The Picturesque Ardennian Valleys: Plio-Quaternary Incision of the Drainage System in the Uplifting Ardenne

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Abstract

As a response to Late Cenozoic tectonic uplift of the Ardenne massif, the Meuse River and its drainage system deeply incised the landscapes of Southern Belgium. Well-preserved terrace staircases flanking the main Ardennian valleys show a break at the height of the Main Terrace Complex, whose younger level (YMT) marks the transition towards the steep-sided lower part of valley transverse profiles. Numerical ^{10}Be/^{26}Al dates obtained for the YMT in various places along the lower Meuse—lower Ourthe—Amblève line yield an age around 620 ka for the pulse of tectonic uplift responsible for increased incision rates and fast valley deepening. They also show diachronic abandonment of the YMT, indicating that post-YMT erosion invaded the drainage system through the migration of knickpoints originating in the $\sim$20 m base level lowering initially created at the margin of the en-bloc uplifted region. A study of knickpoints in modern long profiles of Ardennian rivers fully confirms this view. Assimilation of the new data imposes a revised model be proposed for river incision in the Ardenne. Integrating the climatic control with the various modes of tectonic control over river incision, this conceptual model offers a sounder frame of the Quaternary river system evolution in the Ardenne, also explaining observed cases of stream piracy. Basin average denudation rates published for the Ardenne are also briefly compared with valley incision rates.

10.1 Introduction

The spectacular scenery of the valleys of the Meuse (Maas in Dutch and German) and its tributaries, deeply incised in the Ardenne plateau and so poetically described by Hugo (1842), not only inspired world-renowned landscape painters such as J.M. William Turner but also soon attracted fathers of the geomorphological science such as Albert de Lapparent and William. M. Davis. Since the latter's precursory geomorphological study about the formation of the Belgian Meuse valley (Davis 1895), generations of geoscientists have investigated the Quaternary evolution of the drainage network in the Ardenne massif, focusing in particular on the geometrical and morphological correlations between river terrace levels and the sedimentological analysis of terrace deposits (e.g. Macar 1938; Alexandre 1957; Pissart 1961, 1974; Pissart et al. 1997; Rixhon and Demoulin 2010). The transverse profile of all major river valleys cutting into the Paleozoic basement widely exhibits a typical morphological

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transition between a broad, gently sloping Early Pleistocene valley characterized by extended terrace surfaces and a nested narrow, steep-sided Middle Pleistocene valley with more confined terraces (Fig. 10.1; Van Balen et al. 2000; Rixhon et al. 2011). This transition is materialized by a more or less ubiquitous complex of closely spaced and well-developed terrace levels, the so-called Main Terrace Complex, whose younger level, abbreviated hereafter to YMT, is located directly at the edge of the deeply incised lower part of the valleys (Fig. 10.1). Whilst this morphological hinge is also recognized in the Meuse valley (e.g., Juvigné and Renard 1992; Van Balen et al. 2000), it is particularly conspicuous in its main tributary valleys, such as those of the Ourthe and the Vesdre (Fig. 10.1; e.g., Rixhon et al. 2011). Furthermore, it is also observed in the Rhine drainage system throughout the adjacent Rhenish shield, and especially in the valleys of the Rhine and the Mosel in Germany (e.g. Boenigk and Frechen 2006). It was thus interpreted at the regional scale as the result of a pulse of uplift that affected the whole Ardenne/Rhenish massif for a while around the Early Pleistocene—Middle Pleistocene transition (Van Balen et al. 2000; Demoulin and Hallot 2009).

In the last two decades, many studies based on DEM analysis, numerical modelling, and modern dating methods provided substantial new insights into the spatial and temporal characteristics and the mechanisms of river incision in response to the massif's uplift, which led in particular to the abandonment of the 'YMT floodplain' in the Ardennian Meuse catchment. They encompassed (i) quantification of long-term denudation rates in the Meuse catchment (Van Balen et al. 2000; Schaller et al. 2004; Demoulin et al. 2009), (ii) numerical dating of river terrace sediments by terrestrial cosmogenic nuclides (Rixhon et al. 2011, 2014), and (iii) the modelling of knickpoint migration across the river network (Demoulin et al. 2012a, b; Beckers et al. 2015). The outcomes of these studies, supported by independent morphometric analyses of the drainage system (Sougnez and Vanacker 2011), were far-reaching enough to impose revisiting the accepted understanding of the controls on river incision and developing a new conceptual frame for the Quaternary evolution of the Ardenne (Demoulin et al. 2012b). After a brief presentation of the geological background and an overview of the Ardennian drainage system at the eve of the Quaternary, this chapter thus aims at providing a comprehensive but concise picture of the interplay between tectonics and climate in controlling Quaternary river incision and shaping the Ardenne massif. It focuses first on the morphological and sedimentological characteristics of the main terraces, in particular the YMT, and the recently developed chronological framework. Then, it details the mechanisms at work and how they intermingled to govern incision and denudation in the Ardenne, especially since the

beginning of the Middle Pleistocene. Finally, it underlines how, beyond the vertical component of drainage system evolution, planform changes associated to stream piracy were another product of the specific conditions that determined the geomorphological evolution of the massif in this period of time.

10.2 Geological and Hydrographical Settings

10.2.1 Structural and Geodynamical Framework

The Ardenne massif constitutes the western continuation of the Variscan Rhenish massif in south-eastern Belgium, northern France and Luxembourg (Fig. 10.2a). It extends between the Paris basin to the south and the Cenozoic Anglo-Belgian basin to the north. Overall, the structurally complex basement of the Ardenne exhibits longitudinal ENE-WSW folds and thrust faults cut by numerous NW-SE to NNW-SSE striking normal faults (Demoulin and Ek 1995).

