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FROM PLANATION SURFACES TO RIVER VALLEYS

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Abstract

The morphological expression of fluvial erosion varies greatly in the geological history. This paper examines, by three typical cases from presently different morpho-climatic zones, whether there is a general temporal evolution and spatial similarity in the specific morphological expressions. In accordance with traditional theory, fluvial denudation ended often by the formation of planated surfaces. According to the specific processes involved those surfaces are defined as peneplains, pediplains or etchplains. They formed frequently in the geological past under specific environmental conditions and have an almost global distribution. However, it looks as if their development terminated towards the end of the Tertiary at most places. Since that time local fluvial incision is much more dominant and expressed as entrenched valleys interrupted by terraces. The latter explicitly established since the Pliocene or beginning Pleistocene. This evolution apparently was due to gradually increasing tectonic uplift in all three cases. Other appearing tendencies in the morphological evolution of the drainage systems in the studied regions are the decreasing influence of tropical weathering at different times in geological history and the increasing morphological impact of climatic changes since the Mio-Pliocene.

Keywords

peneplain, planation, erosion surface, fluvial erosion, incision, uplift, etchplain

Résumé

L'expression morphologique de l'érosion fluviatile est largement variable dans l'histoire géologique. Ici, trois cas de différentes zones morpho-climatiques sont examinés afin de trouver une évolution temporelle générale ou une similarité spatiale de morphologies spécifiques. Selon la théorie traditionnelle, la dénudation fluviatile se termine par un aplanissement. D'après les processus invoqués il s'agit des pénéplaines, des pédiplaines ou des 'etchplains'. Celles-ci se sont développées fréquemment et globalement sous des conditions spécifiques. Pourtant, il semble que ce développement se soit terminé en général vers la fin du Tertiaire. Par la suite, l'évolution se caractérise en revanche principalement par une incision fluviatile aboutissant à la formation de vallées encaissées avec plusieurs terrasses étagées. Ce changement s'est produit dès le Pliocène ou début Pléistocène et doit être lié à un soulèvement tectonique dans chacun des trois cas. Cette évolution générale des bassins fluviaux dans les régions étudiées peut être associée à l'influence décroissante de l'altération tropicale pendant différentes périodes dans l'histoire géologique et l'impact morphologique croissant des changements climatiques dès le Mio-Pliocène.

Mots-clés

pénéplaine, aplanissement, surface d'érosion, érosion fluviatile, incision, soulèvement, 'etchplain'

I. INTRODUCTION

The general result of fluvial activity is expressed both by vertical entrenchment and the more or less extended planar levels that episodically interrupt this vertical evolution. We include here in terms as 'fluvial activity' and 'fluvial morphology', next to linear incision, also the impact of surface runoff and gullying, altogether resulting, for instance, in the potential reduction of hillslopes, formation of pediments and general removal of chemical weathering products. The present contribution focuses on the formation of planar levels which show quite varying aspects in terms of lateral extent. At the small-areal end of the scale, narrow surfaces of some tens of m width occur, while at the large-areal end of the scale, wide plains extend over hundreds of km.

At both scales planar level forms may in general be due to fluvial accumulation or erosion. The small-scaled forms may be attributed to temporary lateral fluvial erosion or accumulation and expressed as river terraces. The large-scaled forms may represent (tectonic) basin fills (by river and runoff action) or final stages of fluvial erosion. The latter forms may be interpreted as peneplains or pediplains, potentially after removal of a deeply weathered mantle. Peneplain formation has been described since the early days of geomorphological theory development (Davis, 1899). It may occur at different stages of evolution: from erosion of only weakly resistant bedrock ('partial peneplains') to fully developed peneplains that have abraded even the most resistant bedrock. Similarly, pediments (of limited extent) and pediplains (of wide extent) occur in (semi-) arid environments (King, 1967). Tropical weathering may replace the mechanical action of rivers in temperate conditions, sculpting a new boundary between solid bedrock and the overlying weathered mantle. In such conditions the activity of rivers is reduced to mere removal of the latter soft sediments expressing that more or less flat roof of the solid bedrock ('etchpain' after Büdel, 1977) as a flat surface in the landscape. Originally, the erosion base of a peneplain was put at sea level by Davis (1899). As these peneplains were formed at low elevation they were called 'applanation' levels. They oppose level formation governed by base-levels at high elevation such as tectonic basins, hydrographic systems or groundwater tables (called 'altiplanation'). To include all kinds of denudation levels, some authors involved the term 'erosional surface' or 'planation surfaces' (e.g. Clark *et al.*, 2006). For a discussion see Babault *et al.* (2005) and Calvet *et al.* (2015).

In the present paper, reflections are made on the spatial occurrence of the described erosional forms and potential systematic temporal trends. As concerns the spatial scale, rather than a global, comprehensive inventory, a selection is made of three regions that may be considered as representative for three presently different morpho-climatic environments: a temperate case (the Ardennes-Eifel Massif in Belgium and adjacent Germany), the tropical environment (the near-coastal erosional lowland of the Guyana Shield in Surinam) and the monsoonal setting (the Tibetan Plateau in China). The temporal evolution may be globally or regionally significant and extends from Mesozoic until Pleistocene times. In addition, attention is paid to the processes that were responsible especially for the creation of the large-scaled erosional surfaces as expressed by the involved researchers. For terrace formation we refer to previous work, for instance by Gibbard and Lewin (2009), Lewin and Gibbard (2010) and Vandenberghe (2015).

