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Article

Fluvial terraces of the Amblève: a marker of the Quaternary river incision in the NE Ardennes massif (Western Europe)

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with 7 figures and 2 tables

Summary. The geomorphological analysis of the terraces of the Amblève, an Ardennian subtributary of the Meuse, allows us to reconstruct eleven distinct levels (T1 to T11). Like those of most rivers draining the Ardennes massif, the Amblève terrace profiles also converge in the upstream direction. Moreover, the "Main Terrace" complex, widely recognized in the Rhine and Meuse systems (including their major tributaries draining the Ardennes-Eifel massif), has also been identified in the Amblève valley. However, the lack of terrace remnants in the ~ 10-km-long reach of the Quarreux gorge, combined with the knickpoint observed in the present-day long profile in this reach, leaves some uncertainty in the overall profile reconstruction. Despite the presence of a paleokarst filled by alluvial material in the lower Amblève and diversely dated between ~ 0,5 and ~ 1 Ma, firm chronological data about the Quaternary evolution of the Amblève are still lacking. Therefore, we base our discussion of the temporal evolution of the Amblève incision on geometrical correlations with dated terraces of the Meuse downstream of Liège.

1 *Introduction*

Fluvial terrace sequences constitute the main geomorphic feature to constrain river incision, itself triggered either by climatic fluctuations or by tectonic activity at a regional scale. Therefore, river terraces have been largely used as an indirect tool to study regional tectonic uplift (Antoine et al. 2000, Bridgland 2000, Maddy et al. 2000, Starkel 2003, Westaway et al. 2006), including the Quaternary uplift of the Rhenish shield (Meyer & Stets 1998, Van Balen et al. 2000, Westaway 2002). However, in the western part of the latter, namely the Ardennes massif, the terrace contribution to the knowledge of the tectonic uplift still encounters two major problems:

1. It suffers from a serious lack of reliable data to constrain the chronology of the incision in this part of the massif,
2. Although numerous terrace studies have been carried out in the Meuse valley in France (Harmand 1988, Harmand et al. 1995), Belgium (Macar 1938, Clairbois 1959, Pissart 1961b, 1974b, Juvigné & Renard 1992, Pissart et al. 1997) and the Netherlands (Felder et al. 1989, Van den Berg 1996), and in its major tributaries draining the Ardennes massif (*Ourthe:* Alexandre 1957, Juvigné 1964, Cornet 1995, *Vesdre:* Chapelier 1957, Demoulin 1987a; *Lesse:* Seret 1957, *Semois:* Pissart 1961), the Amblève River, which crosses the NE part of the Ardennes massif, corre-

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sponding to the area of supposed maximal recent uplift, has never been the purpose of a systematic study of its terraces.

The aim of the present work is thus to provide a consistent reconstruction of the Quaternary terrace profiles through the entire Amblève valley, even though a few authors analyzed the terrace remnants only in short valley reaches of the Amblève (Ek 1957, Monjoie 1968, Juvigné et al. 2005). Afterwards, we will correlate our terrace profiles with those of the lower Meuse and we will also try to extrapolate the few dates available for some terraces of the Meuse toward a tentative chronology of the Amblève valley incision.

2 *Study area*

2.1 *Localization of the Amblève catchment*

Located in eastern Belgium, the Amblève River is a second-order tributary of the Meuse draining the northern part of the Ardennes massif (fig. 1A). Flowing in an E-W

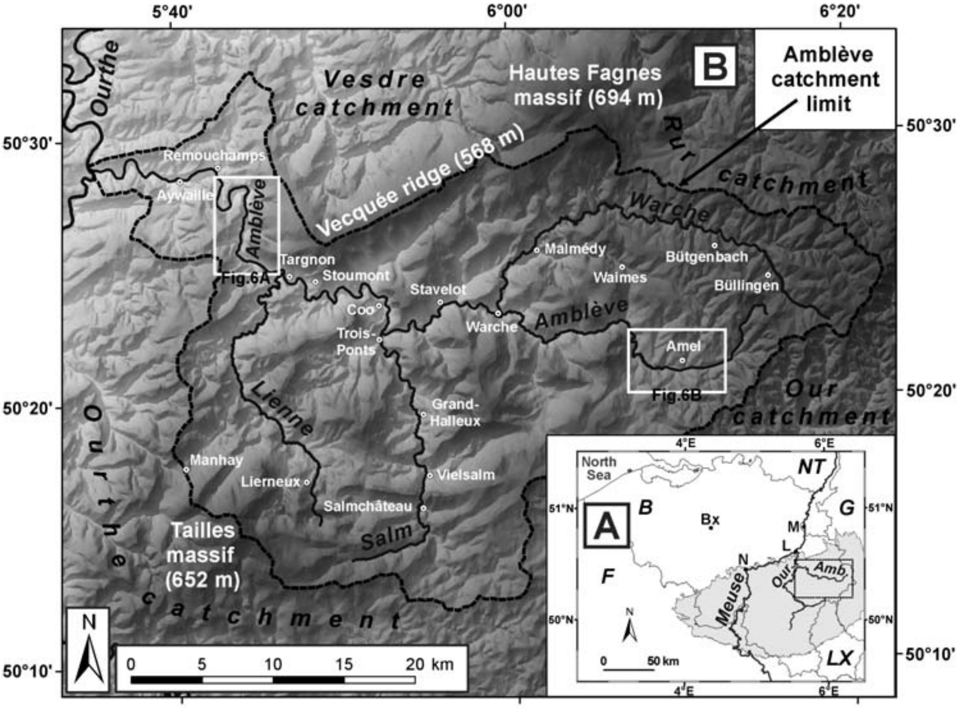

Fig. 1. **A.** Localization of the Amblève River draining the northern part of the Ardennes massif delimited by the grey area (B: Belgium; Bx: Bruxelles; F: France; G: Germany; L: Liège; LX: Luxemburg; M: Maastricht; N: Namur; NT: Netherlands; V: Verviers). **B.** Orography of the Amblève catchment delimited by the dashed black line. Both grey rectangles refer to the localization of the cross sections presented in figure 6.

general direction, the Amblève is about 90 km long with a difference in elevation of about 500 m between the source (~ 600 m) and the confluence (~ 100 m), i. e., an average longitudinal slope of ~ 5.5 ‰. The Amblève drainage area amounts to ~ 1070 km^2 at the confluence with the Ourthe River, the main Ardennian tributary of the Meuse. To the north, the Hautes-Fagnes Plateau and its extension to the SW, the Vecquée Ridge, separate the Amblève catchment from the Vesdre (NW) and Rur (NE) catchments (fig. 1B). To the south-east, the Amblève catchment adjoins the Our catchment, a tributary of the Mosel, while the Tailles Massif separates it from the Ourthe catchment to the south-west. The Amblève has one major right-side tributary, the Warche, and two major left-side tributaries, the Salm and the Lienne (fig. 1B).