A series of Cambro-Ordovician massifs inherited from the Caledonian orogeny and deformed again in Variscan times emerge along the axis of the recently uplifted area, which corresponds to the axis of the Variscan Ardenne anticlinorium. Chiefly made of variably erodible phyllites and resistant quartzites, they are mainly the Rocroi and Stavelot massifs, respectively located in western and north-eastern Ardenne (Fig. 10.2b). Surrounding these Caledonian massifs, the slaty Lower Devonian makes the bulk of the Ardenne anticlinorium and the Neufchâteau synclinorium (Fig. 10.2b). North of the Ardenne anticlinorium, the Dinant synclinorium represents the northernmost unit of the Ardenne allochthon, limited to the north by the Midi-Eifel thrust (Fig. 10.2b). In contrast with the exclusively siliceous rocks of the Lower Devonian Ardenne core, it exposes more varied Middle Devonian to Lower Carboniferous rocks that characterize the lower lying Famenne and Condroz areas. From south to north, a narrow belt of strongly karstified Givetian limestones extends along the northern margin of central Ardenne (see Chaps. 8 and 9), followed by the up to 10-km-wide Fagne/Famenne region, where Frasnian and Famennian shales prone to frost shattering were largely eroded during the cold periods of the Quaternary, creating a 150-m-deep depression between Ardenne and Condroz (Fig. 10.2b). To the north, the latter is then chiefly formed by an alternation of Upper Devonian mica-rich sandstones and Lower Carboniferous limestones cropping out in ENE-WSW trending anticlines and synclines, respectively, and defining a corresponding series of smooth ridges and depressions (Fig. 10.2b). Scattered over the Condroz ridges and the flat summits of W and NE Ardenne, sparse remnants
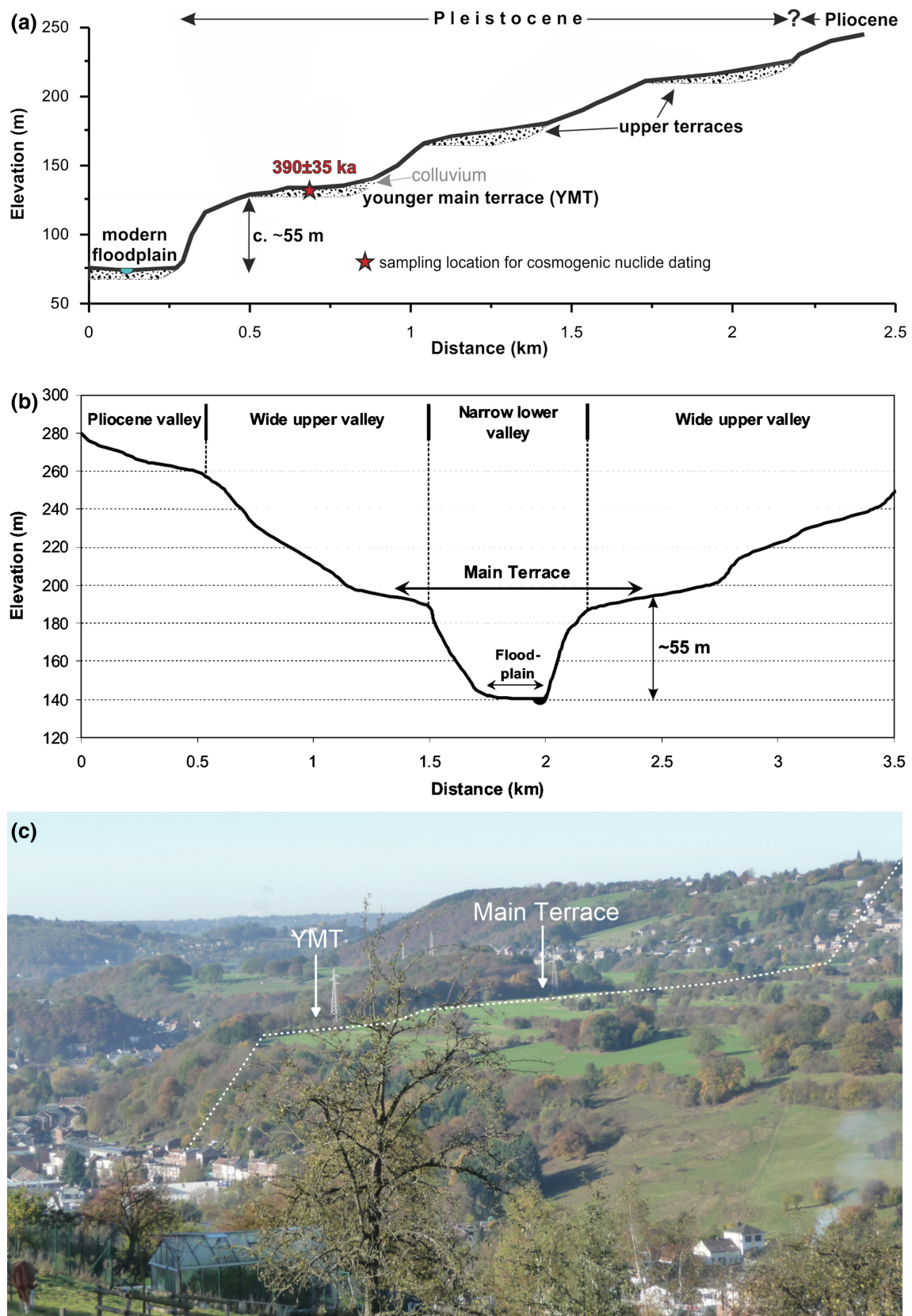
Fig. 10.1 Typical valley cross section of Ardennian (sub-)tributaries of the Meuse as exemplified by the lower Ourthe (**a** adapted from Rixhon et al. 2011) and middle Vesdre (**b** from Rixhon and Demoulin, 2010) valleys and a view of the Vesdre valley downstream of Verviers showing the position of the younger main terrace (YMT) just above the steep-sided lower part of the valley section (**c**). The YMT systematically marks the transition from a broad upper part of the valleys to their deeply incised narrow lower part. The CRN age of 390 ± 35 ka points to the abandonment time of the YMT in the lower Ourthe valley (Rixhon et al. 2011)
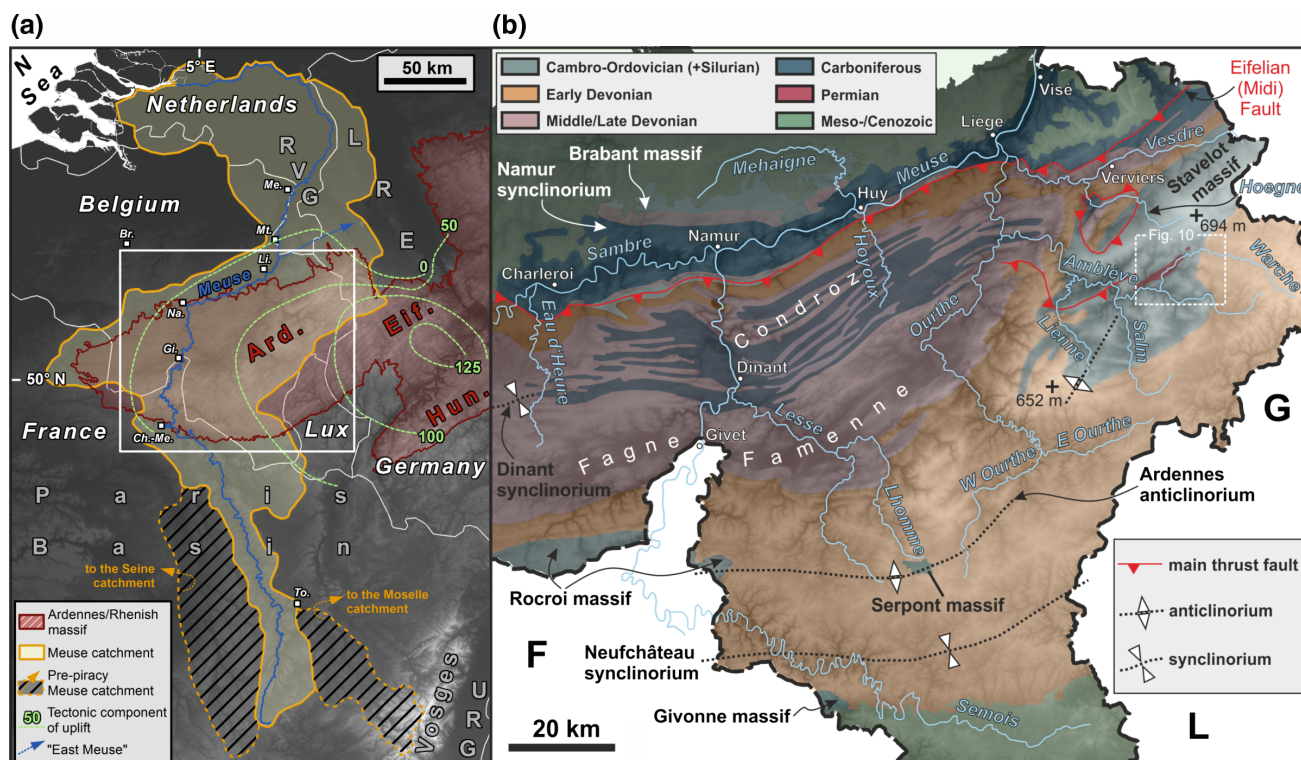
Fig. 10.2 **a** Location of the Meuse catchment within NW Europe. The *white frame* delimits the area detailed in figure. **b** Isolines of the tectonic component of rock uplift in the Ardenne/Rhenish massif since the early Middle Pleistocene are taken from Demoulin and Hallot (2009). *Ard.* Ardenne; *Eif.* Eifel; *Hun.* Hunsrück; *LRE.* Lower Rhine Embayment; *RVG.* Roer Valley Graben; *URG.* Upper Rhine Graben. *Ch-Me.* Charleville-Mézières; *Gi.* Givet; *Li.* Liège; *Me.* Maaseik; *Mt.* Maastricht; *Na.* Namur; *To.* Toul. **b** Simplified geological map of Wallonia, encompassing the Ardennian Meuse catchment in Belgium (Adapted from Bultynck and Dejonghe 2001)

of Upper Cretaceous and Paleogene marine sediments attest that the massif was partly drowned by several Meso-Cenozoic seas and that the subsequent denudation was unable to remove them completely (see Chap. 5).

As a part of the Rhenish shield, the Ardenne experienced late Cenozoic tectonic uplift. Large-scale deformation and present-day elevations of well reconstructed Tertiary erosion surfaces demonstrate that this uplift was primarily of en-bloc type, notably limited to the NE by a narrow marginal flexure and the bounding faults of the Roer Valley Graben, and amounted to ∼450 m, locally even 500 m, since the Oligocene. Even though first signs of uplift are detected as early as during the Selandian (∼60 Ma), the recent deep incision of the valleys into the massif attest a strong Plio-Quaternary increase in uplift rates. From terrace studies in many rivers of the Ardennian Meuse catchment, it is commonly acknowledged that uplift acceleration occurred stepwise, partly also in a pulsed way. With an estimated rate of 0.3–0.5 mm year^{-1} probably lasting a few 10^4 years, the largest and best documented uplift pulse took place around the Early to Middle Pleistocene transition and was responsible for the abandonment of the YMT floodplain level, before the massif underwent anew relative tectonic quiescence since

∼400 ka (e.g., Van den Berg 1996; Quinif 1999; Van Balen et al. 2000; Demoulin and Hallot 2009).

Different possible causes of uplift have been proposed and are still debated: (i) lithospheric thinning underneath the Rhenish massif (e.g. Prodehl et al. 1995), (ii) lithospheric folding as a result of compressive stresses exerted by the Alpine belt on its foreland (e.g. Ziegler and Dezes 2007), (iii) mantle upwelling beneath the Eifel area (Ritter et al. 2001). Recently, Demoulin and Hallot (2009) synthesized geomorphological observations and Demoulin (2011) brought additional morphometric evidence showing that the latest recorded uplift is oldest in the south and youngest in the north. According to them, this suggests that an uplift wave migrated across the massif over the Quaternary, a conclusion that seems to point to lithospheric folding as the most probable cause of uplift of the Ardenne/Rhenish shield.

10.2.2 The Ardennian Meuse Drainage System at the Dawn of the Quaternary

Looking at the main traits of the Ardennian drainage system and, especially, at the course of its trunk stream, the Meuse,

one anticipates that it is the product of a long and complicated history. We briefly summarize this story here as a preamble to the discussion of Quaternary river incision.

Although the central Ardenne was and remained constantly emerged since a much longer time, the last sea that drowned a substantial part of the massif during the Rupelian regressed northwards sometime around 30 Ma. It is commonly accepted that the many N- to NNW-striking drainage axes featured by the then-emerged areas bear witness to the consequent river system that was developed at that time (de Heinzelin 1963). Beyond the Hantes and Eau d'Heure-Piéton lines (*a*, Fig. 10.3) in the west, they are the Amblève-lower Ourthe and the Hoyoux-lower Méhaigne axes (*b*, Fig. 10.3), plus the Meuse reach from Dinant to Namur (Fig. 10.3). The last two axes were perhaps simply the prolongation of preexisting rivers (corresponding to the present middle Ourthe and the Meuse reach between Revin and Dinant) that already drained the continental central Ardenne in the Eocene. This brings us to one of the major unsolved issues of the long-term evolution of the Meuse river course: why does the upper Meuse, flowing north in the Paris basin, leave this low-elevation, readily erodible bedrock to cut across the much more resistant Paleozoic basement of the higher uplifted Ardenne? Although superimposition (e.g., Cornet 1903) and antecedence (e.g. Davis 1895; Bustamante and Voisin 1975) have had their proponents to explain this paradox, the capture hypothesis, though being still not definitely demonstrated, prevailed among Belgian geomorphologists in the past half-century, especially because it was vigorously defended by Pissart (1961, 1974). However, the ~50-m-high erosion scarp that Demoulin (1995) has shown to define the southern margin of the Ardenne already in the Oligo-Miocene (see also Chap. 5) makes highly improbable that a capture could have taken place there sometime during the Middle to Late Miocene at the expense of a river flowing in the Paris basin. Moreover, it would be surprising that, empowered by such a capture, the Meuse catchment would then, even if several million years later, be largely beheaded at the benefit of the adjacent Seine and Rhine catchments (Pissart et al. 1997) for allegedly the same reason, namely uplift of the Ardenne (Fig. 10.3). Superimposition of an Ardennian Meuse initially established on Eocene and Oligocene covers (plus the underlying deep weathering mantle, see Chap. 5), followed by antecedence in response to the Quaternary uplift of the massif seems thus equally probable, to say the least.