II. REGIONAL DEVELOPMENTS

A. Fluvial erosion of the Tibetan Plateau

Clark *et al.* (2006) described remnants of Cretaceous or Eocene 'erosion surfaces', formed at low elevation, across the southeastern Tibetan Plateau margin (Figure 1). Later on, Strobl *et al.* (2012) and Hetzel *et al.* (2011) described also a peneplain on the southern Tibetan Plateau, at present at c. 5300 m altitude, dating from before the Asia-India collision (55-50 Ma) using thermochronology and cosmogenic nuclides. The latter planation process, delivered 3-6 km of sediment to the ocean by river erosion, implying that the peneplanation process persisted near to global sea level until the continental collision (Hetzel *et al.* 2011). However, Rohrmann *et al.* (2012) and Sun *et al.* (2015) claim this planation was formed already in the

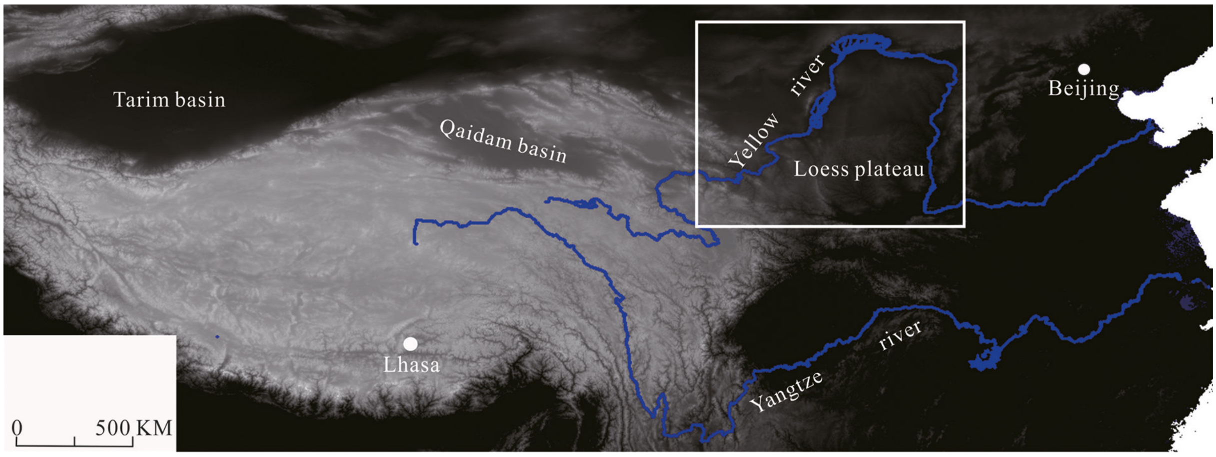

Figure 1. Position of the Tibetan Plateau (derived from ASTER GDEM) with location of Figure 3 (rectangle)

Late Cretaceous, i.e. before the collision, and was substantially uplifted since that time. Many authors describe tectonic uplift and subsequent deformation of the peneplain(s) at different times between middle Eocene and early Oligocene and then up to middle Miocene (e.g. Tapponnier *et al.*, 2001; Y. Wang *et al.*, 2012). But, it is still debated how much of the present elevation of the Tibetan Plateau was reached before the India-Asia collision (Sun *et al.*, 2015). In general, the age of the topographic levels is constrained by the age of posterior tectonic deformation, their burial by undeformed layers and the duration of (river) erosion.

Cui *et al.* (1996) accepted the formation age from Paleogene to Oligocene for the highest 'summit surface' (at present at 5-6 km elevation in the south and probably comparable with the peneplain around Lhasa (cf. supra), at 4-4,2 km in the north) as it truncates Paleogene volcanic rocks. They defined an age of 19 to 15 Ma ago for a lower 'main surface' (at present at 4-4,5 km altitude in the south and c. 3,5 km in the north) that formed as a planation surface on karstified limestone and is connected with Neogene strata in surrounding tectonic basins. An unstable phase of increased sediment accumulation around and in the Xining Basin (NE Tibetan Plateau) was recognized at 20-25 Ma (Xiao *et al.* 2012) and a phase of erosional planation formed at the southern Tibetan Plateau also from post-Oligocene to Late Miocene time (Clark *et al.*, 2006). More to the north of the Plateau, Zhang *et al.* (2012) found truncated bedrock unconformably covered by Neogene sediment (from ~11 Ma onward). Summarizing, it seems that there was peneplain formation right before (and/or after) the plate collision, followed by mountain building/uplift leading to planation surface development ending in the Oligocene (generally in the middle and southern Tibetan Plateau) or (at a lower elevation) in the Middle to Late Miocene (17 to 11 Ma). Finally, we should mention that Yang *et al.* (2015) attribute the formation of remnant erosional surfaces in SE Tibet to tectonically induced disruption of drainage areas instead of peneplain formation at low elevation.

