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Morphological analysis of the drainage system in the Eastern Alps

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ABSTRACT

We study the morphology of the major rivers draining the Eastern Alps to test whether the active tectonics of this part of the orogen is reflected in the shape of channel profiles of the river network. In our approach we compare channel profiles measured from digital elevation models with numerically modelled channel profiles using a stream power approach. It is shown that regions of high stream power coincide largely with regions of highest topography and largest uplift rates, while the forelands and the Pannonian Basin are characterised by a significantly lower stream power. From stream power modelling we conclude that there is young uplift at the very east of the Eastern Alps, in the Bohemian Massif and in the Pohorje Range. The impact of the Pleistocene glaciations is explored by comparing properties of rivers that drain in proximal and distal positions relative to the ice sheet during the last glacial maximum. Our analysis shows that most knick points, wind gaps and other non-equilibrium features of catchments covered by ice during the last glaciations (Salzach, Enns) can be correlated with glacial processes. In contrast the ice free catchments of the Mur and Drava are characterized by channels in morphological equilibrium at the first approximation and are showing only weak evidence of the strong tectonic activity within these catchments. Finally, the channel profiles of the Adige and the divide between the upper Rhine and Danube catchments differ significantly from the other catchments. We relate this to the fact that the Adige and the Rhine respond to different base levels from the remainder of the Eastern Alps: The Adige may preserve a record from the Messininan base level change and the Rhine is subject to the base level lowering in the Rhine Graben.

1. Introduction

The drainage system of the European Eastern Alps is known to be strongly linked to the evolution of the orogen through time (e.g. Frisch et al., 1998). From the onset of the final collision of the Adriatic plate with Europe, the drainage system has responded on lateral and temporal changes in the uplift rate and on the lateral escape tectonics (e.g. Kuhlemann et al., 2007) by an orogen wide reorganization. The most obvious feature documenting this strong interaction are large inner alpine orogen parallel valleys that follow major Miocene to recent fault systems. As drainage systems reach a morphological equilibrium within a short geological time span (~1 Ma), it is still not clear if channel profiles of rivers provide a record of tectonic processes in the Alps (Hergarten, 2007). In order to test this, we compare catchments from the tectonically active Eastern Alps that were: (i) covered by ice during the last glacial maximum (LGM), (ii) not glaciated during the LGM and (iii) catchments with dramatic base level changes during the last episode of the orogenic evolution. Our analysis contributes to the debate about the driving forces behind erosion and uplift of the Alpine mountain belt in the Neogene. Within this discussion it is now being recognized that the Western and Eastern Alps differ with respect to their current tectonic activity, erosion regime and their driving forces.

In the Western Alps, collision has reached a mature stage where the central orogen is seismically and tectonically quiet, passively responding to gravitational forces and erosion (Willett et al., 2006). As such, erosion redistributes the loads to the foreland causing uplift of the range by passive isostatic rebound. The detrital record of the Alpine foreland basins testifies to this passive uplift and erosion (Cederbom et al., 2004). However, the recent uplift in the Western Alps seems to be driven by the passive response due to glacial unloading (Champagnac et al., 2007). This interpretation is supported by GPS studies that have shown that the current rotation pole of the Adriatic plate with respect to Europe is near 9.1°E; 45.36°N (near Torino), so that no current convergence occurs in the Western Alps (Nocquet and Calais, 2003).

In contrast, a significant amount of deformation and uplift in the Eastern Alps is controlled by the still ongoing convergence of the Adriatic plate with Europe. The counter clockwise rotation of the Adriatic plate at a rate of 0.52° per million years implies a convergence rate in the Eastern Alps of some 5 mm per year on the longitude of Vienna some 600 km east of the rotation pole. Active tectonics is also documented by the distribution of seismicity (Grenerczy et al., 2000; Robl and Stüwe, 2005), by young uplift (BEV, 1991; Ruess and Höggerl, 2002) and by the inversion of the Pannonian Basin (Cloetingh and Lankreijer, 2001). This basin inversion commenced with the termination of subduction underneath the Carpathian arc at about 7–10 Ma

