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Quantifying erosion over timescales of one million years: A photogrammetric approach on the amount of Rhenish erosion in southwestern Germany

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ABSTRACT

The Lein valley in southwestern Germany possesses well-preserved Pliocene to mid Pleistocene land surfaces featuring a gentle relief and sediments accumulated by former tributaries of the Danube. This ancient Danubian land surface was captured and incised by mid Pleistocene to Holocene tributaries of the River Rhine. In a photogrammetric approach we calculated the volume of material extracted by Rhenish erosion providing a first quantification of the effects of stream piracy on timescales of about 1 Ma. Using stereoscopic surface modelling software a DEM was generated with a resolution of 5 m. From borehole data, literature, geological maps, and own field observations we determined the morphometric parameters of the ancient Danubian Ur–Lein valley. The gradient was imported as a 3D-breakline into the model where it controls the reinterpolation of surrounding data points. The result is a high-resolution DEM of the valley of the Ur–Lein. Subtraction of the DEM of the actual landscape from the DEM of the ancient Ur–Lein valley yields a model representing the rock volume eroded by the Rhenish Lein which totals 1.39 km^3 and converts into a rate of erosion between 63 and 74 mm/ka over a period of 700 to 600 ka, respectively, in accordance with figures obtained elsewhere in Central Europe through cosmogenic nuclides. It reflects the dominance of frequent fluctuations in climate and is considered to be mainly a product of strong changes in temperature and related processes during the transitional times between mid to late Pleistocene warm and cold states. A filtering procedure applied to cold and transitional state erosion rates of the Middle and Late Pleistocene yielded peak values between 66 and 77 mm/ka, up to three times higher than the modern rate or the rate of warm-state episodes. An assessment of the contribution of Rhenish stream piracy on long-term mid Pleistocene denudation under changing climate conditions resulted in a maximum 4.9-fold acceleration.

1. Introduction

The present-day inventory of landforms in southwestern Germany is mainly a product of two strongly discontinuous processes: a) late Alpine tilting of the foreland crust and subsequent post-collisional isostatic uplift (Strasser et al., 2009), and b) Neogene climate change. Two large rivers competed for the extraction of material: the eastflowing Danube and the northflowing Rhine (Fig. 1; Wagner, 1952, 1953, 1963). Following an episode of prolonged isostatic uplift the Danube came into existence only during the latest Miocene conquering large parts of an ancient network initially draining into the Early Miocene Sea of the Upper Marine Molasse (Fig. 2A) or into the continental basin of the Mid to Late Miocene Upper Freshwater Molasse (Fig. 2B; Villinger, 1986; Schall, 2002; Strasser et al., 2009). The Rhine considerably pre-dates the Danube occupying the Rhine Graben since early Miocene times (20 Ma; Simon, 2008) although only in the Late Miocene did it start to capture large areas of southwestern Germany (Fig. 2B to D; Simon, 1987, 1988; Hagdorn and Simon, 1988; Schall, 2002). Rhenish incision strongly followed the blueprint of original Danubian valley directions and nodes of bifurcation (Dongus, 1977, 2000). Flow reversal resulted in the formation of numerous valley drainage divides moving downstream (in the Danubian sense of flow) as Rhenish incision advanced. Escarpments became deeply penetrated along these pre-existing valleys and scarplands were efficiently attacked through headwater erosion by groundwater sapping working mainly on the backsides of escarpments (Fig. 2). In most places the transition from ancient to young landforms is a sharp break (Wagner, 1953; Dongus, 1977, 2000; Strasser et al., 2008). The flanks of larger Rhenish valleys are often modified by periglacial processes and landslides.

The present watershed between Rhine and Danube is situated near the edge of a large escarpment of Upper Jurassic carbonate rocks corresponding to an intensively karstificated scarpland (Schwäbische Alb, Figs. 1–3). Outside the modern Danubian catchment area remnants of Danubian surfaces are common but especially extensive and well-preserved in our study area (Figs. 1 and 2, Dongus, 1977, 2000). The gentle relief of these surfaces is carved into a scarpland of Late Triassic Keuper sandstones and Early Liassic carbonates, sandstones, and claystones (Fig. 3). During final slow-down of Danubian erosion and

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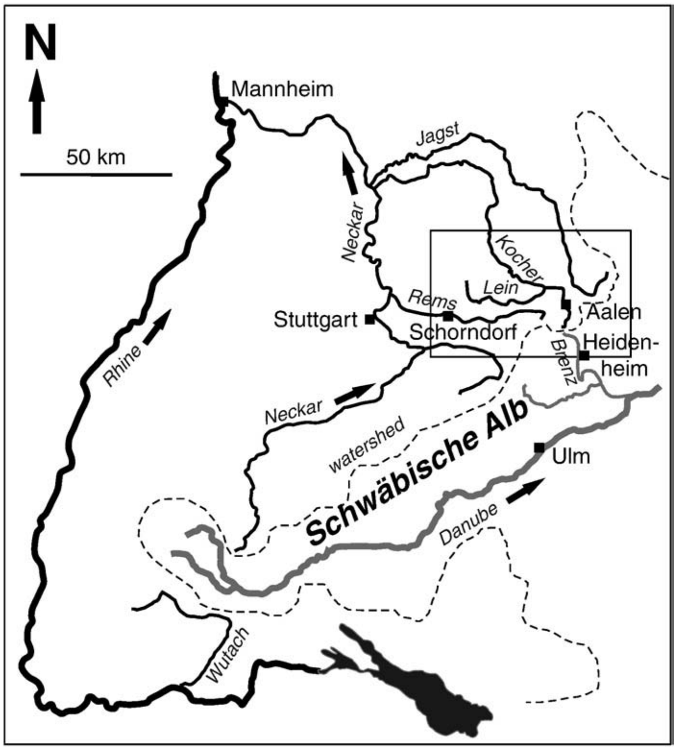

Fig. 1. Actual Danubian and Rhenish river systems and their drainage divide in southwestern Germany. Study area: black box.

just before capture by Rhenian tributaries, the lower part of this scarpland became covered by a blanket of quartz-rich braided river sediments (Goldshöfer Sande, also named Goldshöfe-Sand, Fig. 3) providing an upper reference frame for the calculation of rock volumes extracted by Rhenish incision. Based on some local findings of mammal bones or teeth, or on morphological, morphometrical, petrographical, or palaeomagnetic correlations the capture of the Danubian surface of the study area must have occurred between 700 and 600 ka (Fig. 2c; Simon, 1987, 1988; Hagdorn and Simon, 1988; Etzold, 1994a). Some of the Rhenish valleys undercutting the Danubian surface locally preserve small remnants of early Rhenish river terraces.