Many authors report erosion of the Late Miocene surface level as a result of subsequent renewed

Figure 2. Two wide terrace levels of Miocene age (full lines) near to Xining (Wang *et al.*, 2012) and terraces of limited extent of Quaternary age (dashed lines) in the incised valley of the Huang Shui river (location Figure 2)

tectonic uplift and faulting (e.g. Clark *et al.*, 2006; Tian *et al.*, 2014). For instance, Y. Wang *et al.* (2012) and Chang *et al.* (2015) report abruptly increasing accumulation in the western Qaidam basin corresponding with enhanced tectonic deformation since 15 Ma. X. Wang *et al.* (2012) identified uplift followed by river erosion after prominent peneplain formation associated with tectonic basin fill until 17 Ma at the NE Tibetan Plateau (Figure 2; Dai *et al.*, 2006). It appearsthat main uplift activity and large planation formation ended somewhere at the end of the Middle Miocene but persisted regionally until Plio-Pleistocene times (Pan *et al.*, 2010; Craddock *et al.* 2010).

After extended planation was terminated a general and considerable erosion took place. Westaway (2009) derived river entrenchment at the SE Tibetan Plateau after c. 3 km uplift at that time (~8 Ma). Similarly, Zheng *et al.* (2006) found convincing arguments in thermochronology for tectonic uplift around 8 Ma ago at the Liupan Shan (NE edge of the Tibetan Plateau; Figure 3), followed by new incision. In the Huang Shui catchment (a main tributary of the upper Huang He or Yellow River), the oldest dissection history after the formation of the Miocene peneplain is manifested by two widely extending terraces slightly below that peneplain (Figures 2, 3) (Wang *et al.* 2012). Micromammalian assemblages at the base of overlying aeolian deposits date from the late Miocene (10-6 Ma). In the middle reach of the Huang He, Pan *et al.* (2009, 2010, 2011) identified erosion ending up in a planation surface at c. 1400 m around 3.7 Myr, followed by renewed tectonic uplift and river incision.

Then, from 1.4 and 2 Ma (highest river terraces in Huang He and Huang Shui respectively) river entrenchment increased drastically until now (Vandenberghe *et al.*, 2011; Hu *et al.*, 2016). This entrenchment might correspond with the start of the main incision in the upper Huang He catchment at the Plateau margin at c. 1.8 Ma which was attributed to progressive headward river erosion rather than to a new uplift phase by Craddock *et al.* (2010). The youngest entrenchment led to a most pronounced staircase of strath terraces induced by climatic changes that, at a smaller time scale, overprint the