2.2 *Geological setting*

The Amblève catchment extends on three structural units of the Palaeozoic Ardennes massif: the Stavelot Massif, the Ardennes Anticlinorium and the Dinant Synclinorium. The Amblève has its source in the lower Devonian of the Ardennes Anticlinorium then crosses westwards (> 50 km) the Cambro-Ordovician Stavelot Massif. Afterwards, it flows briefly in the Ardennes Anticlinorium again before ending in the Carboniferous of the Dinant Synclinorium (fig. 2). Because of their differential resistance to erosion, the various rock types present in the basin greatly influence the general valley morphology and the terrace distribution in the Amblève and its main tributaries. A brief description of the rocks cropping out in the Amblève catchment appears thus very useful.

2.2.1 *The Stavelot Massif*

The Devillian (Dv) and Revinian (Rv) formations of the Stavelot Massif are mostly made of quartzites and slates. However, the quartzite/slate proportion is much higher in the Revinian than in the Devillian (fig. 2). Moreover, the Rv quartzites are less weathered and more resistant to erosion than the Dv quartzites. Morphologically, this translates as Rv ridges (Vecquée ridge) opposed to Dv depressions (Bellevaux-Ligneuville and Grand-Halleux depressions respectively in the Amblève and Salm valleys, fig. 1). The Salmian (Sm) formations are composed of slates and quartzitic slates, the particularly erodible slates of the lower Salmian determining marked depressions. North of the Amblève, Permian conglomerates occupy the ENE-WSW trending Malmedy graben. Owing to the weak resistance of these carbonate conglomerates, the graben is morphologically depressed; it is drained by the Warche and the Eau Rouge.

2.2.2 *The Ardennes Anticlinorium*

Encircling the Stavelot Massif, the Lochkovian of the Ardennes Anticlinorium is characterized by a heterogeneous lithology dominated by highly resistant conglomerates and arkoses that contrast with the more erodible slates of the lower Salmian, creating a prominent scarp. The sandy and quartzitic Praguian formations display homogenous resistance to erosion, comparable to that of the Lochkovian rocks. By contrast, the Emsian and Eifelian sandstones, shales and conglomerates are again very heterogeneous.

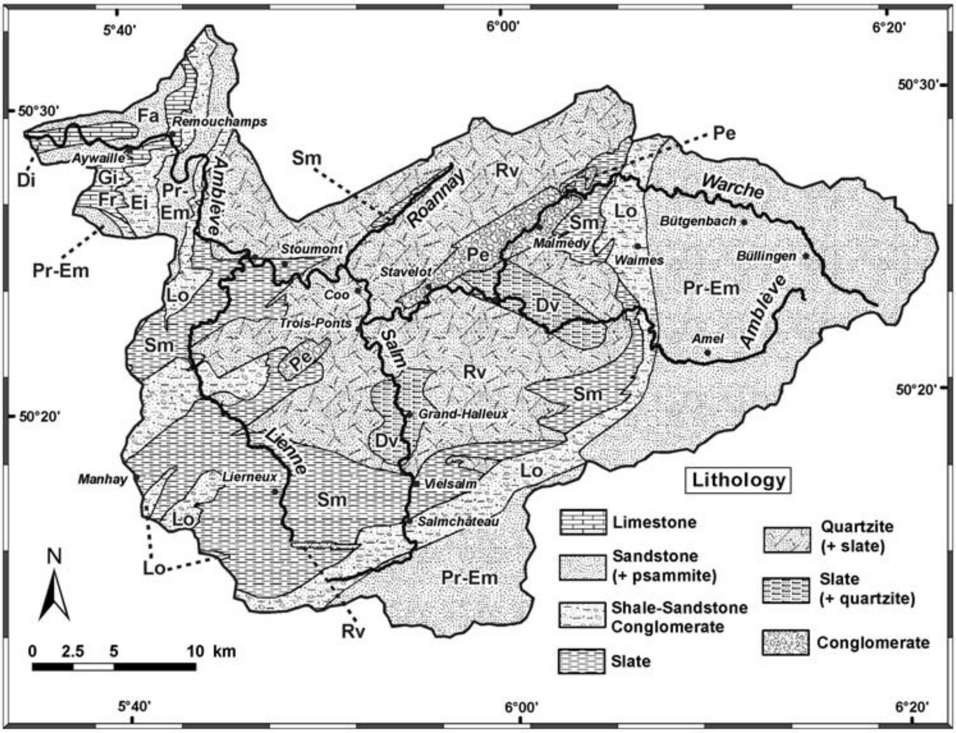

Fig. 2. Amblève catchment lithology. *Stavelot Massif (Cambro-Ordovician)* = Dv: Devillian; Rv: Revinian; Sm: Salmian; Pe: Permian. *Ardennes Anticlinorium (lower and middle Devonian)* = Lo: Lochkovian; Pr-Em: Praguian-Emsian; Ei: Eifelian. *Dinant Synclinorium (middle and upper Devonian and Carboniferous)* = Gi-Fr: Givetian-Frasnian; Fa: Famennian; Di: Dinantian.

2.2.3 *The Dinant Synclinorium*

The Givetian and Frasnian of the Dinant Synclinorium are mainly constituted of limestones, with subordinate shales. The Givetian limestones are strongly karstified. In the westernmost part of the catchment, the alternation of Famennian sandstones and Dinantian limestones determines a succession of ENE-WSW trending smooth ridges (anticlines) and depressions (synclines).