Another peculiar feature of the Ardennian drainage system is the long straight major drain running along the northern margin of the massif (Figs. 10.3 and 10.4). There, the Sambre and the middle Meuse (between Namur and Liège) collect all the waters flowing down the Ardenne and direct them toward ENE, down to Liège where the Meuse changes its course to flow north. However, in older times, the Meuse kept the same ENE flow direction beyond Liège, passing north of Aachen and accumulating sediments in the Lower Rhine Embayment (the Holzweiler Formation) before joining the Rhine near Mönchengladbach (Westerhoff et al. 2008). As revealed by terrace mapping in the Liège–Maastricht–Aachen triangle (Macar 1938; Felder et al. 1989), the change to its modern course, probably caused by uplift and tilt motion of the shoulder of the Roer Valley Graben, occurred by progressive shifting, initially aided by a capture that took place sometime between 2 and 1 Ma (Juvigné and Renard 1992; Van den Berg and Van Hoof 2001; Westerhoff et al. 2008).

The ENE draining of all Ardennian waters by the so-called Sambre-Meuse axis most probably responded to the regional tilt that developed during the Miocene toward the Lower Rhine Embayment, actively subsiding all along the Neogene. This tilt is likewise evidenced in Middle Belgium by the NE retreat of Late Miocene shorelines and the NE preferred orientation of the consequent drainage network that developed on the emerged land tract when the Diestian sea regressed in this direction (Houthuys 2014; see also Chap. 18). It is commonly believed that the Sambre-Meuse drain and, especially, the Meuse valley segment between Namur and Liège were formed by successive regressive erosion of small streams in this WSW-ENE furrow and captures of Ardennian rivers formerly flowing north or NNW. The origin of this remarkably rectilinear major drainage axis is still unsure. While it has often been suggested that the Sambre-Meuse furrow was the result of a slight reactivation of the Variscan Namur syncline during the Miocene (e.g. Cornet 1899; Fourmarier 1926; Macar 1957), Demoulin (1993) proposed that the main factor controlling the location of the rivers within this furrow was the existence of a shear zone active during the Middle Miocene, which is better supported by the rectilinearity of this 170-km-long line and its spatial coincidence with the North-Artois shear zone (Camelbeeck et al. 2007). In any case, the oldest river terraces preserved along this segment of the Meuse valley contain kieseloolite (silicified oolite) gravels (Fig. 10.5a), a petrographic marker that indicates provenance from the Paris basin and unequivocally relates them to the Kieseloolite Formation, dated from the Late Miocene and Pliocene in the Lower Rhine area (Boenigk and Frechen 2006). This demonstrates that the modern course of the Meuse from the Paris basin down to Liège was already installed at least in the Late Miocene.
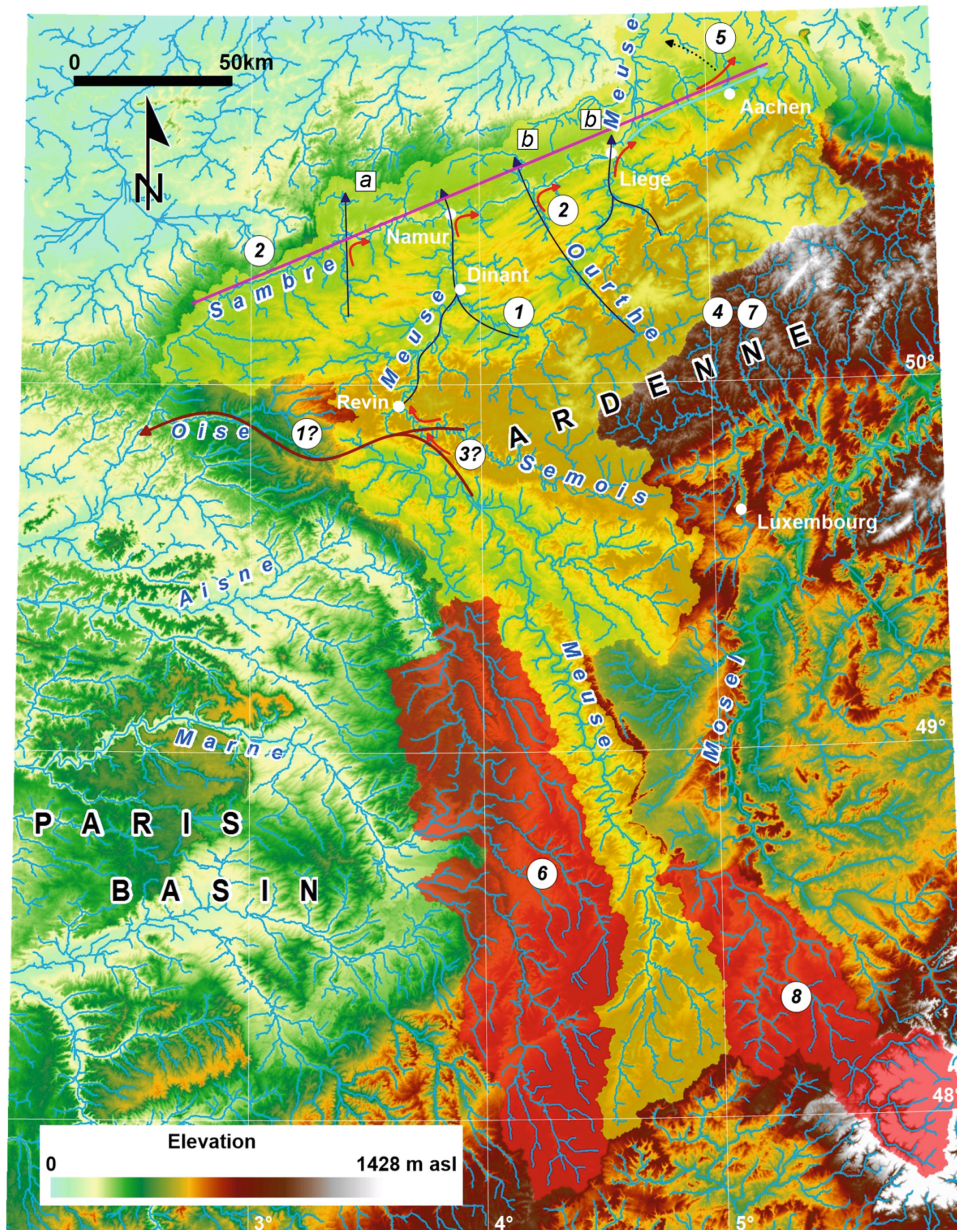
Fig. 10.3 Summary of the Neogene and Quaternary main evolutionary stages of the Meuse catchment (present extension highlighted in *yellow*). *1* N- to NNW-oriented consequent rivers (*thin deep-blue arrows*) drained the Ardenne massif after regression of the Oligocene sea. *a* Eau d'Heure—Piéton axis. *b* Hoyoux—lower Méhaigne and Amblève—lower Ourthe axes. *1?* According to Pissart (1961), the ancient course of the Mesozoic Meuse (i.e. the Upper Meuse, flowing in the Paris Basin) followed the southern margin of the massif and continued in the present Oise (*thick brown arrow*). However, it should be noted that, contrary to Pissart's assumption that a capture was needed to direct the Mesozoic Meuse into the more resistant Paleozoic massif, this ancient course already cut locally into the massif. *2* The Middle to Late Miocene activation of the Sambre-Meuse shear zone (*magenta line*) caused the capture (*red arrows*) of the consequent rivers, now redirected toward the subsiding Roer Valley Graben in the ENE (e.g. Demoulin 1993). *3?* The capture of the Upper Meuse, improbable though claimed by Pissart (1961, 1974) (see text), would

have occurred through regressive erosion of an Ardennian river in the Middle to Late Miocene. *4* The Ardenne undergoes a first episode of moderate uplift during the Pliocene-Early Pleistocene. *5* As a consequence of the associated NNW tilt of NE Ardenne, the so-called 'East Meuse' (*light blue arrow*) is diverted toward a more northern course (*red arrow*) that progressively shifts to the NW (*dotted black arrow*) during the Early Pleistocene (e.g. Juvigné and Renard 1992). *6* The Upper Meuse loses a large part of its drainage area (*highlighted in red*) through multiple captures at the benefit of the Seine catchment around 0.9 Ma (Pissart et al. 1997). *7* The Ardenne undergoes a pulse of accelerated uplift at the Early to Middle Pleistocene transition inducing a wave of erosion into the Ardennian drainage system. *8* The last significant capture in the Upper Meuse catchment occurs during the late Middle Pleistocene, when the Upper Moselle is redirected towards the Rhine catchment (Davis 1895; Harmand et al. 1995; Harmand and Cordier 2012)

10.3 The Main Terrace Complex: A Major Geomorphic Marker in the Ardennian Valleys

10.3.1 Morphological and Sedimentological Characteristics

Located approximately at mid-height of the terrace staircases, the Main Terrace Complex (MTC), displaying 2–4 closely spaced terrace levels, constitutes a conspicuous morphological marker not only in many Ardennian valleys but also in the Meuse valley north of the massif. Both its anomalously great lateral development and its location at the sharp hinge between the upper broad and lower narrow parts of valley profiles make it remarkable (Fig. 10.1). However, despite a kilometer-wide three-level MTC (Macar 1938; Juvigné and Renard 1992), the reach of the Meuse valley between Liège and Visé (see Fig. 10.2) shows a less contrasted transverse profile because recently accelerated incision could not prevent this major river to develop wide floodplains during cold stages. The lower Ourthe and the middle Vesdre are certainly among the places where the two-storey valley profile is best expressed in the topography (Fig. 10.1c). There, the MTC, with its YMT lowest level which defines the upper edge of the deeply incised valley, is typically ∼300-m-wide, attesting the long period of stability that preceded the onset of the recent episode of incision. The YMT is, therefore, a key feature that has often been used as a major marker in studies of the Quaternary evolution of the Ardennian drainage network (Van Balen et al. 2000; Demoulin et al. 2009; Rixhon et al. 2011).

