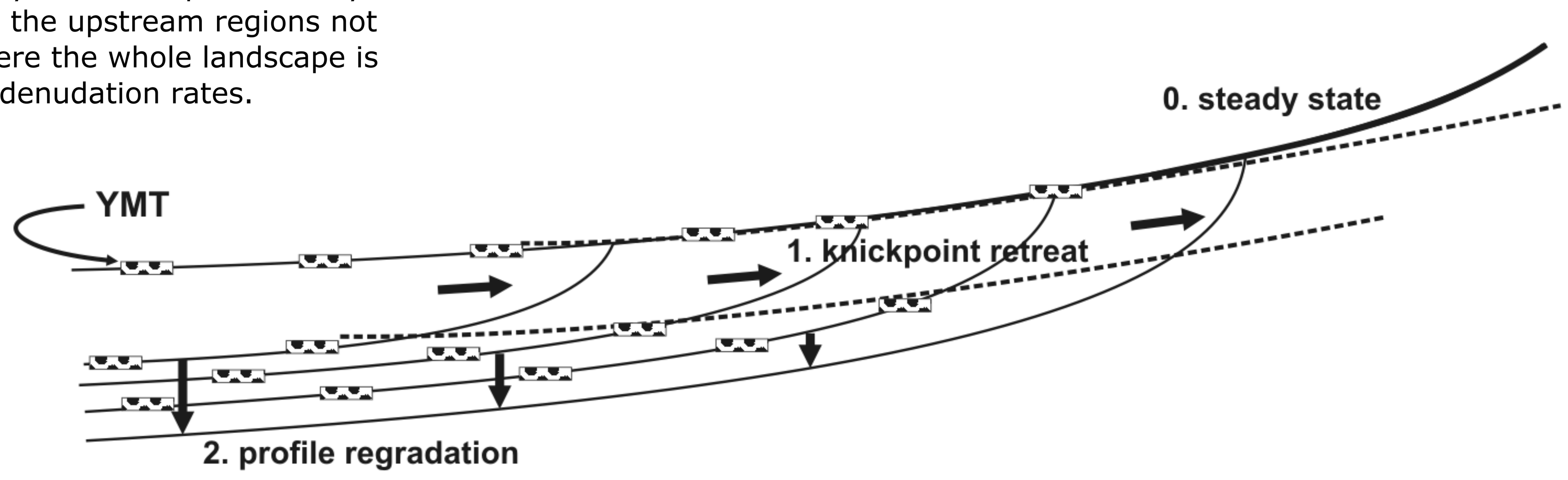
At first glance, our data contradict the common belief that the terraces of the Ardennian rivers were generated by a climatically triggered stepwise general incision of the river profiles. However, several details of the terrace staircases (larger than average vertical spacing between the YMT and the next younger terrace, decreasing number of post-YMT terraces from trunk stream to tributaries and subtributaries) show that a combination of the climatic and tectonic models of river incision is able to satisfactorily account for all available data.

We thus propose a mixed model of valley incision. The transient response of the drainage system to an uplift pulse around 0.73 Ma operated longitudinally by knickpoint migration rather than vertically by ubiquitous profile incision. However, once the knickzone had travelled up stream reaches, the latter kept on deepening each time the climatic conditions were propitious to fluvial erosion, but then after the climatic fashion of simultaneous vertical incision in the whole part of the drainage network situated downstream of the positions reached by the erosion wave, returning there progressively to a new steady state.

Consequently, at every time since the onset of the mid-Pleistocene uplift, the Ardennian drainage network has been divided in three parts of distinct erosional behavior (Fig. 6): (1) the knickzones travelling up the branches of the drainage network and representing the transient response to uplift, where incision results from the longitudinal displacement of the erosion wave, (2) the regions downstream of the knickzones, where the river profiles progressively achieve equilibrium by ubiquitous vertical incision, and (0) the upstream regions not yet attained by the knickzones, where the whole landscape is still in steady state under very low denudation rates.

In this scheme, the glacial-interglacial cycles still impose the temporal frame determining the periods favorable to incision. During glacials, the whole drainage system, up to the smallest streams, was cluttered up with hillslope material, so that bedrock channel erosion, including knickpoint propagation, was temporarily impeded. Incision episodes mainly took place at the warm-cold transitions.

Figure 6. Schematic illustration of the terrace staircase created by and after the propagation of an erosion wave, with a higher vertical spacing between the first two terrace levels reflecting the height of the migrating knickpoint, then slower general incision from the part of the profile situated downstream of the knickzone. The stippled rectangles represent alluvial deposits preserved as terraces.



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