We have selected our study area in the surroundings of the Lein valley (Figs. 1 and 2) because of the good preservation of Danubian land surfaces and Rhenish terraces. Our main objective is to determine volumes of material eroded by Rhenish incision and to convert these figures into rates of erosion since the cessation of Danubian activity. Digital elevation models have been applied to the reconstruction of ancient landforms, in the calculation of eroded rock volumes, and in the determination of erosion rates (Abel et al., 2000; Abel, 2003; Becker-Haumann, 2005, 2007; Gani et al., 2007). A common procedure with GIS applications is to interpolate a palaeosurface from point data. This method yields plausible figures for eroded rock volumes if the data base is dense and consistent. We have optimized data acquisition and minimized possible errors using stereoscopic surface modelling software. Our results provide a first quantification of the effects of stream piracy on timescales of about 1 Ma.

2. Local morphology, hydrology, and palaeohydrology

The study area is drained by the Rhenish tributaries the Kocher, Jagst, and Rems (Fig. 1). The Lein is a tributary to the Kocher maintaining its original Danubian flow direction resulting in an elbow of capture at the confluence (Figs. 1–3).

The Brenz is the only remaining Danubian tributary of the area. The watershed between the sources of the Danubian Brenz and the Rhenish Kocher is a valley drainage divide presently situated at 507 m a.s.l. (Fig. 4). Stream capture has also been effective among Rhenish tributaries resulting in hierarchically less important valley drainage divides such as the one separating the Rems and Kocher north of Essingent (470 m a.s.l.) and another separating the Lein and Wieslauf near Breitenfürst (493 m a.s.l.; Fig. 4). The smooth hills of the Frickenhofer Höhe (Figs. 3 and 4) are an extraordinarily well-preserved remnant of ancient Danubian erosional landforms most probably created during the early Pliocene (Dongus, 1977, 2000). Remnants of the early and mid Pleistocene Goldshöfer Sande (Fraas, 1871) are still widely preserved (Figs. 3 and 4). Their occurrence close to the large escarpment of Upper Jurassic carbonate rocks forming the morphological backbone of the Schwäbische Alb strongly suggests that this escarpment had not undergone substantial changes since their time of formation.

From Late Miocene until early Middle Pleistocene times the Danubian predecessors of today's Rhenish tributaries the Kocher, Lein, Jagst, and Rems drained southward by-passing the escarpment of Upper Jurassic carbonate rocks of the Schwäbische Alb along an antecedent incised valley carved by the predecessor of today's Brenz, the Ur–Brenz (Figs. 2 and 4; Eisenhut, 1975; Simon, 1987, 1988; Hagdorn and Simon, 1988). Near Heidenheim (Figs. 1 and 2) the rocky riverbed of this incised valley has been drilled at 451.5 m a.s.l.. Etzold (1994a) obtained a gradient of 0.2 to 0.5‰ for the Ur–Brenz and its large catchment area (2110 km^2 as compared to 810 km^2 of today's Brenz).

3. Goldshöfer Sande: latest Danubian sediments

The importance of these early Middle Pleistocene deposits as Danubian "last-minute" accumulations forming a decametre-thick (<20 m) veneer of sandy braided river deposits just north of the entrance to the valley incised by the Ur–Brenz (Brenztal-Pforte, Fig. 3) has been emphasized in a long series of geological studies (Fraas, 1871; Scheu, 1909; Schmidt, 1921; Pahl, 1924; Wagner, 1926, 1952). In their present-day state of diagenesis the Goldshöfer Sande appear as decarbonated yellowish to brownish almost pure medium to coarse quartz sands with typical braided stream cross-bedding features indicating flow towards the South and Southeast (Beurer, 1963). According to Pahl (1924), Wagner, R. (1952), and Zeese (1972, 1975)) quartz grains had been washed out from the surrounding scarpland upon the Late Triassic sandstones. Small cliffs of Lower and Mid Jurassic sandstones supplied abundant pebbles admixed to the sands; chert points to local point sources from the escarpment of Upper Jurassic limestones but fragments of Upper Jurassic limestones only occur very close to the escarpment.

North of Aalen drilling has revealed that the Goldshöfer Sande rest unconformably upon two strath terraces: an upper (older) terrace at 482 to 481 m a.s.l., and a lower (younger) terrace starting at 462 to 458 m a.s.l. (Wagner, 1952) dipping towards 456 to 454 m a.s.l. immediately north of the entrance to the valley incised by the Ur–Brenz (Brenztal-Pforte, Fig. 3). Given the age constraints (Villinger, 2004; Villinger and Fischer, 2005) provided by palaeontological data (Pahl, 1924; Hennig, 1952; Adam, 1953, 1961; Koenigswald, 1983), palaeomagnetic studies (Fromm, 1980, 1983; Cande and Kent, 1995), and stratigraphic cross-correlations (Etzold, 1994a), these strath terraces and their discontinuous covering with Goldshöfer Sande reveal important details from the episode when the Danubian regime gave way to Rhenish dominance: 1) Danubian entrenchment producing the set of two strath terraces was still intermittently active while the Goldshöfer Sande were already being accumulated; 2) onlap of braided-stream deposits was a consequence of abundant water supply and concomitant choking of valley floors during climate fluctuations at the transition from Early to Middle Pleistocene; 3) demise of Danubian sedimentation was caused by the rapidly advancing capture of all tributaries.