Being easily identified throughout the Ardennian valleys, the MTC has served as a reference for terrace profile reconstructions for a long time (see the historical review of terrace studies in the Ardennian Meuse catchment in Alexandre and Kupper 1976). A main characteristic of terrace data sets in Ardennian valleys, including the Meuse between Charleville at the southern limit of the massif and Liège at its northern border, is the systematic upstream decrease of the number of terrace levels. Moreover, a careful examination of the representative diagram of Fig. 10.4 shows that this decrease is accounted for essentially by reduced numbers of terrace levels *below* the YMT. In the Meuse valley, the profile reconstruction of Pissart et al. (1997) indicates for example that five post-YMT terraces identified downstream of Liège reduce to three at Namur and only one at Givet, before the YMT tends to merge with the modern floodplain near Charleville (Fig. 10.4). This observation goes hand in hand with that of upstream decreasing relative elevations of the MTC: from 65 m above the modern floodplain of the Meuse near Visé to 60 m at Liège, ∼30 m at Namur and ∼20 m at Givet. Relative elevations of the MTC in the Ardennian tributaries of the Meuse show a similar trend, decreasing for instance in the Ourthe valley from 55 m at 5 km upstream of the Ourthe-Meuse confluence to 44–48 m in the area of the Amblève-Ourthe confluence and ∼34 m at the sharp bend toward NE the river makes in the Famenne (Fig. 10.2b).

If one relies on the widely accepted profile reconstruction of Pissart (1974) for the Meuse terraces, a meaningful feature is the horizontality, or locally even upstream sloping of the MTC levels and all higher terraces between Namur and Liège, i.e., in the river's ENE-striking reach running along the northern border of the Ardenne massif. By contrast, the lower terrace levels remain roughly parallel to the modern long profile in this reach (Fig. 10.4). This profile pattern has both temporal and spatial significance. Spatially, it provides evidence of the geometry of the uplift that deformed the
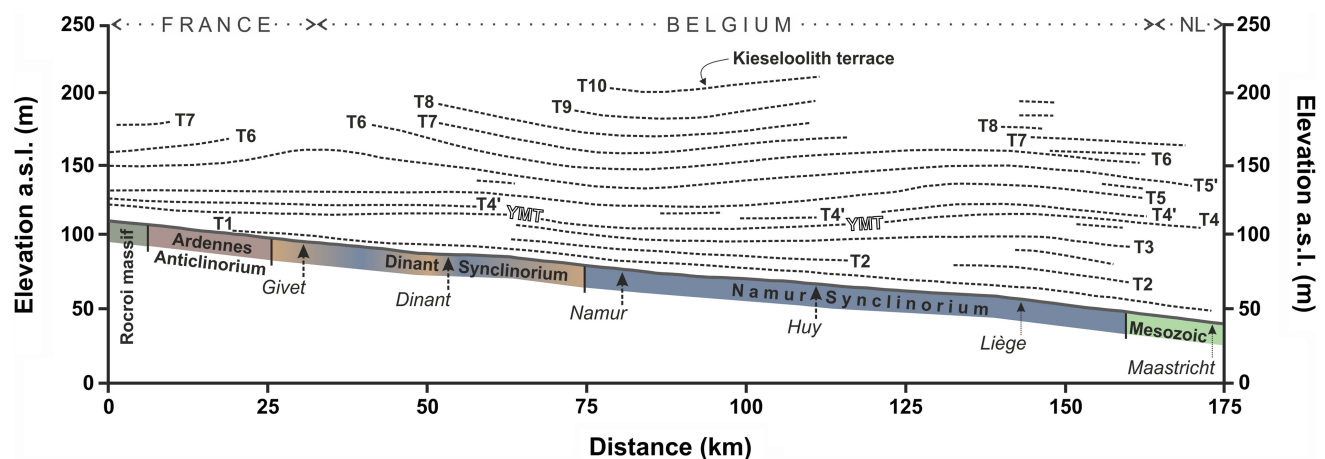

Fig. 10.4 Terrace long profiles of the Meuse in N France and Belgium (adapted from Pissart et al. 1997). Level T4 corresponds to the YMT. Note the profile deformations between Namur and Liege and, for the high terraces, in the Givet area, and the upstream gradual decrease in relative elevation of the profiles

YMT and all higher levels, highlighting the WNW tilting of the margin of the uplifting Ardenne. Temporally, it constrains the time of the deformation, which occurred as a short-lived uplift pulse in the period between abandonment of the YMT and development of the next lower floodplain level.

In the major and middle-sized valleys of the massif, preserved remnants of the MTC usually appear as flat surfaces with minimal transverse slope, extending over a few (in subtributaries) to tens of hectares (in the Meuse valley). Sediment thickness is generally greater in MTC than in other terraces of the same vertical sequence but may vary by a factor 2 or 3 with location in the drainage system, ranging from a mean 7–8 m in the Meuse downstream of Namur to 3–4 m in intra-massif tributaries (Fig. 10.5b). However, anomalously thick alluvial bodies have also been observed in the latter, e.g. >8 m and ∼5 m for the YMT deposits in the lower and upper middle Amblève, respectively (Rixhon

et al. 2011). Sedimentation patterns typical of braided-river systems along with embedded boulders bigger than 1 m in intermediate axis interpreted as ice-rafted material (see Chap. 6), syngenetic cryoturbations and ice wedge casts are widely observed in the MTC terraces of the Meuse downstream of Liège (Fig. 10.5c, d), including on the Campine Plateau (Macar 1957; Pissart et al. 1969; Juvigné 1992; De Brue et al. 2015). All these elements clearly point to deposition under the periglacial conditions that prevailed in Belgium during the Pleistocene cold periods. In the intra-massif tributary valleys, YMT sediments generally consist of massive bodies of coarse pebbles embedded in an abundant silty-sandy matrix and present only scarce sedimentary structures (Juvigné et al. 2005; Rixhon et al. 2011). They occasionally contain quartzite boulders up to 0.5 m in size and may locally be made of very coarse material (a YMT exposure in the upper middle Amblève revealed a D_{50} larger than 20 cm).
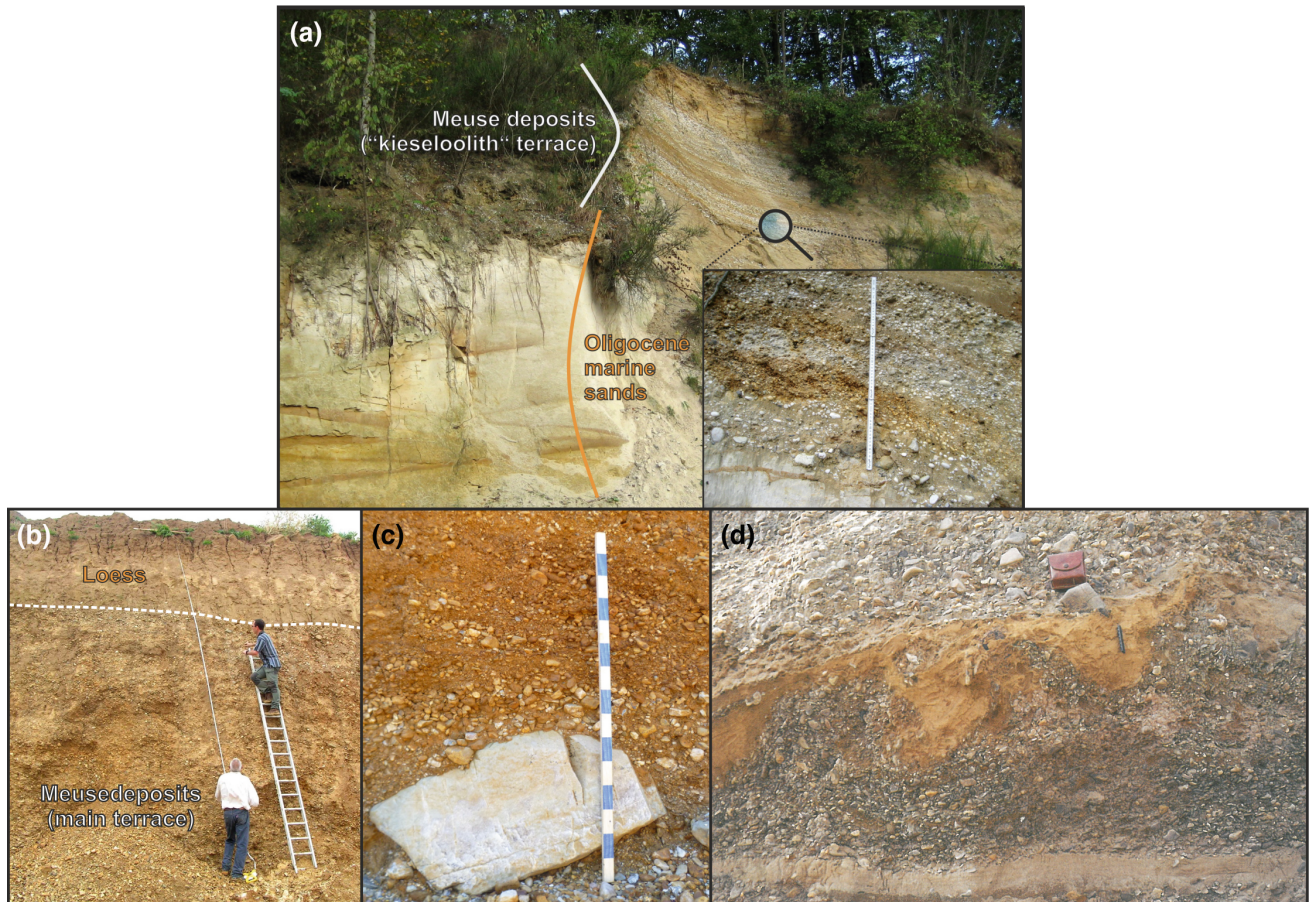

Fig. 10.5 **a** General and closer views of the oldest terrace sediments—the so-called Kieseloolite terrace (T10 in Fig. 4)—overlying Oligocene marine sands atop the left valley side of the Meuse a few kilometres upstream of Liège (*Photographs* G. Houbrechts). **b** View of the Main Teratoprace sediments covered by (mainly) Weichsel loess at Romont, Eben-Emael, close to the Belgian/Dutch border (*Photograph* G. Rixhon). [10]Be and [26]Al concentration measurements dated the terrace abandonment time to 725 ± 120 ka (Rixhon et al. 2011). **c** Boulder (*a*-axis ∼1.25 m) embedded in Meuse terrace deposits of the Campine Plateau north of Liège, generally assigned to the MTC. Such blocks are interpreted as ice-rafted material (*Photograph* from De Brue et al. 2015). **d** Syngenetic cryoturbation features in MTC deposits a few kilometres downstream of Liège (*Photograph* from Cornet 1995)

10.3.2 Age Constraints on MTC and Lower Terraces

Yielding age estimates of the YMT was far from easy until a decade ago because no reliable numerical dating method was available to date fluvial sediments older than half a million years. Supported by sparse measurements elsewhere in the Meuse basin (e.g., Juvigné et al. 2005) and by similar results for the corresponding terraces in the middle Rhine (Koci et al. 1973), paleomagnetic measurements performed in a terrace sequence of the Meuse near Maastricht could at best suggest that the MTC straddled the Matuyama-Brunhes transition and, consequently, that the YMT (called the Sint-Pietersberg 3 terrace in the area of Maastricht) accumulated just after 780 ka (Van den Berg 1996; Westaway 2002). However, the data at hand were differently interpreted by other authors, Van Balen et al. (2000) arguing for instance for a YMT age in the range 0.65–0.72 Ma.