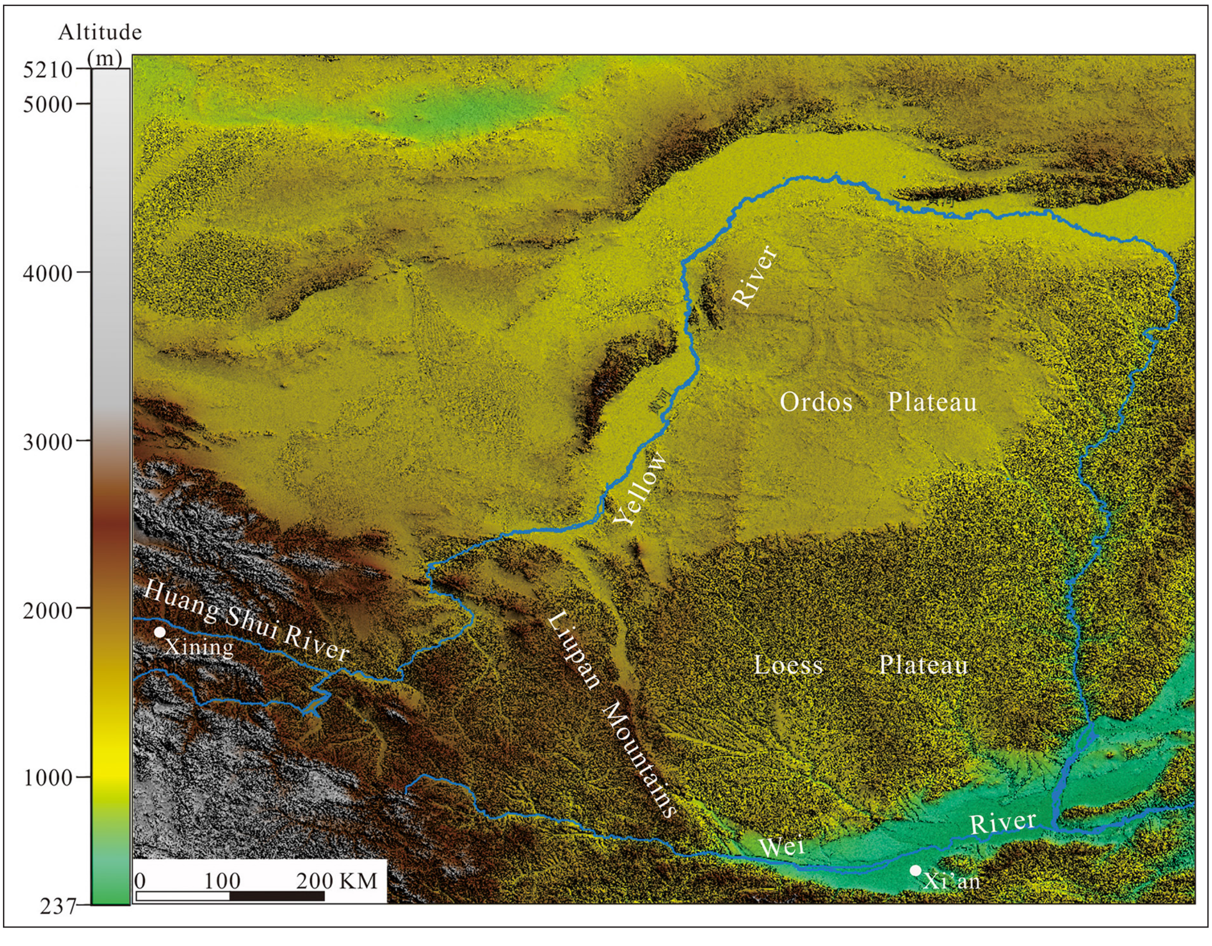

Figure 3. Location map of the Yellow river and Ordos and Loess Plateau

general tectonic uplift (Figure 4) (Pan *et al.*, 2009; Vandenberghe *et al.*, 2011; X. Wang *et al.*, 2014; Zhu *et al.*, 2014; He *et al.*, 2015). It affected both the Proterozoic-Mesozoic substrate of the erosional surfaces and the Cenozoic basin fills.

Already during the Eocene to Miocene period some regional differentiation of tectonic evolution and erosional levels appeared, although this might also be a consequence of dating imprecision. Some planation surfaces have not experienced much or any posterior transformation, except uplift, since the end of the Mesozoic or early Cenozoic, while other levels have experienced one or more phases of fluvial erosion with subsequent formation of new planations (Clark *et al.* 2006). Peneplanation could persist in specific (remote) regions while it was interrupted elsewhere by tectonic deformation followed by renewed fluvial erosion. Calling the planar levels 'erosional surfaces' looks too general as no other processes (as for instance glacial erosion) seem to be involved than fluvial erosion (Lehmkuhl and Owen, 2005). From the Miocene onward the regional differences of the morphological evolution seem more distinct. The wide denudation surface at 1400m in the Huang He developed at the same time (ending 3.7 Ma) as, or a bit later than, wide terraces in the Huang Shui (8-6 Ma). Apparently, dissection of those surfaces started also earlier in the Huang Shui than in the Huang He (Vandenberghe *et al.*, 2011; X. Wang *et al.,* 2012). Thus, the relict landscape is the result of complex local/regional tectonic deformation.

Figure 4. Pleistocene strath terrace of the Huang Shui at +100m above present floodplain. The red arrow points to c. 1 m of fluvial gravel underlying a thick loess cover and overlying a sharp erosional disconformity with the reddish (Mesozoic) bedrock. The blue dashed line depicts the morphological terrace level that is formed on top of the loess that covers the fluvial deposits

B. Denudation of the Ardennes-Eifel Massif

After the Hercynian orogenesis the Ardennes and Rhenish Slate Massif (Figure 5) formed largely as an emerged land during the Mesozoic and Cenozoic. Demoulin (1995a) distinguished several regularly developed and more or less preserved but distinct planation levels dating from the very early Mesozoic onward. In the southern part of

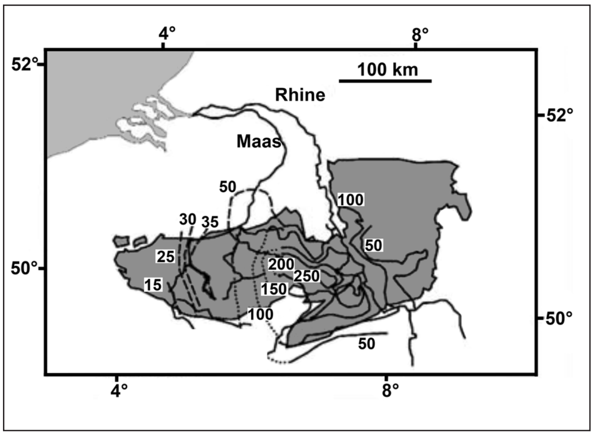

Figure 5. Position of the Ardennes-Eifel region (shaded) and the estimated Middle Pleistocene uplift (modified after Figure 8 in Van Balen *et al.*, 2000, 132)

the Ardennes the oldest level is the post-Hercynian surface. It shows local fluvial deposits from Triassic time without any direct marine influence. This is important as those deposits illustrate the apparent potential of fluvial processes to produce almost plane surfaces although not necessarily lowering them until a real 'planation level' (Demoulin, 1995b). The surface of the Massif continued to develop afterwards at the periphery of Mesozoic and Cenozoic seas. Most beveled surfaces are characterized by the presence of thick soils due to deep chemical weathering in warm and wet conditions. At the base of those soils the weathering front represents another surface, the 'etchplain' in the sense of Büdel (1977). After later removal of the easily erodible soil material, that weathering front may have formed a new planation surface. In this context, the role of rivers was not that of mechanical abrasion of the solid bedrock but was limited to the transport of the already chemically decomposed substrate material. The last general planation surface dominated the landscape of the Massif until the Oligocene. After that, the latter surface was invaded by marine transgressions followed by the formation of a hydrographic network after the marine regression. Since those times, only planation levels of more restricted, local or regional extent were formed until the Early Miocene (Figure 6) (Yans *et al.*, 2003) due to decreased favorable conditions for surface planation: both increased tectonic uplift and cooler and drier climate unfa-

Figure 6. The valley of the Amblève river in the Meuse catchment of the Ardennes Massif near the village of Remouchamps, showing the Oligocene peneplain at c. 320 m altitude (full red line), the wide planation level of (probably) Miocene age at c. 220 m altitude (bluish shaded surface) and the incised Pleistocene valley with some terrace levels of limited extent (indicated by 'A')

vorable for chemical weathering. An example is the so-called Miocene erosional surface formed by renewed chemical alteration under subtropical conditions during the Miocene optimum (Figure 4). Similarly, pediment-like surfaces of limited extent are reported from the Ardennes, probably of Pliocene age and at elevations determined by the local hydrographic network (Gullentops, 1954), and fluvial deposits of that age in the Rhine system (Peters and van Balen, 2007 and references therein).