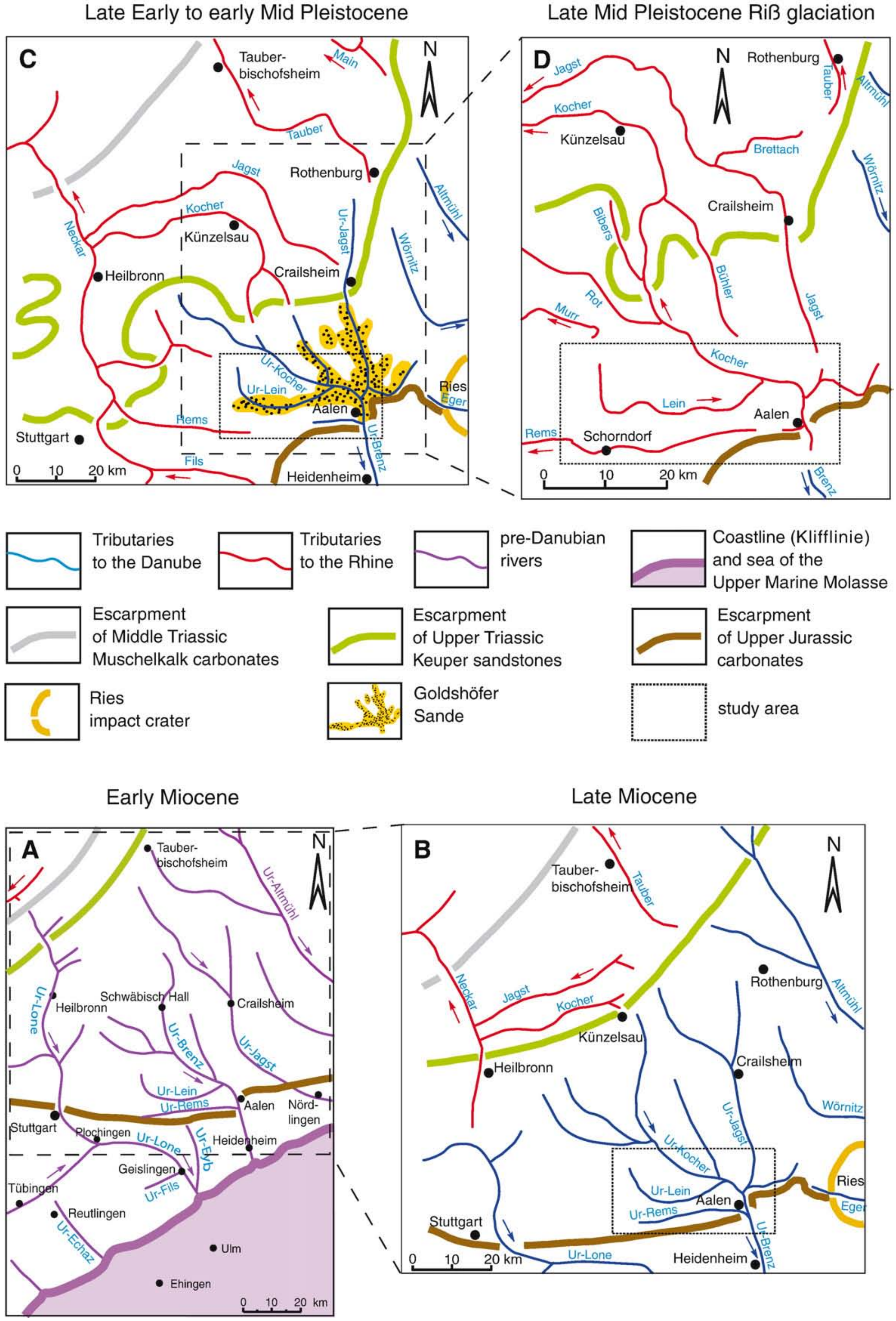

Fig. 2. Capture of pre-Danubian and Danubian rivers by tributaries to the Rhine (modified after Simon, 1988; Schall, 2002). Note that Rhenish incision strongly followed the blueprint of original dendritic Danubian valley directions and nodes of bifurcation; many Rhenish tributaries still maintain Danubian flow directions resulting in elbows of capture at confluences with rivers of comparable category.