New age data were recently gained from a cosmogenic radionuclide (CRN) study performed by Rixhon et al. (2011) on depth profiles of MTC terraces in the Meuse and its Ardennian tributary system. Jointly modelling ^{10}Be and ^{26}Al depth profiles, they overcame the issue of burial of the fluvial sediments by a loess cover and obtained an age of 725 ± 120 ka (time of terrace abandonment) for a 5-m-thick terrace remnant exposed in the Romont quarry at Eben-Emael, ~ 15 km north of Liège (Fig. 10.5b). Careful re-examination of the position of the sampled terrace in the Meuse terrace sequence shows that, contrary to the claim of Rixhon et al. (2011), the Romont terrace pertains to the middle, possibly even the highest level of the MTC, implying an age younger than 725 ka for the YMT, in agreement with the interpretation of Van Balen et al. (2000).

The second Meuse terrace for which numerical ages are available is the Caberg 3 level, at 15–18 m relative elevation in the Liège-Maastricht reach of the river. In the Belvédère site, near Maastricht, the interglacial deposits at the top of the alluvial body have been dated to 250 ± 20 and 220 ± 40 ka by thermoluminescence on heated flint artifacts and ESR on mollusc shells, respectively (Huxtable 1993; Van Kolfschoten et al. 1993), while biostratigraphic consideration and amino acid dating rather favoured an MIS9 age (~ 340–300 ka) (Meijer and Cleveringa 2009). This Caberg 3 terrace is especially interesting because the disappearance of petrographic and mineralogical markers of the upper Moselle basin (Vosgian granite and basaltic hornblende, respectively) in its deposits helps draw a reliable terrace profile all along the Meuse and constrain the time of the Upper Moselle capture at Toul, in French Lorraine (e.g.,

Pissart et al. 1997) (Fig. 10.3). Moreover, U/Th dating of a flowstone sealing the last Moselle deposits before capture in a karstic system at the capture point provided a minimal age of 250 ka (Losson and Quinif 2001). All these data seems to be best fitted by a Caberg 3 terrace having developed during MIS8 and 7 (and 9?) and been abandoned at the MIS7-6 transition.

Contrasting with this relative wealth of data in the Meuse valley, the absolute chronology of terrace systems in the Ardennian tributaries of the Meuse was long neglected. Beyond limited tephrochronological hints of the age of a few lowest terraces (Juvigné 1979) and varied time indications gathered in the Belle-Roche cave fill (Figs. 10.6 and 10.7), located just above the YMT in the lower Amblève (Cordy et al. 1993), crucial data have only recently been provided by Rixhon et al. (2011). At Belle-Roche, Amblève gravels occur at the base of the cave fill and are overlain by slope material brought in the cave by mud flows. Supported by the >300 ka U/Th age of a calcitic flowstone sealing the deposits and paleomagnetic measurements indicating normal polarity, the rich and diversified macro- and microfauna included in this material has been dated to 500 ± 70 ka (Cordy et al. 1993), apparently suggesting a ≤ 500-ka age for the lower lying YMT. Having sampled an ~ 8-m-thick depth profile in the YMT deposits at Belle-Roche, Rixhon et al. (2011) showed that the ^{10}Be concentration profile displayed two superposed signals, whose modelling allowed them not only to provide an estimate of 222 ± 31 ka for the time of terrace abandonment but also to date around 550 ka the beginning of the aggradation phase that constructed the YMT floodplain. Moreover, Rixhon et al. (2014) suggested that the gravels in the cave might represent overflow deposits accumulated in relation with the formation of the lower lying YMT, making both gravel bodies pertain to MIS14, in perfect agreement with the MIS13 paleontological age of the slope deposits in the cave.

Still farther-reaching are, however, the overall results that Rixhon et al. (2011) obtained for the YMT remnants they dated all along the Ourthe-Amblève line (Fig. 10.8a): going upstream, (1) the CRN age of the Romont terrace suggests a corresponding age around 620 ka for the time when the YMT was abandoned in the lower Meuse; (2) combined ^{10}Be and ^{26}Al depth profiles at Colonster yield an age of 390 ka for this same YMT in the lower Ourthe; (3) as stated above, the YMT was abandoned around 220 ka at Belle-Roche in the lower Amblève; (4) two sites sampled in the upper middle Amblève, at Stavelot and Lodomez, provided CRN ages in the range 135–140 ka for the abandonment time of the YMT in this part of the valley.
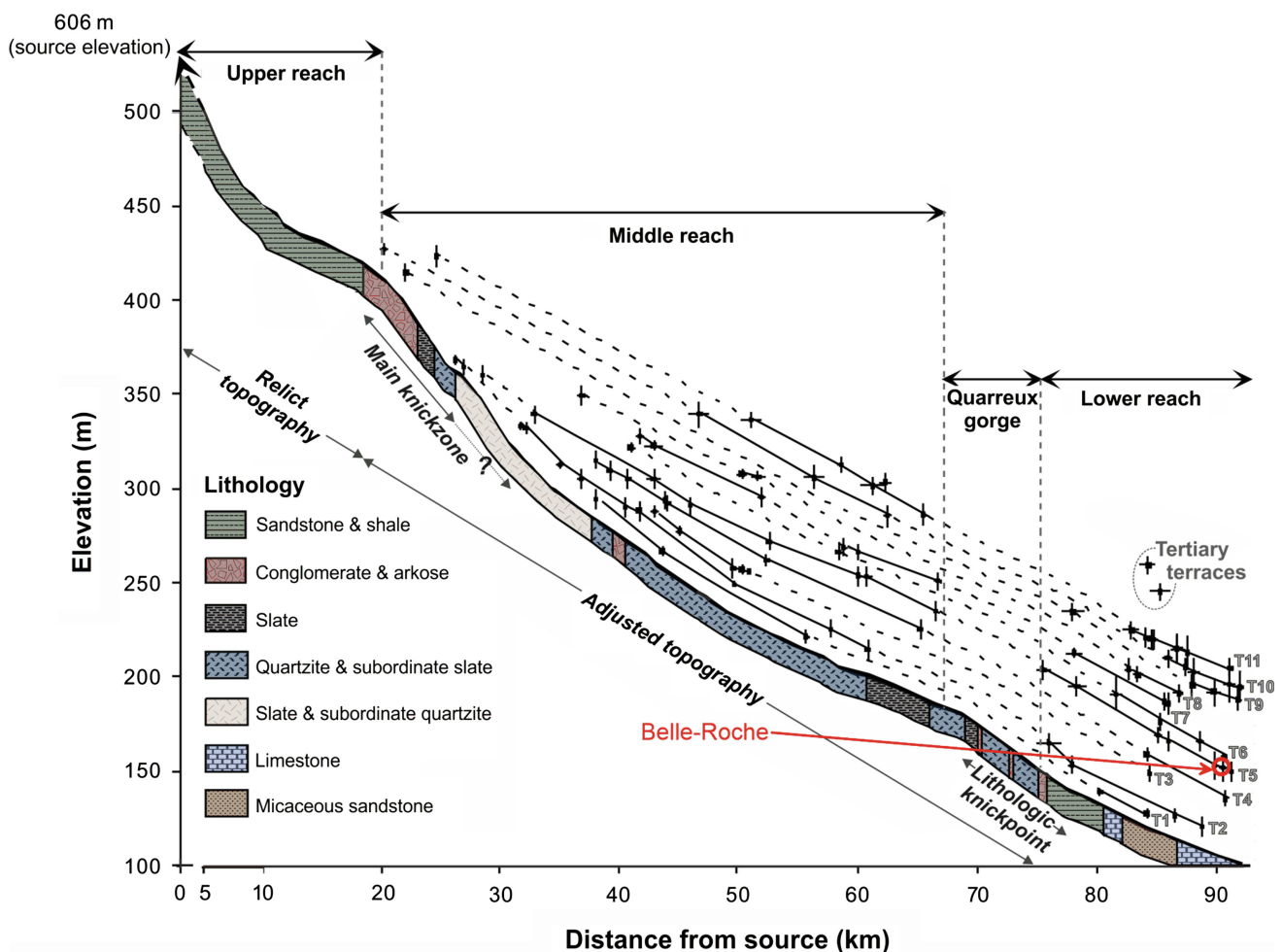
Fig. 10.6 Terrace long profiles of the Amblève River, a main Ardennian sub-tributary of the Meuse, plotted against the present-day river profile with lithology. *Solid and dashed lines* refer to probable and uncertain geometric terrace correlations, respectively. A prominent tectonically controlled knickpoint at km 18 marks the transient boundary between the downstream post-YMT adjusted and upstream relict parts of the profile. The knickpoint in the Quarreux gorge at 70 km is controlled by lithology where the river incises across resistant quartzites (adapted from Rixhon and Demoulin 2010)

10.4 Quaternary River Incision in the Ardenne: A Combination of Tectonic and Climatic Forcing

The main implication of CRN dates decreasing systematically upstream along the lower Meuse—lower Ourthe—Amblève system is that the YMT was abandoned diachronically, due to the propagation of an erosion wave in the Ardenne drainage system. This obvious conclusion cannot be obscured by remaining issues regarding the propagation's varying celerity between the dated sites, which probably relates to the varying duration of the successive periods favourable to incision rather than to other factors invoked by Demoulin et al. (2012b). This important Middle Pleistocene event, which, according to the Romont CRN date, started around 620 ka, has not yet come to an end. Not only does the morphometry of catchment, valley and river profile show that the Ardennian rivers have not yet reached steady-state (Sougnez and Vanacker 2011) but, more importantly, knickpoints are still observed in the upper reaches of many of them at points where the YMT, which converges upstream with the modern floodplain, finally merges into it (Beckers et al. 2015) (Fig. 10.8b, c). As was confirmed by the successful modelling of their migration through the drainage system (Beckers et al. 2015), these lithology-independent knickpoints are tectonically triggered features locating the current position of the erosion wave.