2.3 *Main characteristics of the Ardennian river terraces*

According to Pissart (1961, 1974b), 12 terrace levels of the Meuse River may be distinguished in its course across the Ardennes massif. At the northern margin of the massif, downstream of Liège, Juvigné & Renard (1992) recognized 23 distinct levels while Van den Berg (1996) identified up to 31 levels in the area of Maastricht (Netherlands). In comparison, the Rhine valley shows 15 successive terrace levels

(2 Pliocene and 13 Pleistocene) in its crossing of the Rhenish massif between Bingen and Bonn (Boenigk & Frechen 2006).

If the terrace sequence of the Meuse is strongly variable depending on the reach of the valley considered, the main Ardennian tributaries of the Meuse also have different numbers of terrace levels: 8 in the Semois (Pissart 1961), 10 in the Lesse (Seret 1957), at least 10 in the Vesdre (Chapelier 1957, Demoulin 1987a) and up to 21 in the Ourthe (Cornet 1995). However, the terrace longitudinal profiles of these Ardennian tributaries share the same characteristic: they generally converge in the upstream direction (Macar 1946, 1957a, Alexandre & Kupper 1976, Cornet 1995). Three possibly combined explanations have been proposed for this morphological feature.

(i) Macar (1946) suggested that, during valley downcutting, the hillslopes grew in such a way that the material delivered to the valley bottom increased in size and volume. In order for river transport to keep pace with this increased sediment supply, the river competency was reinforced through steepening of the longitudinal slope.
(ii) Another hypothesis considers that, as fluvial erosion increases downstream, so does crustal unloading, and the more pronounced isostatic rebound results in a greater downstream uplift and a progressive flattening of the successive paleo-floodplain profiles (Quitzow 1974).
(iii) Finally, Cornet (1995) argued that the meander development during river incision might be partially responsible for an apparent decrease of the longitudinal slope of the older terraces. This artefact would result from the projection of less sinuous, hence shorter, older long profiles on a longer, widely meandering current profile.

Another main characteristic of the terrace staircase of the valleys incising the Rhenish shield is the presence of a well-developed terrace level, the so-called Main Terrace, which has been widely recognized in the Rhine and Meuse valleys (Macar 1938, Boenigk 1995, Hoselmann 1996, Van Balen et al. 2000) and in their major tributaries draining the Ardennes-Eifel massif (Macar 1957a, Meyer & Stets 1998). According to Juvigné & Renard (1992), the Main Terrace level is generally represented by a complex of several levels located very close to each other in elevation. In a typical cross-section of most valleys of the Rhenish shield, this terrace (or terrace complex) corresponds to the sharp morphological transition zone (fig. 3) between a broad, gently sloping upper part characterized by wide terrace surfaces and a narrow lower part with steeper slopes and more confined and scarcer terraces (Hoselmann 1996, Meyer & Stets 1998, Van Balen et al. 2000, Houtgast et al. 2002).

3 *Methodology*

The terrace mapping was carried out through analysis of aerial photographs at the ~ 1:18,500 scale and careful field examination of all identified terrace remnants. The benches on which no fluvial gravel was observed in the highest part of the valley slopes have been interpreted as traces of pre-Quaternary planation surfaces (Alexandre 1958) and are not included in the study.

Plotting the terrace data against the present-day long profile of the river and interpolating successive terrace levels by geometric correlation between nearby remnants of similar relative altitude is classical, though often delicate. This kind of pro-

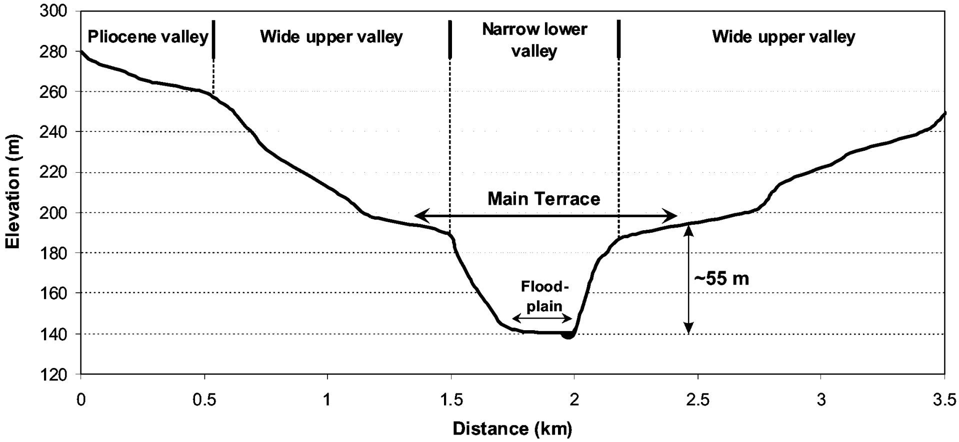

Fig. 3. Cross section of the Vesdre valley (northwards of the Amblève catchment) in the neighborhood of Verviers showing the Main Terrace level which corresponds to the sharp morphological transition zone between a broad, gently sloping upper part and a narrow lower part with steeper slopes.

file reconstruction suffers generally from the uncertainties associated with the vertical and horizontal positioning of the remnants. The horizontal uncertainty depends on how the remnant is projected on the current channel and may amount sometimes to several hundreds of metres, e. g., for higher terraces located in the loop of an elongated meander. The vertical uncertainty amounts often to a few metres, increasing when the contact between gravel and bedrock cannot be observed or when the terrace topography is irregular or displays a transverse slope.

Two reference levels, that is, either the terrace top or the gravel/bedrock contact, may be used to determine the relative altitudes of the terraces. Here, we chose the terrace top for two main reasons. Firstly, it is much more easily identified. Secondly, the gravel/bedrock contact may also be quite irregular (e. g., Dewez 1998, Juvigné et al. 2005). According to Houtgast et al. (2002), mapping the top of the terrace deposits would even provide a more accurate picture of the terrace morphology, as the height variability at the top is smaller than the height variability at the base.

Petrographical analyses of the gravels of several terrace levels were also carried out. Previous studies showed the usefulness of this technique to refine the terrace profile reconstructions (Boenigk & Frechen 2006, Cordier et al. 2006). For each deposit, random samples of 120 to 160 pebbles in the 4–8 cm size class were examined.

4 *Results: the Amblève terraces*

4.1 *Terrace distribution, valley morphology and present-day longitudinal profile*

We collected a dataset of more than 100 reliable terrace remnants in the Amblève valley. Their varying spatial density, related to the changing valley morphology, justifies the distinction of four successive valley reaches (fig. 4).