The development of planation surfaces until the Early Palaeocene is called 'acyclic' by Demoulin (1995a, b) stressing the balance between weathering rate and uplift rate, in contrast to the 'cyclic' evolution during the Cenozoic determined by a shift to preponderant tectonic uplift from the Oligocene onward. Summarizing, after fluvial denudation during the Trias, the planation process during the Jurassic-Cretaceous until the earliest Cenozoic was explicitly by chemical denudation (acyclic evolution), while the planation processes during the Cenozoic correspond more with common fluvial, including hillslope, evolution. This change in morphological process corresponds with changes in climatic conditions from (sub)tropical to semi-arid and ultimately temperate together with increased impact of tectonic uplift (see below). All planation levels with ages until the Oligocene may be considered as peneplains with marine base-levels whether or not in combination with etchplain formation. Development of planation surfaces of post-Oligocene age was limited by local bedrock lithology and/or linked with the internal drainage network (instead of directed by sea level).

An abrupt increase of river incision of Meuse and Rhine in the Ardennes and Eifel occurred around the Plio-Pleistocene transition due to increased tectonic uplift (van den Berg 1996; Peters and van Balen, 2007) while uplift accelerated again early in the Middle Pleistocene (van Balen *et al.* 2000; Rhixon *et al.*, 2014). The latter uplift is expressed in the morphology of both river systems by the change from widely developed terraces to a staircase of narrow terrace surfaces (Figure 6) (Pissart, 1974).

C. Denudation development of the Guyana Shield of Surinam (South America)

From the tropical environment we choose an example at the northern rim of the South American continent in Surinam (Figure 7). The next morphological descriptions and interpretations are largely based on Zonneveld (1993) with approximate dating of the surface levels based on correlation with ages extrapolated from the coastal sedimentology (Krook, 1994) and paleomagnetic dating (Théveniaut and Freyssinet, 2002). In general, a cyclic evolution induced by climatic changes resulted in alternating planation processes and fluvial erosion against a background of tectonically uplift of the Guyana Shield since Cretaceous time. During the warm-humid (pluvial) periods tropical weathering played the dominant role initiating the formation of thick weathered mantles and etchplains. However, during those pluvial periods the removal of the weathered products by surface erosion was limited due to the abundant tropical vegetation. Nevertheless, the rivers were able to incise. Occasionally, river incision continued until it reached the actual or former top surface of unweathered bedrock forming local irregularities in the river thalweg (called 'sula's 'in Surinam; Figure 8). When conditions were more arid (interpluvial periods) a savannah landscape developed in which the vegetation cover was less dense and was not able to protect the surface in the same way (Zonneveld, 1993). Denudation processes, as gully erosion and sheet floods, eroded previously weathered surface sediments and transported them towards the rivers resulting in the formation of pediment-like planation surfaces during the interpluvial periods. Afterwards, the surface sediments at those planation levels were affected by tropical pedogenesis, i.e. the formation of lateritic soils.

A high summit level at c. 300 m elevation, dating from the Cretaceous (Krook, 1994; Théveniaut and Freyssinet, 2002), was covered after its formation by lateritic duricrust during the Early Tertiary. It should be one step lower than the 'Gondwana surface' of King (1962) occurring mainly in nearby Venezuela and dating from the late Cretaceous or older. Remnants of lower planation levels date from the Mio-Pliocene and were also covered with a lateritic crust. One of them formed at about 115m above the present Suriname river. A subsequent widely occurring planation was formed slightly lower (at c. 90 m above the present-day river plains) during the Pliocene or early Pleistocene. It is striking that all those planation levels dip gradually to the north following the general gradient of the drainage systems. It means also that the given elevations are only