These findings have fundamentally questioned several well-established truths about the Quaternary evolution of the Ardenne and its river system. As most terraces bear witness
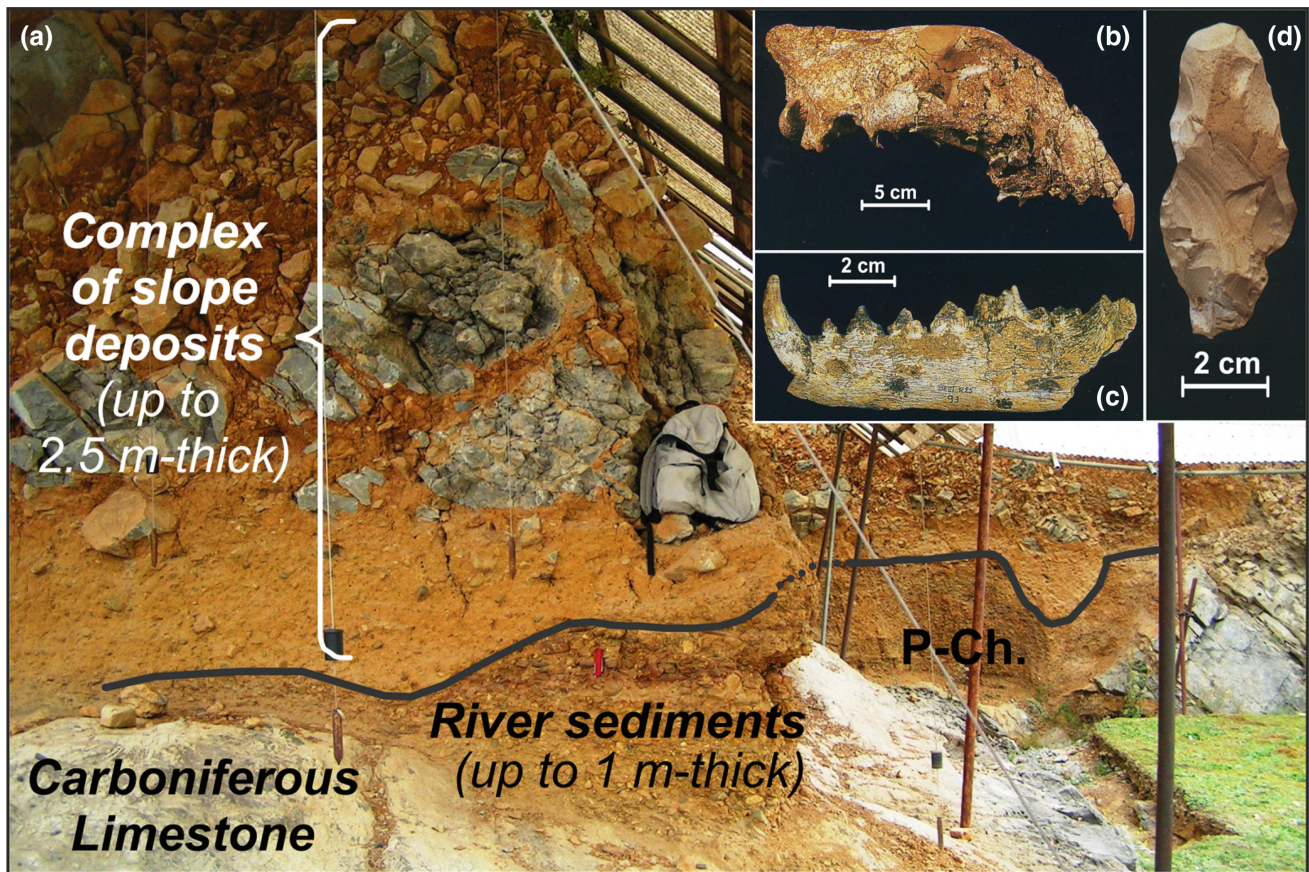
Fig. 10.7 a General view of the infill sediments in one gallery of the Belle-Roche palaeokarst in the *Lower* Amblève valley (see position in Fig. 10.6). The sedimentary sequence consists of up to 1 m-thick river deposits of the Amblève at the base, overlain by up to 2.5 m-thick slope deposits (mostly runoff and solifluction products). The latter contain many palaeontological and archaeological remains (**b** skull of *Panthera onca gombaszoegensis*; **c** jaw of *Canis mosbachensis*; **d** flint biface). The very rich palaeofauna assemblage (>50 species, Cordy et al. 1993) has been assigned a biochronological age of 500 ± 70 ka (All *photographs* from Rixhon et al. 2014)

to aggradation under cold-stage conditions, it is widely accepted that each terrace level was representative of one climatic (sub)cycle, the succession of Quaternary glacial-interglacial cycles being responsible for the formation of the terrace staircases (e.g., Van den Berg 1996). This classical scheme of climatically driven alternation of terrace formation and river incision, adopted far beyond the Ardenne area (e.g. Bridgland and Westaway 2008), conveys the implicit assumption that every particular level formed synchronously and thus has the same age everywhere in the drainage system, from the Meuse between Liège and Maastricht down to the tiniest of its Ardennian tributaries. However, the new data show this is incorrect at least for the YMT. Beyond the conceptual change it imposes, the observed diachronism in local river incision also entails that calculations derived from a single age of the YMT throughout the Ardenne to map uplift rates or estimate time-dependent eroded volumes (Van Balen et al. 2000; Meyer and Stets 2007) are basically flawed.

In order to account for the new knickpoint and terrace age information, Demoulin et al. (2012b) proposed a new evolutionary model of river incision in the Ardenne. Its main focus is on integrating the effect of the tectonically triggered longitudinal propagation of a post-YMT erosion wave with that of climatically controlled episodic vertical incision in response to background uplift. Starting from the steady-state reached by the wide YMT valleys at the dawn of the Middle Pleistocene and still attested all over the massif by the barely incised uppermost reaches of the Ardennian valleys, this model acknowledges the uplift pulse recorded by the deformed terrace levels of the Meuse between Namur and Liège and the larger than usual vertical spacing between the YMT and the next lower terrace observed in all valleys. Dated to ∼620 ka at Romont, this essentially en-bloc uplift of the Ardenne created a ∼20-m-high knickpoint in the Meuse long profile in the vicinity of Maastricht, which in turn initiated the propagation of a wave of regressive erosion in the drainage system. This propagation was, however, also
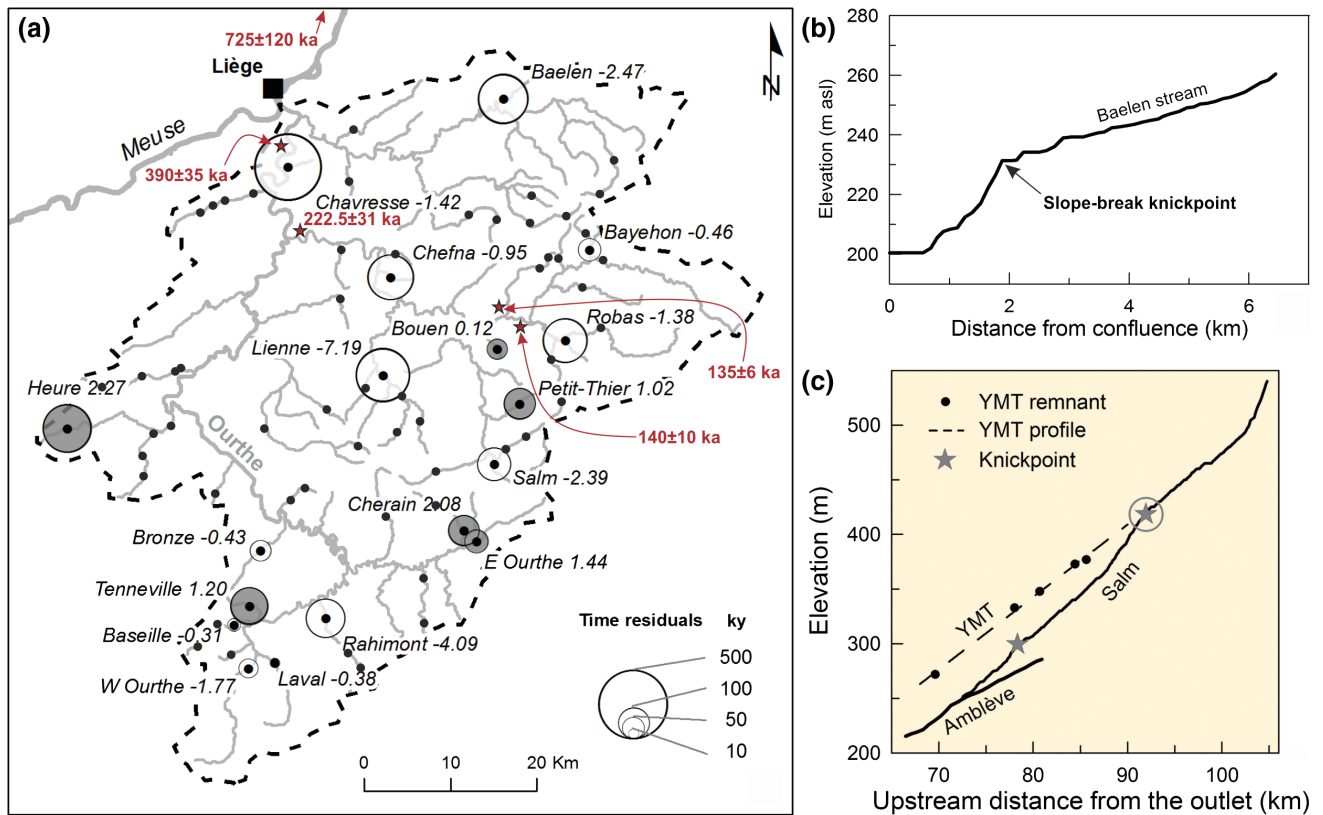
Fig. 10.8 a Spatial distribution of knickpoints (*black dots*) in the Ourthe catchment (modified from Beckers et al. 2015). Only circled dots are safely associated to the post-YMT wave of erosion. *Open and solid grey circles* refer to knickpoints delayed with respect to, and ahead of, their modeled position, respectively. Circle size quantifies time residuals whereas distance residuals are given in km by numbers behind every river name. *Red stars* and *red numbers* refer to MTC (north of Liège) and YMT sediments dated by ^{10}Be concentration profiles (Rixhon et al. 2011). **b** Long profile of the Baelen creek displaying a slope-break knickpoint typical of the post-YMT erosion wave (modified from Beckers et al. 2015). **c** YMT profile of the Salm River plotted against the current river profile. The knickpoint marked as a *circled star* indicates the present-day position reached by the post-YMT erosion wave, which is also the point where the YMT profile merges upstream with the modern profile