4.1.1 *Lower reach*

The highest concentration of terrace remnants is found in the lower course of the valley, where the river flows across the western margin of the Ardennes Anticlinorium and the Dinant Synclinorium. Most remnants belong to the main and higher terraces with relative elevations between 50 and 110 m. A noteworthy concentration of extended very high terraces (relative elevation > 75 m) is observed in the area of Aywaille (fig. 5), the highest remnants (HT-L: 125 m relative elevation; HT-U: 140 m relative elevation, figs. 4, 5) being located north of Aywaille at the limit between Carboniferous limestones and Famennian psammites.

The fewer remnants of middle and lower terraces (relative elevation between 7 and 35 m) are generally localized on the inner bank of meanders. They are of smaller size and the lowest terraces display a fairly marked transversal slope (fig. 6A, C).

4.1.2 *Quarreux gorge*

In the next reach of the Quarreux gorge, the river flows across a zone of Variscan faults at the contact between the Revinian quartzites of the Stavelot Massif and the

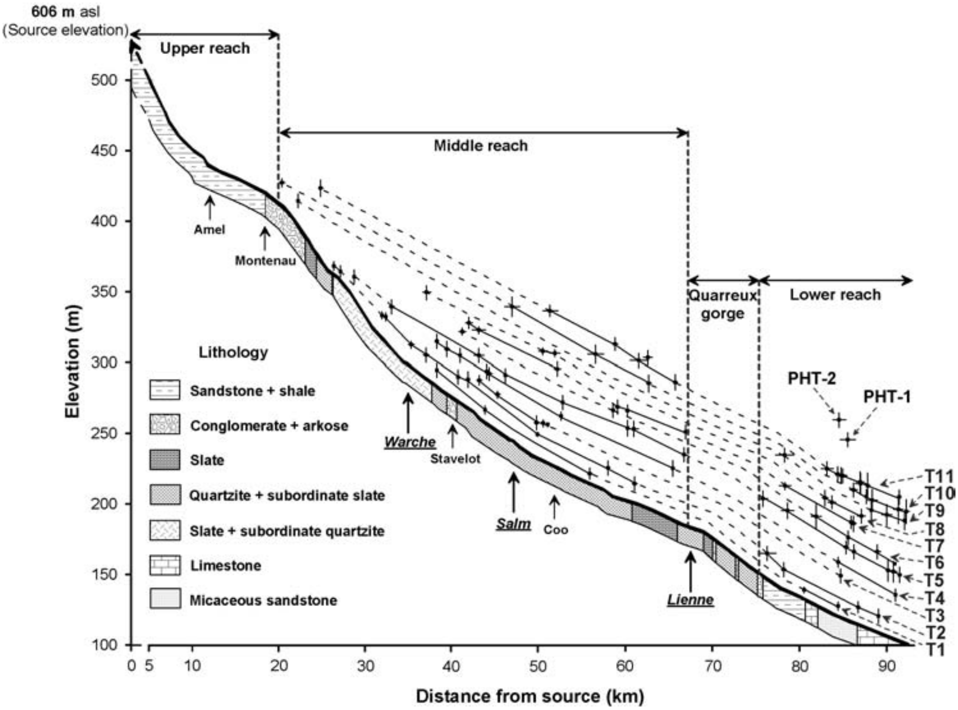

Fig. 4. Amblève longitudinal terrace profile plotted on the present-day long profile with lithology. Each terrace remnant is affected by a double error bar (planimetric and altimetric uncertainties). T1 to T11: terrace levels; HT (U&L): highest terraces (upper and lower); solid line: undoubted terrace correlation; dashed line: uncertain terrace correlation.

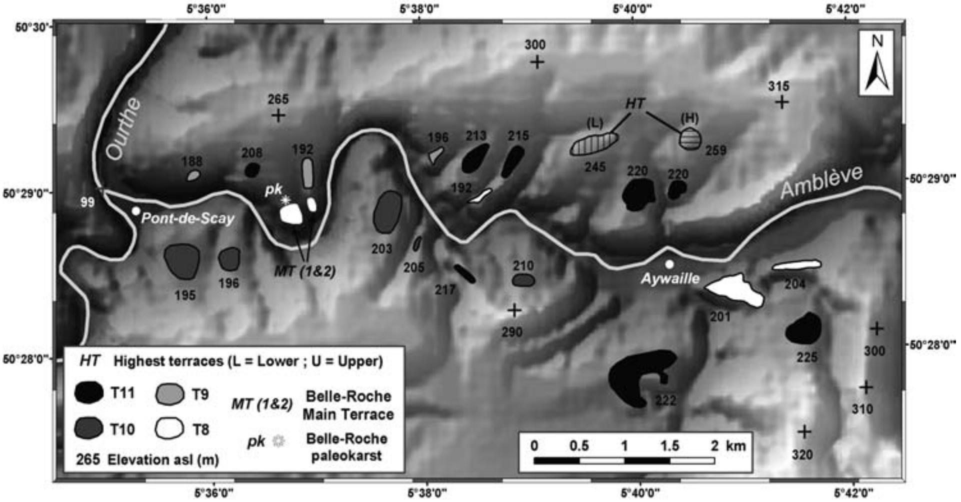

Fig. 5. Concentration of very high terraces (T8 to T11 whose relative elevation above the present-day floodplain is greater than 75 m) in the lower reach of the Amblève and localization of the *Belle-Roche* terraces (Main Terrace level and paleokarst).

Lochkovian conglomerates of the Ardennes Anticlinorium. It has incised a narrow, locally > 250 m deep gorge with a narrow or even absent floodplain (fig. 6A, C). No terrace remnant is preserved on the steep hillslopes of this 8-km-long reach (fig. 4), which is also marked by a sharp knickpoint in the present longitudinal profile (fig. 4). This irregularity of lithological origin in the present profile strongly complicates the correlations between the terraces located downstream and upstream of the gorge and thus affects the reliability of the overall profile reconstruction (see 4.2.1).