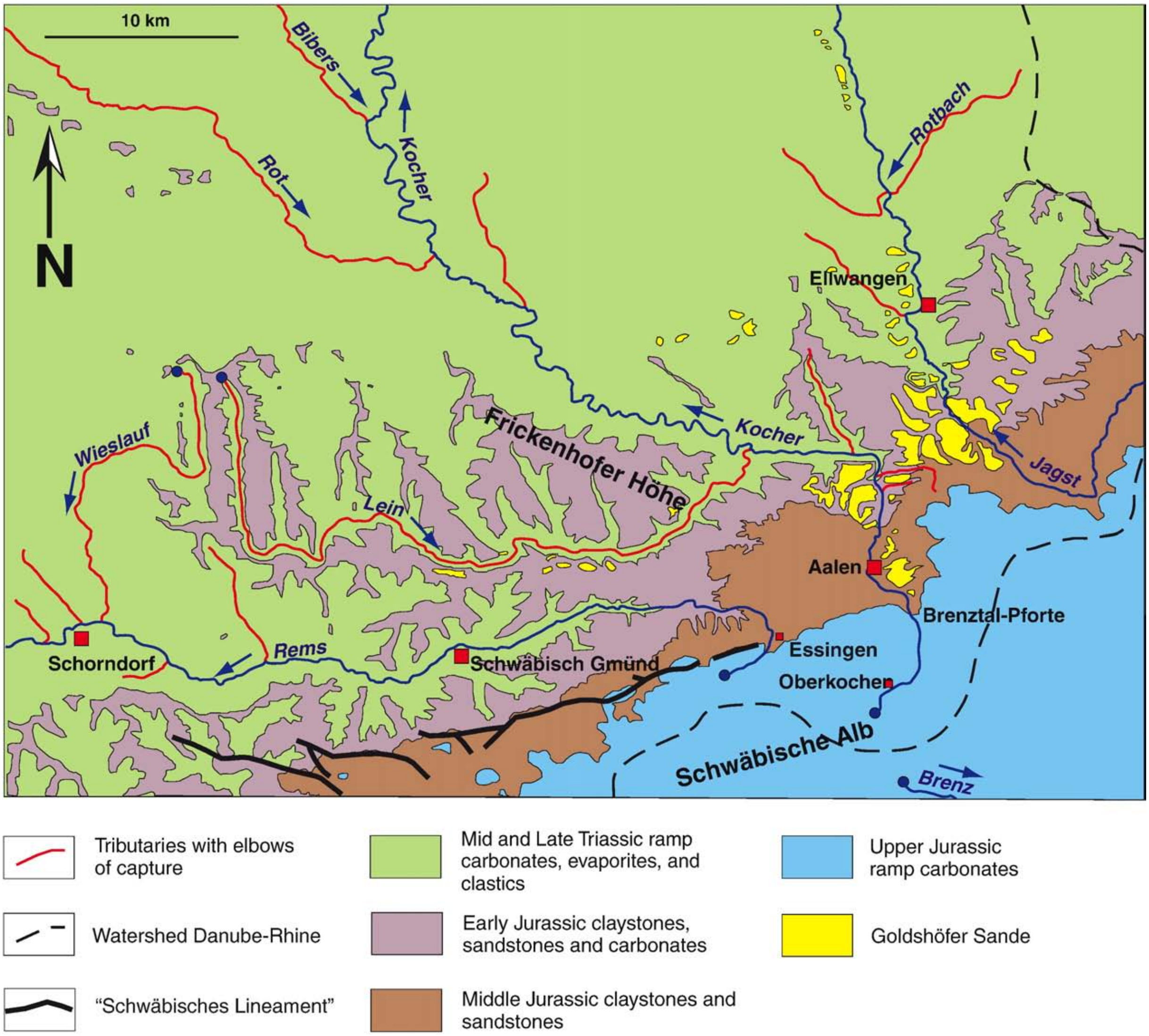

Fig. 3. Geological map of the study area and its surroundings (modified after Landesamt für Geologie, Rohstoffe und Bergbau, 1996). Note that the Frickenhofer Höhe, where most of the former Danubian drainage system is preserved, is part of an extended scarpland mainly underlain by Early Jurassic claystones, sandstones, and a few metres of carbonates. The River Lein is presently incising sandstone of the Late Triassic. Relics of Goldshöfer Sande are mainly concentrated along the upper courses of the Kocher and Jagst and along the Lein.

4. Rhenian terraces

A 90 m-terrace found within the Rhenish Kocher valley correlates with the younger (lower) terrace of the Goldshöfer Sande placing it into the crucial time-span (early Middle Pleistocene) just before the cessation of Danubian activity. This means that during the transition time from Danubian to Rhenian hegemony both river systems left their final and initial marks, respectively, and some remnants of these sedimentary documents escaped later erosion. In our opinion, this is a strong point in favour of local tectonic quiescence and an overwhelming control of climate over morphology.

According to Eisenhut (1962, 1971, 1972, 1975), Frank and Vollrath (1971), Hagdorn and Simon (1988), Etzold (1994a), Hönig (1994), Villinger (2004), and Villinger and Fischer (2005) the following correlations can be made among terraces lower than 90 m. A marked terrace situated at 60 to 50 m above present valley floor (Talrandterrasse) is observed in the Rems and Lein valleys; most probably it corresponds to the Hoßkirch glaciation (OIS 12 glaciation after Winn et al. (1998); ~500 ka to ~460 ka after German Stratigraphic Commission (2002), and Villinger (2004)). A 30–20 m terrace found within the Kocher and Rems valleys correlates with the Riß glaciation (OIS 6 glaciation after Winn et al. (1998); ~215 ka to ~130 ka after German Stratigraphic Commission (2002), Villinger (2004), and Villinger and Fischer (2005)). The lowest and youngest terrace (Niederterrasse) is located at 5 to 10 m but locally underlies Holocene deposits and correlates with the Würm glaciation (OIS 2 glaciation after Winn et al. (1998); 25 ka to 15 ka after Villinger (2004), and Villinger and Fischer (2005)).

Rhenian entrenchment was at its maximum during the transition from the Riß glaciation to the Eem warm state (126 ka–115 ka, Villinger and Fischer, 2005). Choking of the Eemian valley floor and subsequent incision/refilling are correlated with the Würm glaciation and the Holocene, respectively. Net Holocene infilling totals 5 to 8 m in the Kocher valley and 3 to 7 m in the Lein and Rems valleys (Eisenhut, 1972; Etzold, 1994a).

5. Methods

5.1. Generation of and corrections on the DEM

A DEM was generated using 329 aerial photographs taken in 1968 showing the landscape in a state of comparatively low urbanization and prior to the onset of widespread industrial crop production techniques; the forest coverage was slightly less than today. Automatic digital aerial