climatically controlled in the sense that it went on essentially during climatic transitions, when stream power largely outbalanced hillslope sediment delivery, allowing river incision (e.g. Vandenberghe 2003). Owing to the direct dependence of knickpoint migration rate on drainage basin size, the erosion wave was possibly able to travel the whole distance of the Ardennian Meuse valley within one or two such transitions. Moreover, transport-limited conditions rapidly caused diffusive dampening of the knickpoint form in this major valley. However, knickpoint propagation rate decreased significantly when proceeding toward the smaller branches of the Ardennian tributary system, thus extending the drainage network's transient response over multiple glacial–interglacial cycles, up to the present time. In parallel, once a knickpoint had migrated past a valley reach, erosion kept on deepening it, but to a much slower rate in equilibrium with the constant background uplift rate <0.05 mm/year of the last half-million years. Now, this took

place after the climatic fashion of ubiquitous vertical erosion, but only in that part of the drainage network in equilibrium with the new background uplift rate downstream of the front of the erosion wave. While this process nicely accounts for the upstream diminishing number of post-YMT terraces in the Meuse catchment, it has a profound impact on the way terrace levels should theoretically be reconstructed and, consequently, on the age of each particular terrace remnant. As no other significant tectonic perturbation occurred after the 620-ka uplift pulse, the post-YMT levels basically display profiles parallel between each other and with the modern floodplain and intersect the YMT profile all the more upstream as they are younger (Fig. 10.9a).

The interaction between the climatic and tectonic controls on river incision is thus twofold. While the classical model only recognized that uplift was required to cause incision under episodically favourable climatic conditions, the new one adds the effect of change in uplift rate, with fast rates
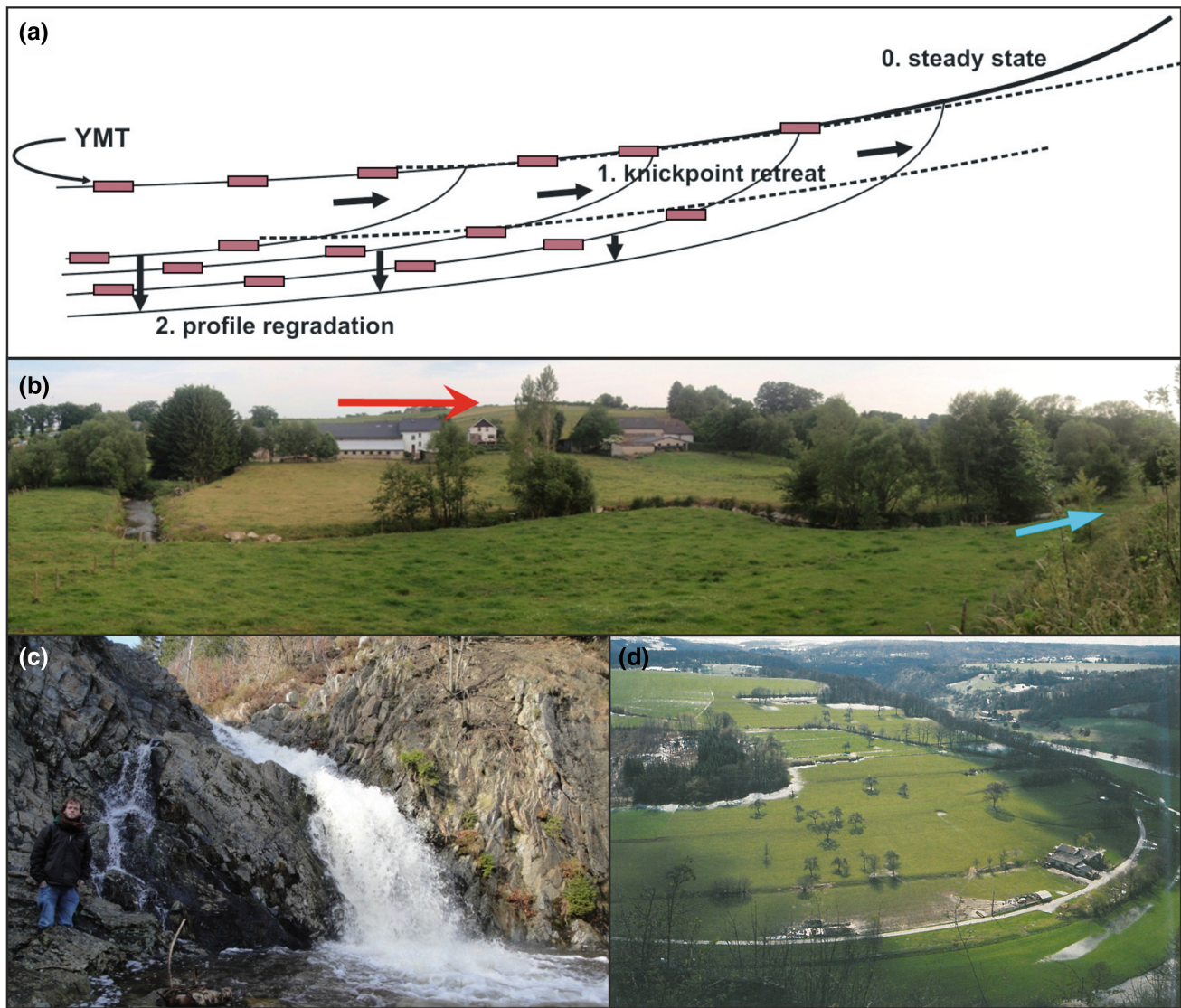
Fig. 10.9 a Conceptual sketch of the formation of a time-transgressive terrace (e.g. the Ardennian YMT), showing also the three regions of specific incision behaviour associated with the transient response to an uplift signal (*solid purple rectangles* denote terrace remnants). From source to outlet, in the Ardennian example: *0* upstream of the knickzone, almost no incision occurs in the profile part still in equilibrium with the extremely small pre-event uplift rate; *1* fast vertical erosion is associated with the migrating knickzone; *2* measurable vertical incision ubiquitously lowers the river profile where a new equilibrium has been established with the post-event uplift rate downstream of the knickzone. The height of the propagating knickpoint is given by the difference in elevation between the YMT and the next terrace profile at the point downstream where a base level fall initiated the wave of erosion (from Demoulin et al. 2012b). **b** View of the upper reach of the Amblève valley upstream of the knickzone (flow direction as *blue arrow*). The relict landscape evolves very slowly, in continued steady state with the quasi-zero uplift rate of the Early Pleistocene, with a river developing free meanders in a broad floodplain barely incised into Neogene planation surfaces (*red arrow*) (*Photograph* from Rixhon 2011). **c** Waterfall in the Bayehon stream (person for scale), materializing the present-day position reached by the post-YMT erosion wave in the Ardennian network. Incision occurs here in resistant quartzites of the Cambro-Ordovician Stavelot massif (*Photograph* A. Beckers). **d** View of the Ham meander in the lower Ourthe valley showing continued erosion after the passage of the post-YMT erosion wave. The climate-dependent terraces that form the gentle slope from the YMT flat summit down to the present floodplain are not directly distinguished in the topography, where extended scarplets are not terrace risers but lynchets (*Photograph* from Cornet 1995)

allowing the creation of knickpoints at the edge of the uplifting area in the time span between two erosion phases, thus causing the propagation of erosion waves. During the Quaternary, such a situation occurred only once in the Ardenne, around 620 ka. Since then, at every time until the transient response of the system will be completed, three

distinct parts of the Ardennian drainage network display specific behaviours: (1) the front of the erosion wave, where rapid incision results from the passage of migrating knick-points (Fig. 10.9c), (2) downstream of the front, where river profiles keep on regrading at a slower background pace by ubiquitous vertical erosion (Fig. 10.9d), (3) upstream of the front, where barely changing Early Pleistocene steady-state river profiles still characterize the regions not yet reached by the uplift signal, thus preserving the ancient equilibrium with quasi-zero Early Pleistocene uplift rate (Fig. 10.9b).