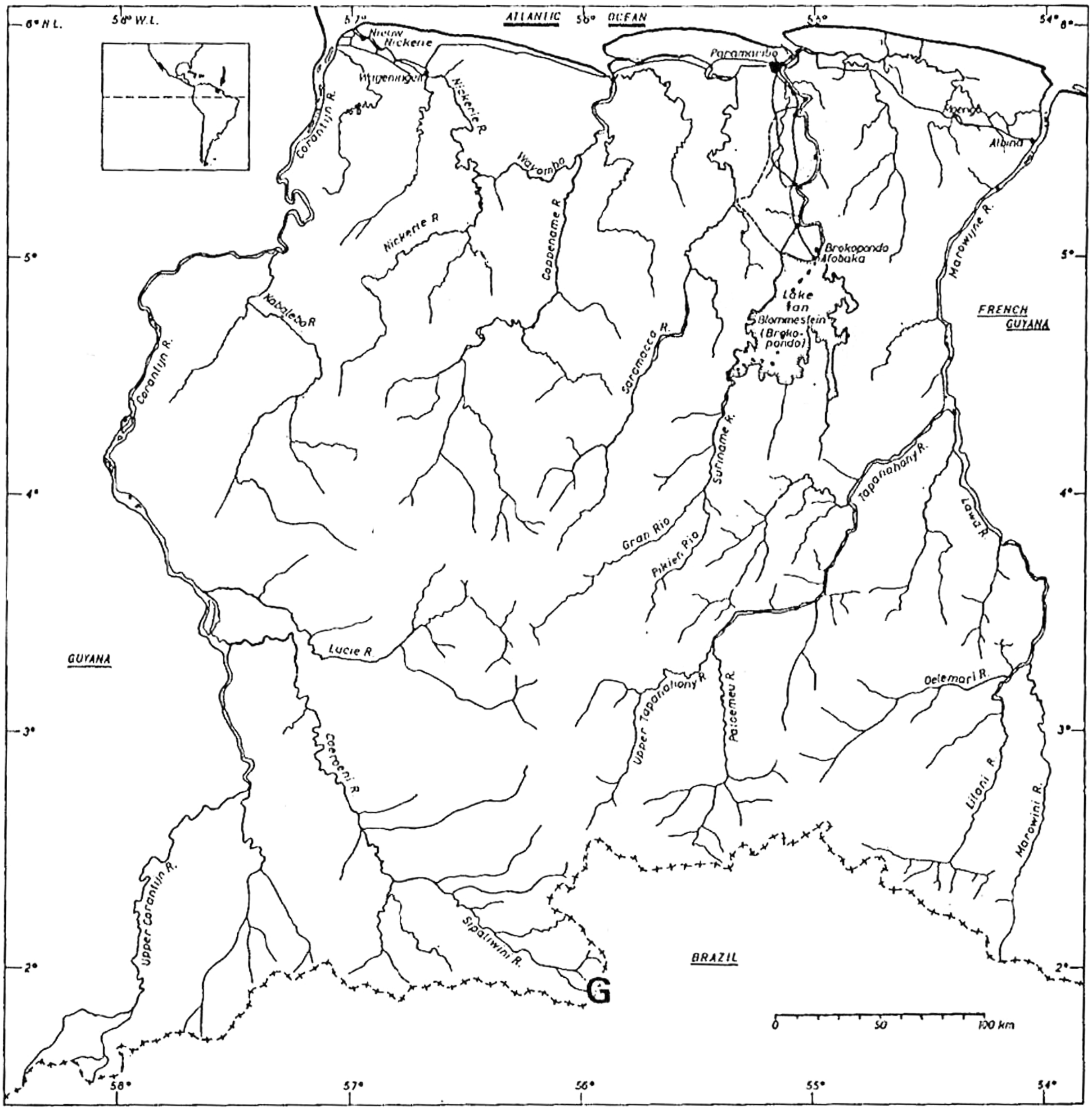

Figure 7. Hydrographic pattern of Surinam (modified after Zonneveld, 1993, Figure 3)

valid for central Surinam. They were linked with the respective ocean margins (Van der Hammen and Wijmstra, 1964; Krook, 1994) and thus may be considered as peneplains or exhumed etchplains. In Pleistocene times vertical erosion became dominant over planation formation. The cyclic evolution became now expressed in the morphology by the formation of river terraces (Kips and Snel, 1979; Vandenberghe, unpubl.), exceptionally interrupted by planations (according to Zonneveld, 1993, for instance at 30 and 15 m above the present river plains). However, care should be taken to the sometimes poor dating and the elevations given above as the latter may vary regionally according to the individual drainage catchment and local tectonic movement. For the same reason estimation of tectonic uplift rates or fluvial incision rates should be too speculative now.

III. DISCUSSION

A. Common characteristics in geomorphological evolution of the three studied regions

The general morphological evolution shows striking similar, but not exactly identical, characteristics in the three regions. Very widely extending planation levels were formed until the end of the Mesozoic. In general, most erosional surfaces formed prior to the Late Oligocene may be considered as pe-

Figure 8. 'Sula's' in the middle reach of the Saramacca river in Surinam

neplains or pediplains (formed at both high and low elevation), sometimes in combination with (exhumed) etchplains. Owing to the tropical warm and wet environment at that time, chemical weathering dominated over mechanical erosion in the Ardennes-Eifel region. Chemical weathering was persisting in the tropical environments of Surinam during the Tertiary. Planation surfaces developed progressively at lower elevation since the beginning of the Cenozoic in the Ardennes-Eifel Massif (after the Cretaceous transgression), and a similar evolution may be supposed for the Guyana Shield. In China a similar evolution started also, although with much more pronounced relief differentiation, from c. 55 Ma onward, i.e. after the India-Asia collision. Erosional platforms dating from the Oligocene are also reported from other regions. An example is the Oligocene 'truncation surface' occurring on top of the Afar plume in the northeastern sector of the Afro-Arabian continent, followed by post-Oligocene rifting and fluvial erosion (Avni *et al.*, 2012).