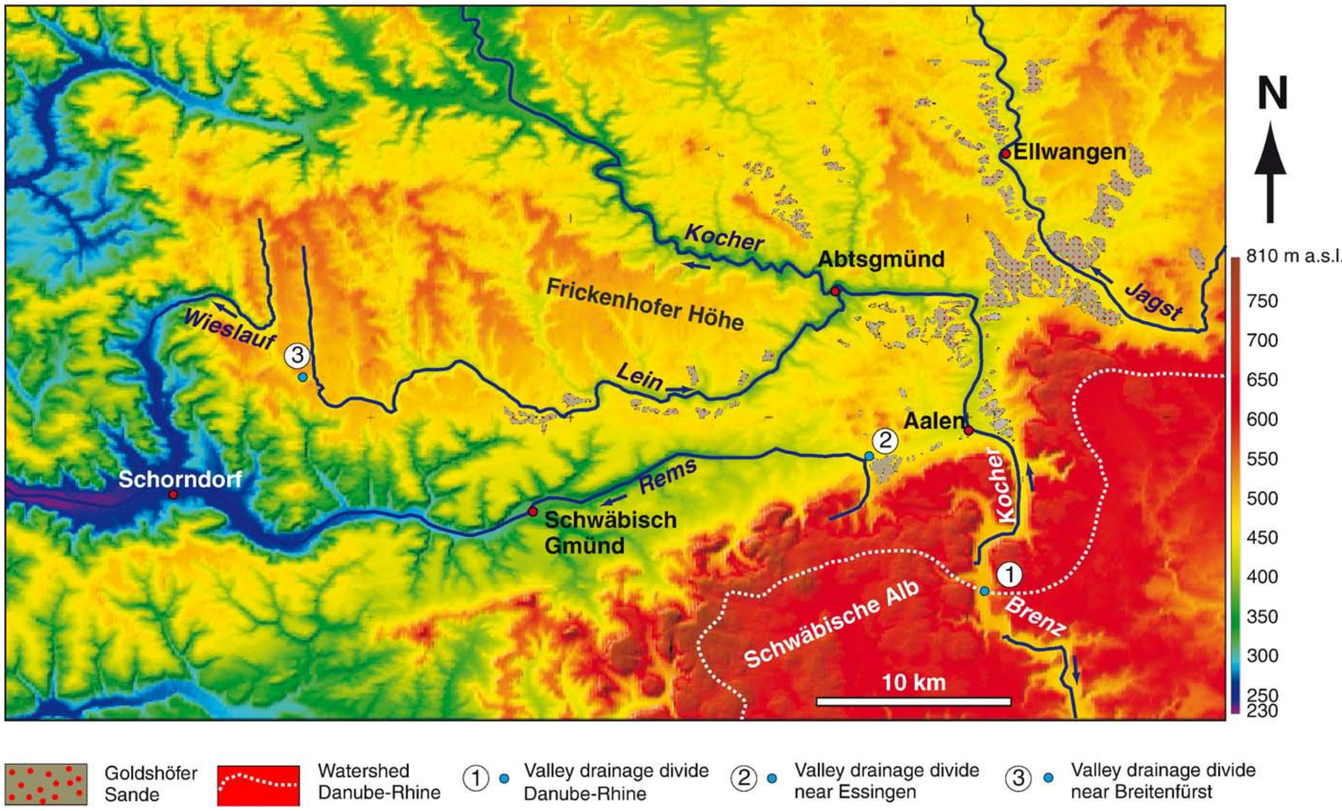

Fig. 4. Shaded relief showing main geomorphic features in the surroundings of the study area. Reprocessed SRTM DTED® Level 1 data overlain with position of Goldshöfer Sande (locations of Goldshöfer Sande after Etzold, 1994b; Laske and Reicherter, 2000; Reicherter, 2000a,b; Etzold and Nitsch, 2007). Valley drainage divides are marked.

triangulation and generation of a DEM with a resolution of 5 m were performed using software MATCH-AT (Inpho) and MATCH-T (Inpho), respectively. The accuracy of the DEM was controlled using triangulation points located in the north, centre, and south of corresponding pairs of aerial photographs. The model obtained had to be corrected for small errors in relative orientation caused by low image quality commonly resulting in considerable differences in absolute height. In areas with vertical differences surpassing 5 m the accuracy of the model was increased through corresponding corrections in relative orientation. The combined procedure resulted in an accuracy of ± 1 m for most of the study area (Fig. 5A). Small forested areas, especially within the Lein valley, were semiautomatically corrected directly within the model using software DTMaster (Inpho) in stereoscopic mode. The volume corresponding to large forests, however, was calculated on an average height of 15 m. This figure (0.032 km^3) must be added to the volume of eroded rocks obtained in the final step of balancing.

5.2. Construction of a palaeosurface

Within the Lein valley abundant remnants of the younger terrace of the Goldshöfer Sande provide the reference frame for the reconstruction of the palaeosurface of the Ur–Lein valley. From borehole data, literature, geological maps, and our own field observations we determined the morphometric parameters: valley width, absolute height, and sector-specific gradient. The decreasing 3D-gradient was then digitized as a breakline in DTMaster (Inpho) where it controls the reinterpolation of surrounding data points from the DEM of the actual surface. The result is a high-resolution DEM of the valley of the Ur–Lein during the time of deposition of the Goldshöfer Sande (Fig. 5B).

We have restricted the area to be reconstructed to those parts of the Lein valley where both the Rhenish Lein and the Danubian Ur–Lein have been flowing. This restriction was necessary because otherwise results would not have been representative for the entire valley: the upper course of the actual Lein formerly only was a tributary to the Ur–Lein, but the Ur–Lein originated beyond the present valley drainage divide near Breitenfürst where corresponding gravel is preserved at 490 m a.s.l. (Fig. 4, Eisenhut, 1972). The reconstructed palaeosurface therefore starts in the West at the valley drainage divide near Breitenfürst. In the East it ends at the confluence with the Kocher valley.

6. Results

6.1. Morphometric results

Fig. 6 shows long profiles of the actual Lein valley and the Ur–Lein valley. We have extended the profile into a part of the ancient Danubian Ur–Kocher valley (the Rhenish Kocher is the successor to the Danubian Ur–Kocher flowing in reverse direction, and the Ur–Lein was a tributary to the Ur–Kocher mouthing into the Ur–Brenz valley, Fig. 2) because morphometric data are scarce from the lowermost Lein valley, but well represented within the Kocher valley. The length of the profile is 44.25 km; correspondingly, the base of the Goldshöfer Sande descends from 490 m a.s.l. in the west to 453.3 m a.s.l. in the east resulting in an average palaeogradient of 0.82‰ (Fig. 6) decreasing from 1.28‰ through 0.71‰ to 0.46‰ in the upper, middle, and lower course, respectively. In contrast, the present Lein valley has an average gradient of 4.1‰ (2.8‰ in the reconstructed sector).

Further quantitative morphometric results can be obtained when subtracting the DEM of the actual landscape (Fig. 5A) from the DEM of the ancient Ur–Lein valley bottom (Fig. 5B). The result is a model representing the rock volume excavated by the Rhenish Lein (Fig. 5C). Depth of excavation ranges from 20 m near the upstream end of the model to 90 m near the confluence with the Kocher, and lowering of valley flanks is in the order of 5 to 50 m. These are minimum figures as some vegetation upon steep slopes may have escaped correction in the DEM (Fig. 5A).