Beyond their respective role in river incision, tectonics and climate have also been considered as concurrent factors of massif-wide denudation during the Quaternary. Analysing their CRN-derived denudation rate estimates in the Meuse catchment, which increase from values around 30 mm/ky in the period 1.3–0.7 Ma to 60–80 mm/ky in the Late Pleistocene, Schaller et al. (2004) suggested that the change might result from both the Early Middle Pleistocene uplift acceleration and the climatic deterioration that took place roughly at the same time (Mudelsee and Schulz 1997). Based on geomorphic data, Demoulin et al. (2009) calculated denudation volumes due to various processes in the Meuse catchment upstream of Liege since 700 ka. They showed that river incision (84 km^3 issued from valleys representing 22% of the catchment area) and interfluve denudation (292 km^3 delivered by the remaining 78% of interfluves) were equally effective on average, leading to a regional denudation rate of 27 mm/ky. However, this figure calls for two major comments. First, while river incision is homogeneously governed by tectonically driven knickpoint migration and regressive erosion throughout the catchment, with lateral erosion acting only as a second-order factor of spatial variability, interfluve denudation is spatially very heterogeneous because lithology-dependent sensitivity to climate leads to highly contrasted denudation rates between regions within the massif. Demoulin et al. (2009) provide for instance denudation estimates in the order of 5–10 mm/ky for the flat interfluves of central Ardenne that still preserve remnants of loose sediments of Late Cretaceous and Oligocene age as well as extended patches of Mesozoic and Neogene deep weathering mantles (see Chap. 5), and 150 mm/ky for the lower lying Fagne-Famenne region (Fig. 10.2b), where pure shales are extremely sensitive to frost shattering and underwent very rapid erosion under the periglacial conditions of the cold periods. Second, there is a discrepancy between the geomorphic estimate of 27 mm/ky and an averaged CRN estimate that, based on all values provided by Schaller et al. (2004), is in excess of 40 mm/ky since 700 ka. If significant, this discrepancy might originate in overestimated [10]Be rates obtained from samples that did not represent equally all parts of the catchment because of,

e.g. inadequacy of the sampled grain size, quasi-zero denudation in some areas, or low to near-zero quartz content of carbonate bedrock. According to Demoulin et al. (2009), the CRN estimates would, therefore, be closer to valley incision rates than catchment-scale denudation.

10.5 Capture Phenomena

The response of the Ardennian drainage network to the 620-ka uplift pulse entailed not only vertical erosion but also planform changes of river courses. We shall not discuss the numerous river captures (upper Aisne, which formerly included also the upper Marne and its tributaries; Aire; upper Moselle) that almost beheaded the Meuse at the benefit of the Seine and Rhine basins (Fig. 10.3), because they occurred outside the Belgium–Luxembourg area dealt with here and, although they are dated to the period 900–300 ka (Pissart et al. 1997; Harmand and Cordier 2012), their relation to the uplift pulse in the Ardenne and NE Paris basin is still more theorized than demonstrated.

However, smaller scale stream piracy has also been observed within the Ardenne as a consequence of the migration of the post-YMT erosion wave. In NE Ardenne, two successive captures affected the Warche and its tributary, the Trô Maret, the first one having taken place between 78 and 50 ka (Juvigné and Schumacker 1985). Flowing westward, the former Warche once made an S-bend to the north and, as proved by petrographically signed sediments, followed the valley of the modern Eau Rouge before joining the Amblève at Stavelot (Fig. 10.10a, b). When travelling knickpoints reached this area, the one migrating in the palaeo-Warche (now Eau Rouge) proceeded much more slowly in the resistant quartzite rocks of the Stavelot massif than another one that propagated in a small tributary of the Amblève draining the weaker Permian bedrock of the Malmédy graben. Consequently, faster regressive erosion in, and lower elevation of, the latter stream allowed it to divert the Warche at Bévercé (Pissart and Juvigné 1982). Importantly, the reconstruction of the long profile of the Warche before capture clearly evidences the knickpoint buried below thick slope deposits in the abandoned valley and the 78–50 ka age of this knickpoint fits perfectly in the series of data points (CRN dates, modern knickpoints in the profiles of the Amblève and the Warche) that attest the propagation of the erosion wave (Demoulin et al. 2012b). After this first capture, the upper Trô Maret continued to flow through the abandoned corridor and the Eau Rouge valley (Fig. 10.10c) but was soon captured in turn by a small creek eroding the part of the abandoned valley that now opened into the incised new Warche.
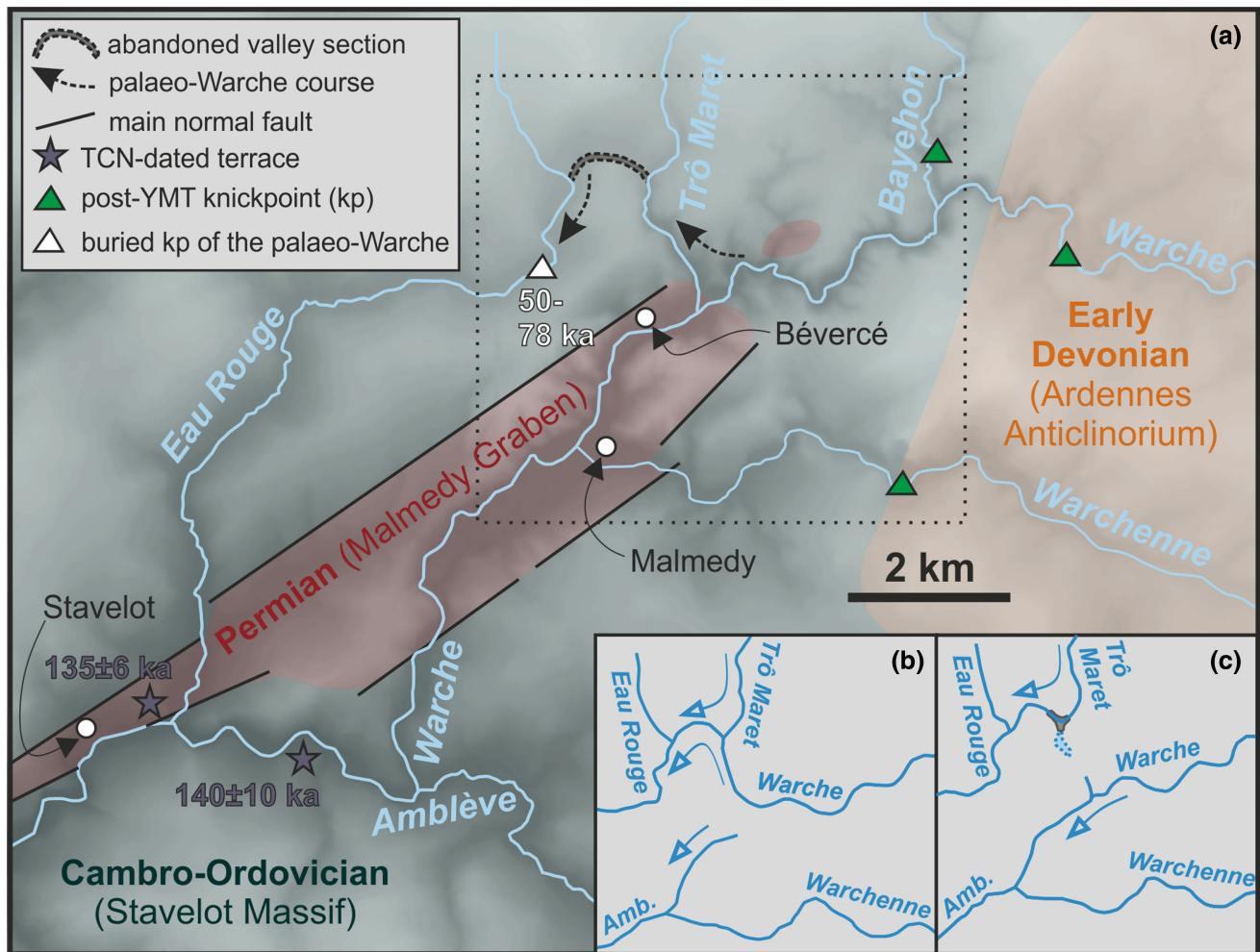
Fig. 10.10 a Simplified geological map of the upper Amblève catchment showing the capture of the Warche river and its palaeo-course (modified from Pissart and Juvigné 1982 and Demoulin et al. 2012b). The *white triangle* locates the knickpoint buried in the former course of the Warche through the current Eau Rouge valley (estimated age range according to Demoulin et al. 2012b). The *lilac stars* locate YMT terrace sediments dated by CRN (Rixhon et al. 2011).

b–c describe the hydrographic network before and after the Warche capture, respectively. Note that a second capture was later responsible for redirecting the Upper Trô Maret toward the new Warche. This second capture occurred through spillover of the small lake that had formed upstream of the alluvial fan accumulated by the Trô Maret in the abandoned valley after the first capture (modified from Pissart and Juvigné 1982)

10.6 Conclusion

The scenic landscapes of the Ardennian valleys with their well-preserved terrace staircases are marked by the dual character of broad Early Pleistocene upper transverse valley sections going into steep-sided narrow Middle Pleistocene lower sections. CRN dating of the younger main terrace (YMT), a prominent marker among the stepped terrace levels, along the lower Meuse—lower Ourthe—Amblève line not only confirmed that the pulse of tectonic uplift responsible for the latest episode of fast river incision in the Ardenne occurred in the Early Middle Pleistocene, sometime around 620 ka, but showed also that the drainage system response took the form of an erosion wave causing the diachronic abandonment of the YMT. This implies a major revision of

the classical model of climatically driven river incision and terrace formation in uplifting massifs in order to fully integrate the diverse ways tectonic uplift controls river incision, including in particular the formation of knickpoints in the river long profiles under increased uplift rates and the associated longitudinal mode of migrating incision. Subordinately, planform changes of the drainage network also resulted from the Quaternary uplift of the Ardenne and the NE Paris basin. While stream piracy was caused by changes in the balance between competing major catchments (Seine, Meuse, Rhine) at the regional scale, it was related to differences in knickpoint migration rates between adjacent streams at the local scale.

First numerical ages of Ardennian river terraces have fundamentally changed our understanding of the

Quaternary evolution of the massif's river system but, be that as it may, further dating effort is required to extend the data set in time (dating other terrace levels) and space (obtaining terrace ages in the middle and upper Meuse and in other tributaries) in order to refine the chronology of river incision. In any case, new, still unpublished, CRN ages obtained for the YMT in the middle Ourthe valley and CRN burial ages of cave sediments in karstic systems associated with several terrace levels in the lower Ourthe seem to fully confirm the new model.

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