4.1.3 *Middle reach*

Terrace remnants reappear upstream of the Quarreux gorge and the Lienne confluence (fig. 4). Several high terraces are located in the Stoumont-La Gleize area and a well-preserved sequence is observed in the meander of Coo. Upstream of the Salm confluence, another concentration, mainly of low and middle terraces, is preserved on the right valley-side near Stavelot. A few terrace remnants still exist upstream of the Warche confluence, up to Montenau. The contrast observed in the middle reach of the valley between extended, well levelled higher terraces and narrow lower terraces replicates that already described in the lower reach. Finally, the current longitudinal profile is characterized by another clearly marked knickpoint just downstream of Montenau (fig. 4).

4.1.4 *Upper reach*

This ~ 20 km-long river course is devoid of terrace remnants (fig. 4). However, the Montenau-Amel reach displays a typical broad valley bottom with gentle hillslopes and an up to 500-m-wide present floodplain (fig. 6B, C). Moreover, the river gradi-

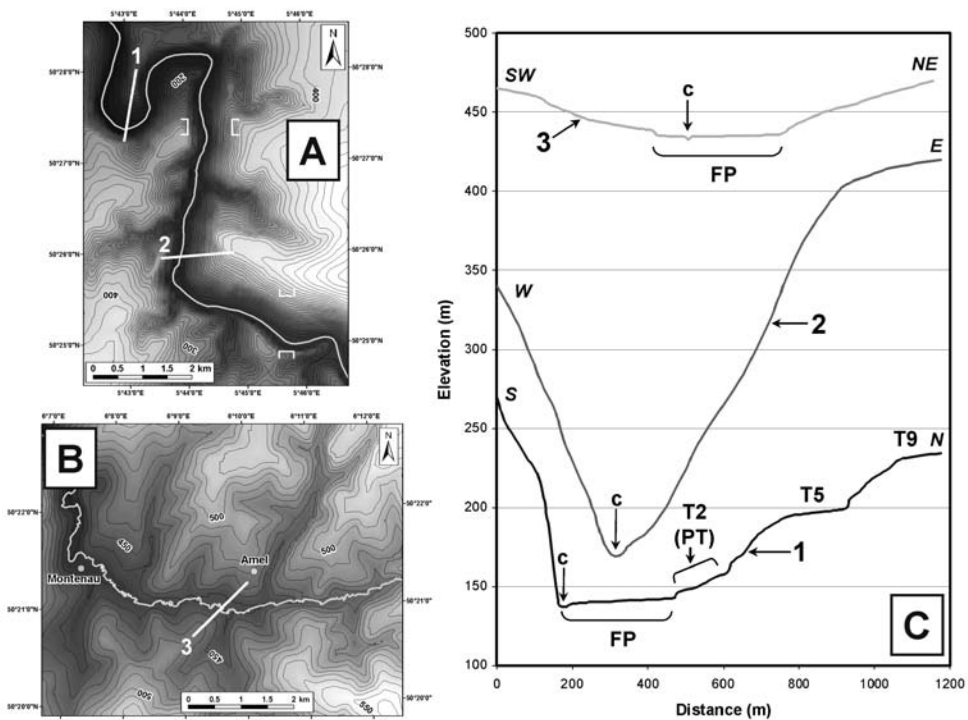

Fig. 6. Localization and topographic profiles of three cross-sections of the Amblève valley. **A.** Lower reach/Ham meander (1) and Quarreux gorge (2) cross sections;] [: Quarreux gorge reach. **B.** Upper reach cross section (3) in the area of Amel. **C.** Topographic profiles of the cross sections. c: current channel of the Amblève River; FP: present-day floodplain; PT: polygenic terrace and T2, T5 and T9 refer to terrace levels.

ent decreases dramatically (fig. 4), leading to a major change in the fluvial style of the river, which develops numerous free meanders (fig. 6B). Then, from Amel up to the source (606 m asl), the gradient increases again.

4.2 *Terrace profile reconstruction*

Eleven terrace levels, numbered from the lowest (T1) to the highest (T11), have been recognized in the Amblève valley (fig. 4). This is slightly more than the nine levels identified by Ek (1957) in the lower reach. The lowermost level identified on aerial photographs (T1) is located ~ 6–7 meters above the current floodplain (fig. 5), while the average relative elevation of the oldest level (T11) slightly exceeds 100 m (~ 103–105 m). An occasionally very low terrace level (~ 1–1,5 m above the current floodplain) has been observed in some places but it is hardly recognizable on aerial photos and it is not considered in this reconstruction.

4.2.1 *Shape of the terrace longitudinal profiles*

As in many other rivers of the Ardennes massif (Macar 1957, Alexandre & Kupper 1976, Cornet 1995), the Amblève terrace levels converge in the upstream direction (fig. 4). The profile reconstruction is carried out up to the Montenau knickpoint, upstream of which no terrace remnant is identified. The heterogeneous resistance to erosion of the locally outcropping rocks (Devillian and Salmian slates, Revinian quartzites, Lochkovian conglomerates) rules out a lithological cause of this knickpoint (fig. 4). Rather, the profiles of the highest terraces are in the exact prolongation of the current profile of the upstream reach, suggesting that the latter is inherited from these early Pleistocene floodplains. The knickpoint thus marks the place reached by the wave(s) of regressive erosion since the time incision started, leading to the abandonment of these paleofloodplains. The upstream propagation of the knickpoint has fairly preserved its original shape, so that its height (~ 100 m) still roughly corresponds to the amount of Quaternary incision in NE Ardennes.

Downstream of Montenau, profiles T2, T5, and, to a lesser extent, T11 display a wealth of terrace remnants. The favourable spatial distribution of these best-preserved levels within the terrace sequence is a major support to the whole reconstruction. However, in the absence of dating or stratigraphic markers, all levels suffer more or less from locally uncertain correlation. In this respect, the main problem was the total lack of terrace remnant in the Quarreux reach. Combined with the presence of a lithological knickpoint in the river profile at the place where it crosses resistant Revinian quartzites and Lochkovian conglomerates, this broke every possible link between the downstream and upstream parts of the terrace profiles. We solved this problem by considering that a lithological knickpoint is fixed in space, so that we assumed that all terrace profiles were affected by a similar local irregularity (fig. 4).