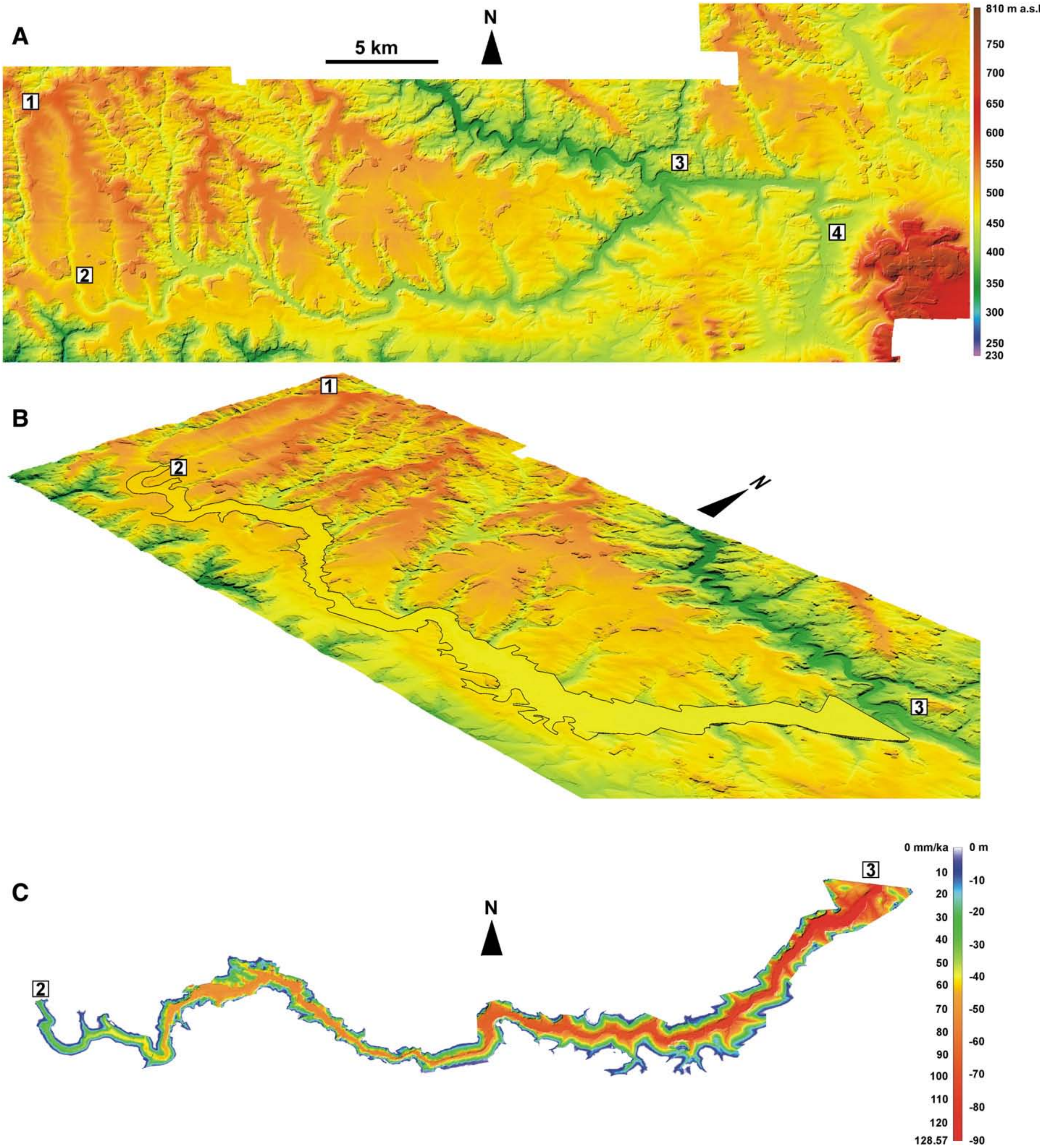

Fig. 5. A) High-resolution DEM of the study area; B) reconstructed palaeosurface (area 29.75 km^2) of parts of the valley of the Danubian Ur–Lein. The low gradient of the valley ranging from 490 to 457 m a.s.l. between (2) and (3) is visible through colour transitions from dark yellow to slightly greenish yellow; C) depth of excavation into the palaeosurface performed by Rhenish incision. Scale is converted into a long-term-averaged rate of erosion assuming steady surface lowering. The true advancement of erosional fronts may have differed locally through time.

6.2. Rates of erosion

The model represented in Fig. 5C yields a minimum volume for the mass of rock eroded and exported during Rhenish incision. Calculation was done with Scop++ (Inpho). The volume between the actual DEM (Fig. 5A) and the basal plain of the Goldshöfer Sande totals 1.074 km^3. It became extracted over a time-span of roughly 700 ka, resulting in hypothetic long-term-averaged rates of erosion. Assuming steady surface lowering these rates range from 30 mm/ka through 70–80 mm/ka to 128 mm/ka in the upper, middle, and lower courses, respectively. Upon slopes the range is between 7 and 70 mm/ka (Fig. 5C).

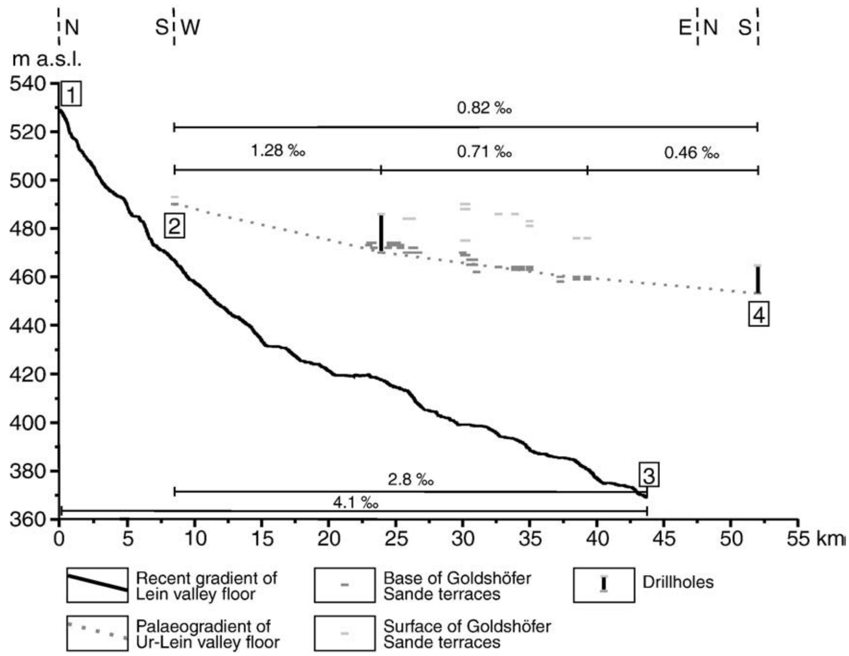

Fig. 6. Long profiles of the actual Lein valley and the Ur–Lein valley. Exaggeration is ×180. (1), (2), (3), and (4) are reference points marked in Fig. 5A, B, C. Morphometric data are scarce from the lowermost Lein valley, but well represented within the Kocher valley. The long profile of the Danubian Ur–Lein is therefore extended into a part of the Kocher valley (reference points (3) to (4)).