Since that time, fully developed peneplains were not identified anymore. In Late Miocene and Pliocene times, they were replaced by wide but incompletely developed planation levels or terraces formed in all the reported cases, often separated from each other by rather small scarps. Their exact extent is sometimes difficult to reconstruct due to posterior tectonic deformations. Subsequent fluvial dissection took place globally from the Pliocene onward. Later intensified river entrenchment due to accelerated tectonic uplift during the Pleistocene is a typical and common phenomenon, although at very different rates and starting at different times: 1,1 Ma on the SE Tibet Plateau, 1,4 Ma in the Huang He catchment, around 2 Ma in the Huang Shui basin, and early Middle Pleistocene in the Ardennes- Eifel Massif.

B. The role of climate in the geomorphological development

Denudation induced by chemical weathering is characteristic for humid tropical environments. As aconsequence its role in the morphological sculpting of Surinam is more pronounced than in other environments. In addition, this preponderant process was persisting at least during the entire Tertiary in Surinam, in contrast to the relatively declining importance of the chemical weathering in the course of the Tertiary in extra-tropical regions. The pre-Miocene planation levels in China were generally called peneplains (implying fluvial erosion), however without much argument for the exact process, except for Cui *et al.* (1996) who identified truncation of the bedrock by fluvial erosion, covered by fluvial and fluvio-lacustrine residual sediments. The latter authors invoke both peneplanation and deep weathering on limestone during the Miocene, probably inter-connected in the sense of the 'double levelling surface' ('doppelte Einebnungsfläche') of Büdel (1977). Towards the end of its development the 19 à 15 Ma old 'main surface' of Cui *et al.* (1996) should have been prone to pedimentation. A more prominent role for tropical weathering was put forward by Demoulin (1995a), rather than fluvial erosion, for the Mesozoic and early Cenozoic planation in the Ardennes-Eifel Massif.

In the Eifel-Ardennes Massif chemical weathering as a dominant process was gradually replaced by physical erosion from the early Tertiary onward (Demoulin, 1995b) although deep chemical weathering persisted in the Early Miocene (Yans *et al.*, 2003). It may be supposed that the general change from dominantly chemical to physical denudation in the late Tertiary and Pleistocene may be attributed to a progressive shift from tropical to more temperate conditions, although occurring regionally at different times, and in combination with increased tectonic uplift (see below). The establishment of terrace staircases, generally developing since Pliocene time, is in broad terms supposed to coincide with glacial-interglacial alternations (e.g. Bridgland and Westaway, 2008). This climatic effect overprinted the effect of the generally more gradual tectonic uplift. Such climate changes were mostly not obviously expressed in the morphology during the Tertiary, except in Surinam where humid-dry alternations resulted in shifts between tropical forests and savannah environments respectively and were held responsible for alternating processes of chemical weathering and morphological dissection by Van der Hammen and Wijmstra (1964), Zonneveld (1993) and Krook (1994).

C. The role of tectonic movement in the geomorphological development

The origin of tectonic uplift is beyond the scope of this paper and is still debated; but the timing of the uplift in relation with the general geomorphological evolution is more important here. In the mechanism for drainage basin uplift, as hypothesized by Westaway (2012 and references therein), increased erosion in uplands and sedimentation in depocentres induce flow of lower-crustal material from beneath the depocentres to beneath the uplands. The latter author and Bridgland and Westaway (2009, 2012), linking climate and tectonic movement, suppose this lower crust flow and subsequent uplift in the Cenozoic should be a result of global climate-induced erosion not only in intraplate regions but also, for instance, in the southeastern Tibetan Plateau (Westaway 2009). According to the latter author the Late Miocene river entrenchment in that region should correspond with the maximum strength of the Asian monsoon. According to Clark *et al.* (2006) and Hetzel *et al.* (2011), however, the present height of the relict beveled landscape of the southern Tibet Plateau has to be attributed to isostatically compensated thickening of the lower crust rather than to isostatic rebound and lower crust flow due to surface erosion since the narrow gorges produced a too small volume of eroded material for such an effect.

Regardless of the origin of the tectonic uplift, its effects on the geomorphological development in pre-Pleistocene times may have been outpaced by the effects of chemical weathering, especially in regions that were not intensely affected by tectonic movements as, for instance, the Ardennes-Eifel Massif (Demoulin, 1995b). This is in contrast with the strongly uplifted Tibetan Plateau that shows considerable mechanical denudation during the Tertiary and a relatively much reduced chemical denudation during the Pleistocene.

Although only based on the investigation of three pilot regions, it looks as if rates of fluvial incision intensified globally since the Pliocene and Early Pleistocene and continued progressively from that time onward. Accelerated tectonic uplift, as the cause for the Pleistocene entrenchment, amounts to c. 0.21 m/ka on the NE Tibetan Plateau (which is the average for the past 2 Ma in the Huang Shui catchment (Vandenberghe *et al.*, 2011; Wang *et al.*, 2012) and Weihe catchment (Pan *et al.*, 2007). Also Tian *et al.* (2014) derived uplift rates of 0,3 to 0,8 m/ka since the end of the Miocene for the eastern Tibetan Plateau. Comparable values of 0,1 à 0.5 m/ka appeared on the SE Tibetan Plateau, but increased to c. 2 m/ka for the past 0,063 Ma (Zhao *et al.*, 2011; He *et al.*, 2015). And, detailed dating of a terrace sequence in the upper Brahmaputra catchment in the Himalayan region showed a gradual increase in uplift rate from c. 0,1 m/ka at c. 2 Ma ago to 1 m/ka for the past 0,010 Ma (Zhu *et al.*, 2014). Similarly, high modern uplift rates of 2 to 6 m/ka are derived for the eastern Tibetan Plateau by precise leveling (Hao *et al.*, 2014). Further, this supposes an uplift rate that strongly contrasts with the much weaker uplift rate of the southern Tibetan Plateau before the Pliocene averaging c. 0,01 m/ka (Hetzel *et al.*, 2011; Strobl *et al.*, 2012), notwithstanding additional reliable ages are highly desirable for a robust and coherent reconstruction of uplift and river dissection history.