4.2.2 *Specific features of T1–T2 and T5*

The two lowest terrace levels of the Amblève (T1 & T2) show the same morphological characteristics. They are of limited extent, longitudinally elongated and they slope markedly down to the river. The latter feature might result from either lateral shifting during incision (polygenic terrace, Cornet 1995) or reworking of surficial deposits, e. g. by solifluction. Although Ek (1957) suggested a lithological control of polygenic terraces, the uniform appearance of T1 and T2 through the whole valley indicates that they rather responded to the climatic scheme recently proposed by Bridgland & Westaway (2008) for the interglacial/glacial transition (cooling phase), with simultaneous downcutting and aggradation.

Most terrace remnants of T5 are well-levelled, hectometre- to kilometre-sized benches showing often unusually thick fluvial deposits (> 6–8 m). This makes T5 a particularly well-preserved level at relative elevations of ~ 50 m. Through the main terrace level of the Ourthe valley, also at ~ 50 m relative elevation near the Amblève confluence (Cornet 1995), the T5 terrace of the Amblève may be geometrically correlated with the main terrace complex of the lower Meuse (Juvigné & Renard 1992) (see 5.2.1).

However, although the typical cross-section of many valleys inside the Rhenish shield situates the main terrace at the marked hinge between a broad, gently sloping upper valley and a narrow, steep-sided lower valley (Hoselmann 1996, Meyer & Stets 1998, fig. 3), this transition is not so conspicuous in the Amblève valley, where the sharpest morphological step is located higher (especially in the middle reach) and corresponds to an earlier episode of incision, probably during the early Pleistocene or even at the Tertiary/Quaternary transition.

4.2.3 *Quartz content of the Amblève terraces*

Petrographic analyses have been carried out in several terrace remnants of the Amblève in order to support the profile reconstruction. The most striking result is the consistent decrease of the quartz content from high terraces to low terraces. As shown in table 1, the highest remnant (HT-U) preserved in the lower Amblève and the T11 terrace remnants have quartz contents greater than 50 %, whereas the gravel of T4 to T6 terraces contain between 12 and 22 % quartz. A similar evolution of the quartz content was also observed in the Ourthe terraces (table 1). Juvigné & Renard (1992) and Juvigné et al. (2005) have interpreted it as a consequence of the progressive dilution of residual quartz gravel derived from the Tertiary deep weathering mantle veiling the Ardennes interfluves in the fresh rock material originating from the incising valley itself.

Unfortunately, the quartz content variations show only a general trend, without clear breaks that could be used as stratigraphic markers. This is all the more true as variations within a particular terrace level may also be high, and the uncertainty associated with our counting amounts sometimes to 10 % (table 1). However, it is possible to separate two groups of terraces, respectively with more and less than ~ 25 % quartz. Interestingly, the main terrace (T5) belongs to the second group, poor in quartz, which might suggest a relatively young age for this level.

5 *Discussion: terrace correlations and chronology of the Amblève incision*

5.1 *Deficiency of chronological data in the Amblève valley*

Besides the morphological reconstitution of the Amblève terrace profiles, the river incision chronology has still to be constrained. Unfortunately, reliable chronological data are lacking. Indeed, only two kinds of age information are available in the Amblève valley:

– The filling of a cave located two kilometres upstream of the Ourthe confluence (*Belle-Roche*, fig. 5), has been investigated by different dating methods. Perched ~ 58 m above the current floodplain and thus belonging to T6, the cave sediments starts with ~ 1 m of alluvial gravels of the Amblève (fig. 7A) overlaid by a complex of run off and solifluction deposits made of clayey silts including mainly limestone pebbles and blocks, with some reworked gravel and numerous macrofauna remains (and subsidiary flints). Based on the fauna, Cordy (1982) ascribed this complex to OIS 13 or 15, and Cordy et al. (1993) finally proposed an age of 0,5 ± 0,07 Ma (fig. 7B). Moreover, an U/Th dating of a speleothem capping this complex gave an age > 0,35 Ma (fig. 7B). Finally, paleomagnetic data from the cave deposits (Cordy et al. 1993) and the Main Terrace remnant (MT1, figs. 5, 7C) located a few metres below the cave (Juvigné et al. 2005) showed all a normal polarity (fig. 7B, C), except one

Table 1. Quartz content of Meuse catchment terraces. TM: “Trainée Mosane” terraces; GL: “Graviers Liégeois” terraces; (#): terrace levels classification of Cornet (1995); (*): data from Pissart (1964); (**): data from Juvigné et al. (2005).

Terrace Name	Location	Elevation (m)		Terrace level	Pebble size range (cm)	Quartz-% (± 2σ)
		asl	realtive			
Hermée	Lower Meuse	114	65	MT	4 to 6	**24** (± 4.2)
Rabosée	Lower Meuse	174	115	TM	4 to 6	**51**
Bruyères	Lower Meuse	177	115	TM	4 to 6	**58** (± 9.8)
Mons-lez-Liège	Lower Meuse	185	120	TM	4 to 6	**41**
Bierset	Lower Meuse	195	126	TM	4 to 6	**57**
Beauregard (*)	Meuse/Ourthe interfluve	~ 260	~ 180	GL	4 to 6	**52** (± 7.1)
Sart Haguet (*)	Meuse/Ourthe interfluve	~ 260	~ 182	GL	4 to 6	**47** (± 7.1)
Sart Tilman (*)	Meuse/Ourthe interfluve	~ 230	~ 157	GL	4 to 6	**50** (± 7.1)
Colonster	Lower Ourthe	82	2	T1 (#)	4 to 6	**11** (± 4.1)
Colonster	Lower Ourthe	132	52	T5 (#)	4 to 6	**13** (± 4.7)
Colonster	Lower Ourthe	176	96	T9’(#)	4 to 6	**28** (± 6.4)
Colonster	Lower Ourthe	188	108	T11 (#)	4 to 6	**39** (± 6.9)
Trou Bottet	Lower Ourthe	190	95	T10 (#)	4 to 6	**52** (± 15.2)
Belle-Roche (Magain Farm)	Lower Amblève	207	106	T11	2.3 to 6.4	**63** (**)
Belle-Roche Paleokarst	Lower Amblève	158	57	T6	2.3 to 6.4	**14** (**)
B-R MT 1&2	Lower Amblève	152	51	T5	2.3 to 6.4	**14–18** (**)
Henumont	Lower Amblève	188	61	T6	4 to 8	**22** (± 6.6)
Rouvreux	Lower Amblève	196	89	T9	4 to 8	**36** (± 7.9)
Florzé	Lower Amblève	220	103	T11	4 to 8	**59** (± 8.1)
Rouvreux (Gotale)	Lower Amblève	212	104	T11	4 to 8	**53** (± 8.3)
HT (U)	Lower Amblève	259	139		4 to 8	**69** (± 7.4)
Stavelot	Middle Amblève	305	25	T4	4 to 6	**12** (± 6.5)
Lodomez	Middle Amblève	370	77	T9	4 to 6	**25** (± 8.8)