The true volume of material extracted, however, must also include the volume of Goldshöfer Sande eroded since then. Thickness increases downstream (Fig. 6); in the calculation we use an average of 9.5 m which is a minimum value given the fact that due to surface runoff the true initial thickness is nowhere preserved. Over the model area (29.75 km^2) this results in 0.283 km^3 and a subtotal of 1.357 km^3. Finally, the volume corresponding to large forests not directly corrected in the DEM must be added. Based on an average height of 15 m this results in an additional 0.032 km^3. The final corrected volume for the volume of rock extracted by Rhenish incision is then 1.389 km^3. Given the time-span in question (700 ka and 600 ka) and the extension of the present-day surface underneath the model area (31.31 km^2) the long-term rate of erosion within the Lein valley is 63.4 mm/ka to 74 mm/ka.

7. Discussion

7.1. Palaeogradients, long-term erosion rates and associated processes

In the vicinity of our working area the palaeogradient of the Ur–Brenz was in the order of 0.2 to 0.5‰ (Etzold, 1994a). This agrees with the value of 0.46‰ we obtained for the lower course of the Ur–Lein valley. For the catchment area of the Neckar (Fig. 1) Schaller et al. (2001) reported rates of erosion between 43 and 112 mm/ka for the time-span between 40 and 10 ka. For the catchment area of the lower Meuse in the Netherlands (200 to 250 km from the river mouth) upstream rates of erosion were 25 to 35 mm/ka for the time between 1.3 and 0.7 Ma, 80 mm/ka for the time after 0.7 Ma, and 30 mm/ka for the Holocene (Schaller et al., 2002, 2004). In the catchment area of the Wutach (Fig. 1), Morel et al. (2003) determined 12 to 18 mm/ka for erosion upon sandstone and 35 to 47 mm/ka for erosion upon granite averaged over an episode of 18 ka. These values typical for Central European river systems were obtained through cosmogenic nuclides; they differ considerably from measured values of sediment load in actual rivers (with rates of erosion between 23 and 27 mm/ka determined by river load gauging in the catchment area of the lower and middle course of the Neckar, Schaller et al., 2001).

Our long-term value (63 mm/ka to 74 mm/ka) is comparable to the 80 mm/ka obtained by Schaller et al. (2002, 2004) for the time after 0.7 Ma. During this mid to late Pleistocene episode northern hemisphere glaciation was at its maximum, and frequent and strong changes in temperature were a dominant mark (Peizhen et al., 2001; Zachos et al., 2001). In cold states erosion was strongly enhanced by periglacial processes (e.g., solifluction, gelifluction) resulting in largely increased sediment supply (Peizhen et al., 2001; Eberle et al., 2007). Transitional times between cold and warm states were especially prone to high erosion rates because of scarce vegetation and the availability of running water removing large parts of the unconsolidated periglacial regolith (Hinderer, 1999, 2001). According to Peizhen et al. (2001) it is the magnitude and frequency of change between the cold and warm states which globally controls high erosion rates in the Pleistocene (Molnar and England, 1990; Molnar 2004). Within the Alps denudation rates probably varied by a factor of 14, especially during glacial/interglacial cycles (Hinderer, 1999, 2001). Deglaciation during the last 17 ka resulted in denudation rates five times higher than the modern value (Hinderer, 1999). In eastern North America fluvial incision rates have increased since the late Miocene reflecting long-term cooling and lowering of sea level (Mills, 2000). For the New River in the Appalachians Ward et al. (2005) calculated an average incision rate of 43 mm/ka for the last 1 Ma accompanied by a corresponding regional oversteepening in relief (Hancock and Kirwan, 2007). During specific time intervals incision rate approached 100 mm/ka, which is considerably higher than the modern erosion rate of >25 mm/ka. Glacial–interglacial climatic control on fluvial erosion is also well-recorded from the central Rocky Mountains (Ward et al., 2005) and through high sediment accumulation rates within the basins of the U.S. middle Atlantic continental margin (Poag and Sevon, 1989).

7.2. Filtering cold and transitional state erosion rates

Our long-term average erosion rate (63 mm/ka to 74 mm/ka over 700 to 600 ka) differs considerably from the average for the Holocene (25 mm/ka, Schaller et al., 2001). Extraction of the Holocene (11.5 ka, Villinger and Fischer, 2005) value results in a net mid to late Pleistocene average of 64 mm/ka and 75 mm/ka. Further extraction of warm-state episodes (400 to 415 ka and 115 to 126 ka, Villinger and Fischer, 2005) with climatic conditions comparable to those of the Holocene raises the cold or transitional state average erosion rate towards 66 to 77 mm/ka, three times higher than the modern rate.

7.3. Temporary sediment sinks

Some remnants of Rhenish terraces in the area of the confluence of the Lein and Kocher rivers reflect such high erosion rates. Material eroded during cold states accumulated in thick sediment bodies, but later-on became mostly removed during the following deglaciation/glaciation cycles. The terrace corresponding to the Hoßkirch glaciation (60 to 50 m above present valley floor) is only preserved at three localities forming small accumulations of sand with a thickness ranging between 1 and 3 m; in the lower course of the Lein, however, it is commonly developed as strath terrace. The terrace corresponding to the Würm glaciation is locally preserved in height positions below and above Holocene sediments (Fig. 7); near the confluence of the Lein and the Kocher one prominent remnant can be correlated suggesting a thickness in excess of 10 m. Holocene accumulations are not in excess of 5 m. The volume of sediment stored in present temporary sinks such as the Würm terrace and Holocene valley fills totals approximately 0.034 km^3 (calculated on a valley area of 6.75 km^2 and an average valley fill of 5 m). In our calculation of eroded volumes and erosion rates, however, this figure does not appear. The corresponding amount of material has been eroded indeed, but in contrast to the bulk of extraction it has not been exported and dispersed elsewhere; it is still there.

7.4. Assessing contributions of climate and stream piracy on long-term erosion rates

Stream capture is accompanied by a lowering of the base level, which in turn affects rates of erosion and incision. Rhenish valley bottoms consistently show higher gradients than their Danubian predecessors. In our study area, both the Rhenish Kocher and its Danubian predecessor the Ur–Kocher were active in Pleistocene times. Thus, the difference in rates of incision will be a gauge of the contribution of stream piracy on long-term denudation under changing climate conditions.