Using their concept of climate-related lower crustal flow, Bridgland and Westaway (2008) suggest that global uplift resulted from late-Pliocene global cooling. Also Charreau *et al.* (2011) adopted a significant climatic impact for the abrupt increase of erosion rate at 2.5 Ma for the Tian Shan (central Asia). However, not considering tectonic changes, they suggest the increased erosion was due to a shift from fluvial to glacial erosion at the onset of Quaternary ice ages. However, at least this explanation cannot be generalized since increased incision rates are also obvious in non-glaciated catchments.

Similarly, the widely recognized mid- Pleistocene accelerated uplift was attributed to different causes. Bridgland and Westaway (2008) invoke erosional isostasy due to increased severity of glacial periods from the Mid-Pleistocene Revolution onward. For the Ardennes-Eifel Massif uplift, lithospheric processes of local to regional extent were suggested by Garcia-Castellanos *et al.* (2000) and Van Balen *et al.* (2000). Diapiric mantle plumes were invoked, for instance, for the Mongolian plateau (north of the Tibetan Plateau) whose uplift was not driven by the India-Asia collision (Windley and Allen, 1993). Finally, at a local-to-regional scale glacio-isostasy may be held responsible for tectonic movements, for instance in north-central Europe (van Balen *et al.* 2000, 2010; Winsemann *et al.*, 2015). Again, the absence of ice sheets - as for instance in the Huang Shui catchment (China) - opposes the generalisation of such an explanation. To conclude, the variety of local causes and the unequal timing of accelerated uplift at a global scale do not seem to be in favour of a common explanation for the initiation of accelerated river entrenchment at c. 3 Ma and in the mid-Pleistocene.

IV. SYNTHESIS: PLANATION SURFACES AND TERRACE STAIRCASES

Our understanding of the uplift history of erosional planation surfaces has considerably increased in the last decades thanks to a boost of dating techniques of those surfaces (e.g. by thermochronology) and the improved knowledge of deep-seated solid-earth processes (Calvet, 2015). Three kinds of fluvial denudation took place successively. At first, planation surfaces of very wide extent dominated during the Mesozoic and early Tertiary. In general, it looks as the impact of intense chemical weathering was preponderant during the Mesozoic and continuing into the Tertiary with regionally varying degrees. The Oligocene planation surface, despite its loosely defined time frame, is well pronounced in many regions and appears to be the last one of those widely extending planations. The intensity of chemical weathering gradually slowed down during the early Tertiary when widely extended planation levels were formed by erosional truncation. Mechanical erosion by rivers and surface runoff became more and more important although they played a significant role before in removing the products of the chemical weathering. This transition corresponds with the change from acyclic to cyclic planation by Demoulin (1995a, b). In Surinam, however, chemical weathering continued its dominant impact on landscape denudation until Pliocene times before cyclic fluvial erosion was initiated (Zonneveld, 1993). However, in the course of the Tertiary all regions experienced relatively more important tectonic uplift that created the relief intensity and river gradient that was required for fluvial denudation and the formation of distinct topographic steps between different planation surfaces (Vandenberghe and Maddy, 2001).

Secondly, widely developed terraces and planations of regional extent formed from the end of the Miocene or Pliocene onward. Both in north China and the Ardennes-Eifel Massif wide terraces separated by relatively small escarpments initiated this process. Thirdly, after that real staircases with much more expressed scarps started from the Early or Middle Pleistocene onward. Thus, in the latter period river entrenchment was more important than lateral expansion of floodplains as a result of further increased tectonic uplift. When looking in detail, the sharp incision started at different times and incision rates reflect spatial and temporal differences (Pan *et al.* 2009; Wang *et al.*, 2014; He *et al.*, 2015; Hu *et al.*, 2016). This regional and temporal variability makes it difficult to invoke a global cause that was occurring at the same time, whether it would be of tectonic or climatic origin. However, mere climatic alternations cannot be held responsible for terrace staircases as vertical incision requires always a sufficient river gradient that can only be provided by relative uplift of the catchment (Vandenberghe and Maddy, 2001). Nevertheless, a general (global) tendency should not be completely ruled out, especially when taking into account the local/regional role that may be played by locally differentiated tectonic movements and climate-related delay effects and crossing of thresholds in geomorphological development (Schumm, 1979; Vandenberghe and Woo, 2002).

Finally, it is important to stress that the resolution of the timescale that we apply in the present analysis is coarser and coarser when going back in time. Thus, it may be possible that events that we now consider ‘contemporaneous’ during pre-Pleistocene time occurred with similar temporal differences as those that we are distinguishing within the Pleistocene. However, even in such a hypothesis some of our general tendencies remain upright. For instance, it is impossible to negate completely the greater role played by tectonic uplift since the end of the Tertiary, the generally declining importance of tropical weathering with time and the increasing importance of climatic alternations since the Mio-Pliocene.

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