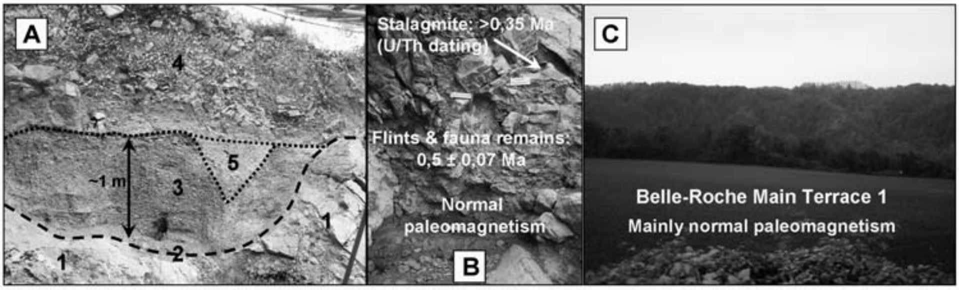

Fig. 7. *Belle-Roche* terraces in the lower Amblève. Section in the *Belle-Roche* paleokarst. 1: limestone bedrock (Dinantian); 2: former channel; 3: fluvial gravel; 4: overlying deposits (mostly run off and solifluction deposits) containing fauna remains (and flints); 5: postdepositionnal deformation. **A.** Detailed view of the overlying deposits characterized by a normal paleomagnetism and the presence of fauna remains and flints dated around 0,5 ± 0,07 Ma (Cordy et al. 1993) and including a speleothem older than 0, 35 Ma (U/Th dating). **B.** Belle-Roche Main Terrace 1 seen from the paleokarst (mostly normal paleomagnetism).

sample at the base of MT1, which displayed a questionable intermediate polarity (Juvigné et al. 2005).

– Bustamante Santa Cruz (1974) and Juvigné (1979) found minerals of the Rocourt tephra, dated between 74 and 90 ka (Pouclet et al. 2008), in a very low terrace situated ~ 1 m above the present-day floodplain in the Coo meander, near Trois-Ponts (fig. 1B). However, this tephra was absent in remnants of T1 and T2 near Remouchamps. Consequently, Juvigné (1979) considered these terraces older than the Rocourt tephra and concluded that the recent incision of the Amblève in the reach between Coo and Aywaille was in the range 1–6 m since 74–90 ka.

5.2 *Correlations with the lower Meuse terrace sequence*

Owing to the poor local age information, constraining the incision chronology of the Amblève requires to correlate it with that of better dated valleys. In this respect, the well-developed terrace sequence of the Meuse in the Liège-Maastricht area has been studied extensively (Macar 1938, Huxtable & Aitken 1985, Felder & Bosch 1989, Juvigné & Renard 1992, Van Kolfschoten et al. 1993, Van den Berg 1996, Houtgast et al. 2002, Westaway 2002) and provided age data for some terrace levels, in particular the Main Terrace complex.

5.2.1 *Geometrical correlations*

Table 2 describes the geometrical correlations of terrace levels between the Amblève and the lower Meuse trough the lower Ourthe on the basis of our Amblève data and a literature compilation for the Ourthe and lower Meuse. However, two morphological features strongly complicate this correlation. Firstly, the number of terrace levels is different in the different valleys: 11 (13) in the Amblève valley, 21 in the lower Ourthe (Cornet 1995) and 23–31 (depending on the authors) in the lower Meuse

Table 2. Terrace correlations between the Amblève, the Ourthe and three reaches of the Meuse (Ardenne, Liège and Maastricht), including the ages of two (or three) levels in the lower Meuse. (^) : thermoluminescence and paleontological remains dating ; (#) : paleomagnetic dating ; (§): U/Th and U/U dating ; BR MT1&2 : Belle-Roche main terrace 1 and 2 ; BR pk : Belle-Roche paleokarst ; HT (L) : lower highest terrace ; HT (U) : upper highest terrace. References : 1&1' : Pissart, 1974 and Pissart et al., 1997 ; 2 : Felder & Bosch, 1989 ; 3 : Juvigné & Renard, 1992 ; 4 : Van den Berg, 1996 ; 5&5' : Cornet (1987,1995) ; 6 : Renson et al. (1999) ; 7 : Juvigné et al. (2005).

Meuse							**Ourthe**	**Amblève**			
1&1'	**2**	**3**	**4**	**Age**							
(Ardennes)	(Maastricht)	(Liège)	(Maastricht)	MIS **(2)**	Measured		**5&5'**	**This paper**	**1'&5'**	**6**	**7**
	Oost Marland 2	Herstal	Geistigen	0.013			T1	**T1**			
	Oost Marland 1		Mechelen a/d Maas								
	Gronsveld	Jupille	Eisden-Lanklaar	0.12			T1				
T1	Caberg		Caberg-3	0.26	0.25 Ma (^)						
			Caberg-2								
		Caberg	Caberg-1				T1"	**T2**			
T2	Rothem-2	Trou-Louette	Rothem-2	0.32			T2				
	Rothem-1	Cornillon	Rothem-1	0.43			T2'	**T3**			
T3	Gravenvoeren	Fouron-le-Comte	Gravenvoeren	0.52			T3	**T4**			
	St Pietersberg-2	Lorette	St Pietersberg-3	0.61			T4				
			St Pietersberg-2								
T4	St Pietersberg-1	Hermée	St Pietersberg-1	0.7	< 0.78 Ma (#)	0.62–1.1 Ma (§)	T5	**T5/BR MT 1&2**	BR pk		BR MT1&2
T4'	St Geertruid-2	Eben St Geertruid	St Geertruid-3	0.89			T5'	**T6/BR pk**		BR pk	