In the Kocher valley near Abtsgmünd the bases of the upper (older) and lower (younger) terraces of the Goldshöfer Sande are situated at 110 m and 85 m above the present valley floor, respectively (Fig. 7). The age of the younger terrace is known (~780 ka, Fromm, 1980, 1983; Etzold, 1994a) but the older terrace is only roughly supposed to fall within the time-span between 1.6 and 1 Ma (Etzold, 1994a). Average thickness of both terraces is 9.5 m. Thus, the original height of the older terrace should have been around 119.5 m above present valley floor, resulting in a Danubian incision from the surface of the upper to the base of the lower terrace of 119.5 m minus 85 m = 34.5 m (Fig. 7). The time involved ranges between 820 ka (1.6 minus 0.78 Ma) and 220 ka (1 Ma minus 0.78 Ma). Therefore, the Danubian predecessor of the Kocher incised at rates between 42 mm/ka and 157 mm/ka (Fig. 7).

Rhenish erosion started between 700 and 600 ka reaching its maximum at the end of the Eem warm state or before onset of the Würm glaciation, respectively (115 ka). During the Würm glaciation the overdeepened valley became choked with about 10 m of sediment, which in turn was partially removed and refilled in Holocene times (Fig. 7).

Consequently, maximum incision of the Rhenish Kocher totals 99.5 m (85 m above present valley floor for the younger terrace of the Goldshöfer Sande plus 9.5 m average terrace thickness plus 5 m incision below present valley floor). The time involved ranges between 585 ka (0.7 minus 0.115 Ma) and 485 ka (0.6 Ma minus 0.115 Ma). Therefore, the Rhenish Kocher incised at rates between 170 mm/ka and 205 mm/ka (Fig. 7).

The difference between Danubian and Rhenish incision rates converts into the contribution of stream piracy on long-term denudation under changing climate conditions. The minimum gain is a 1.1-fold acceleration through stream piracy whereas the maximum gain is a 4.9-fold increase. The deeply entrenched Rhenian valleys strongly suggest that capturing might have accelerated incision by a factor well beyond 1.1 implying that the older terrace of the Goldshöfer Sande possesses an age older than 1.0 Ma.

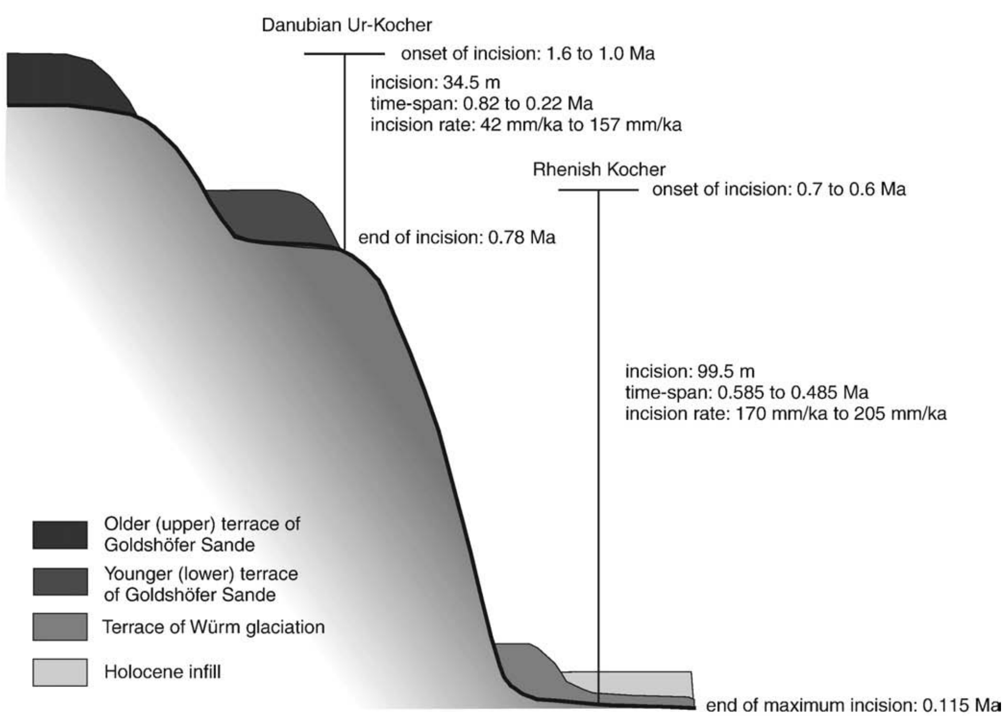

Fig. 7. Difference in rates of incision between the Rhenish Kocher and its Danubian predecessor Ur–Kocher.

8. Conclusions

A corrected DEM produced from aerial photographs was modified according to available morphometric criteria resulting in a model of the palaeovalley of the Ur–Lein. We consider the model of the palaeosurface to be realistic because calculated palaeogradients were introduced to control the best fit between slope angle and river course. The volume of rock extracted during Rhenish incision (1.389 km^3) is the difference between both models; the corresponding long-term average rate of erosion is 63 mm/ka to 74 mm/ka. A subtractive 3D-model visualizes the depth of Rhenish excavation into the Danubian palaeosurface. Long-term rates of erosion obtained through cosmogenic nuclides from river systems in Central Europe are of the same order confirming that the photogrammetric method yields reliable erosion rates over time-spans of 10^5 to 10^6 a. The averaged long-term erosion rate in the Lein valley reflects the dominance of cold-state erosion and is considered to be mainly a product of frequent and strong fluctuations of temperature and their effects on periglacial processes, vegetation, and water supply during the mid to late Pleistocene. A filtering procedure applied to cold and transitional state erosion rates of the mid and late Pleistocene yielded peak values between 66 and 77 mm/ka. The obtained net erosion rates for cold and transition state episodes suggest that during the past 600 to 700 ka warm state erosion (including the Holocene) did not significantly influence long-term bulk erosion rates. An assessment of the contribution of Rhenish stream piracy on long-term mid Pleistocene denudation under changing climate conditions resulted in an 1.1-fold to 4.9-fold gain.

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