	St Geertruid-1	Bombaye	St Geertruid-2	1.05		T6	**T7**	BR pk
T5		Wonck	St Geertruid-1					
	Valkenburg-2	Lixhe	Valkenburg-2	1.19		T7		
T6	Sibbe	Trembleur	Sibbe-1	1.41		T9		
	Margraten	Rabosée	Margraten	1.56		T9'	**T9**	
T7	Simpelveld	Bruyères	Simpelveld	1.8				
T8	Noorbeek	Houlpaix	Noorbeek	1.93		T10	**T10**	
	Crapoel	La Havée	Crapoel	2.03		T11		
		Haute-Saive (TM)				T12	**T11**	
T9	Kosberg	Rocourt (TM)	Kosberg	2.2		T13		
T10	Brunssum	Beyne-Heusay (TM)	Brunssum			T14	**HT (L)**	
							HT (U)	
						Sart-Tilman (GL)		

(Juvigné & Renard 1992, Van den Berg 1996). Secondly, the vertical amplitude of the terrace staircase also varies in the different reaches of these rivers: it amounts ~ 112 m in the middle Amblève, ~ 103 m in the lower Amblève (up to 140 m if HT-U is included), ~ 125 m or even ~ 137 m in the lower Ourthe and ~ 135 m in the Meuse at Liège (including the 'Trainée Mosane' terraces). As a systematic "one-to-one level correlation" between the Amblève and the lower Meuse terrace profiles is thus impossible, we based our analysis on the most easily identifiable and/or best preserved terrace levels, i. e., especially the Main Terrace level. In the lower Meuse, the latter corresponds to the Hermée terrace of the Liège area (Juvigné & Renard 1992) and the St Pietersberg terraces of the Maastricht area (Felder & Bosch 1989, Van den Berg 1996) with relative elevations varying between 63 and 67 m. This complex of terraces was correlated to T5 in the lower Ourthe (Cornet 1995), which is itself easily correlated with our level T5 in the Amblève (table 2). In the same manner, the lowest level in the Amblève (T1) was geometrically correlated to the Herstal and Geistigen terraces in the lower Meuse (table 2), all of them being located around 6–7 m above the current floodplain.

5.2.2 *Age control*

5.2.2.1 *Main Terrace complex/level*

Within the terrace sequence of the lower Meuse, the age of the Main Terrace complex (St-Pietersberg terraces) has been largely debated. Felder & Bosch (1989) and Van den Berg (1996) correlated their respective terrace sequence in the Maastricht area with the OIS and they elaborated corresponding age models for the evolution of the lower Meuse since the beginning of the Quaternary. Felder & Bosch (1989) distinguished two levels among the St-Pietersberg terraces (table 2) and Van den Berg (1996) individualized three levels. They ascribed them respectively to OIS 15/16 + 17/18 (~ 0.61 to 0.7 Ma) and OIS 20 to 26 (~ 0.78–0.95 Ma). However, these models are questionable because they assume that terrace formation in the lower Meuse is systematically related either to warming conditions (glacial/interglacial transition, Felder & Bosch 1989) or glacial conditions (Van den Berg 1996). Yet, several studies have shown that downcutting and aggradation can also occur under other climatic conditions, in particular cooling conditions (interglacial/glacial transition, Bridgland 2006, Bridgland & Westaway 2008). Revisiting the van den Berg's terrace staircase, Westaway (2002) correlates now the St-Pietersberg terraces with OIS 18 to 22 (~ 0.72–0.87 Ma).

In the lower Amblève, as the sediments trapped in the *Belle-Roche* paleokarst and the underlying gravels (T6) have been dated around 0,5 Ma (Cordy et al. 1993), the Main Terrace level (T5) should be younger than 0,5 Ma. According to Cordy et al. (1993), the normal polarity found in the paleokarst deposits points to the Brunhes Period. However, on the basis of their terrace correlation with the lower Meuse, Renson et al. (1999) and Juvigné et al. (2005) attributed the normal paleomagnetism in the paleokarst to the Jaramillo event (0,99 to 1,07 Ma) and concluded that the Main Terrace at Belle-Roche was deposited probably just after the Matuyama/Brunhes transition (0,78 Ma). As the Belle-Roche paleomagnetic data are not enough discriminant and the < 0.5 Ma age of the Belle-Roche main terrace is strongly supported by the rich local fossil fauna, an older age of this level remains nevertheless highly controversial despite any good geometrical correlation with remote data.

5.2.2.2 *Lower terraces*

In the area of Maastricht, the Caberg–3 terrace has been dated around 0,25 Ma (table 2) by thermoluminescence (Huxtable & Aitken 1985) and paleontological remains (Van Kolfschoten et al. 1993). Unfortunately, this terrace has no geometrical equivalent in the Amblève valley but it is situated between T1 and T2. Given that no trace of the Rocourt tephra has been found in the two lowest terrace levels of the Amblève, they have been interpreted older than 90 ka (Juvigné 1979). This does not contradict the 0.25 Ma age of the Caberg33 terrace. By contrast, a > 90 ka age of T1 is inconsistent with ascribing its geometrical Meuse equivalent at Maastricht, the Geistingen terrace, to OIS 2.

6 *Conclusion*

The reconstruction of the Amblève terrace profiles has highlighted the following results:

– Four geomorphic sectors are distinguished along the Amblève valley. In particular, the 8-km-long Quarreux gorge causes a big gap in the terrace data and makes the profile reconstruction somewhat difficult.
– Eleven terrace levels have been recognized in the Amblève valley between 7–8 and > 100 m relative altitude. There is a clear trend towards a decrease of the quartz content from the high terrace to the low terrace gravels.
– Despite its good preservation and the extent of its remnants, the main terrace T5 is less well morphologically marked in the transverse profile of the Amblève than in that of other Ardennian valleys.

Although the available age data are contradictory, the most reliable of them suggest that the main terrace level could have been abandoned later in the Amblève valley than in the lower Meuse. This might have resulted from the delayed propagation of an incision wave within the Ardennian hydrographic network, starting around 0.7 Ma in the Meuse at Maastricht and reaching the Belle Roche site in the Amblève valley later than 0.5 Ma. However, further terrace age data in the Ardennian valleys are needed to support this hypothesis.

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