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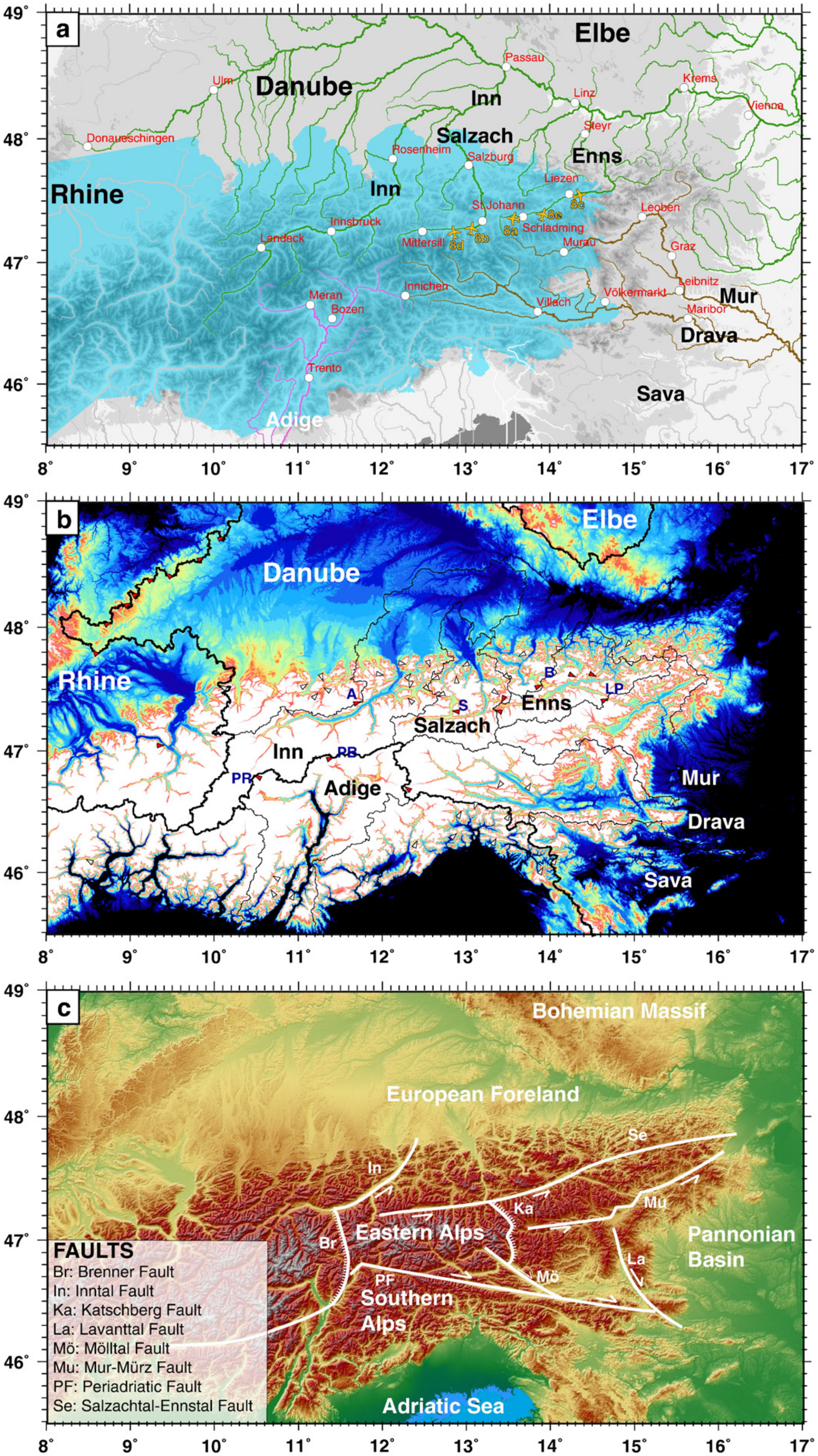
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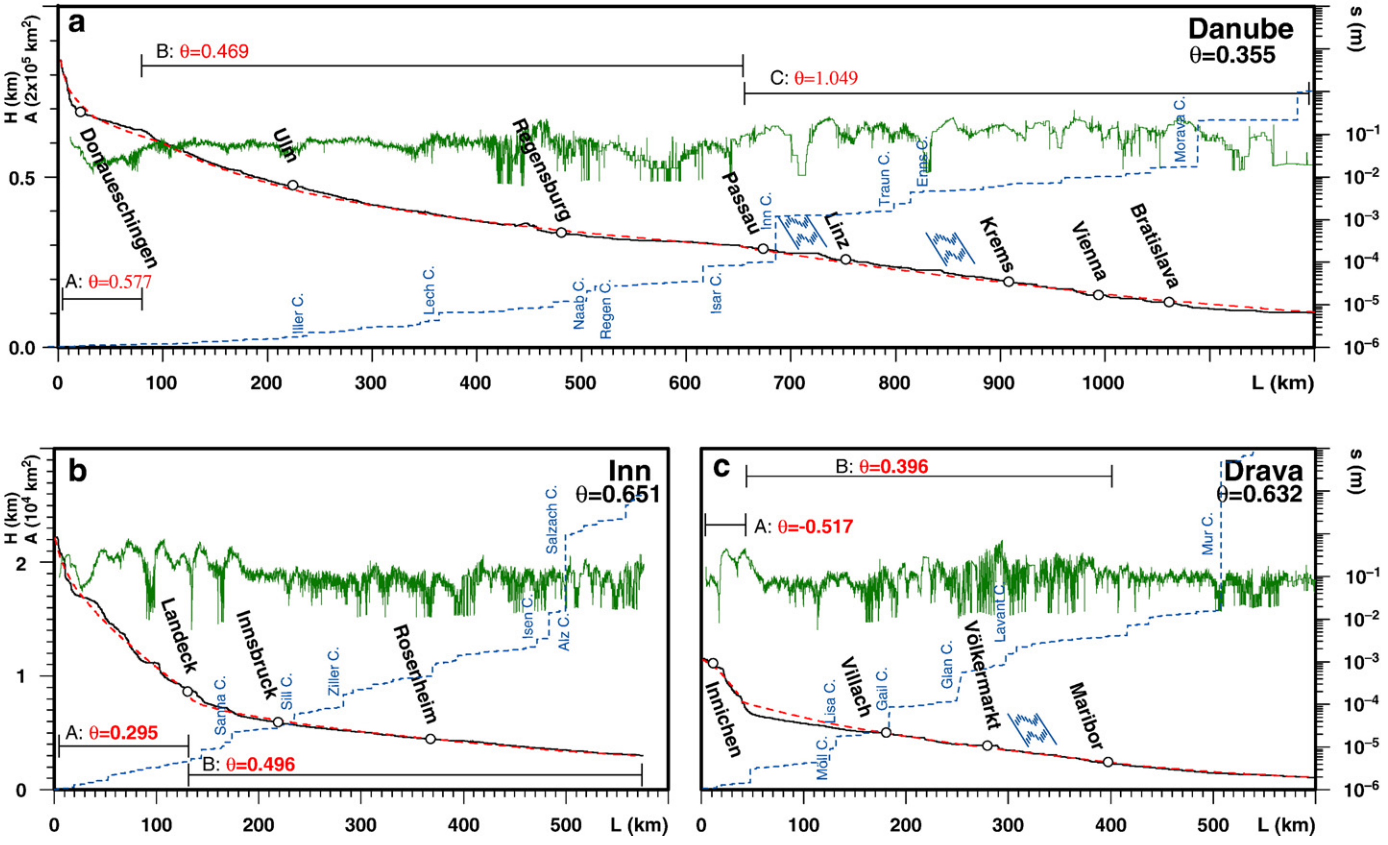

Fig. 2. Channel profiles of the Danube, Inn and Drava rivers. The black line is the channel profile as measured from the DEM. *H* is elevation and *L* is distance along the channel. The area–distance relationship is indicated by dashed blue lines and labeled as A on the left margin. Major confluences are labeled. The dashed red line shows the modelled best fit equilibrium channel profile by optimizing the curvature index (θ). This fit was done separately for segments of the river separated by knick points as indicated. The green line represents stream power (Eq. (1)) determined from the DEM using a moving window algorithm with a window size of 1 km.

(e.g. Peresson and Decker, 1997). This process invoked a change of the lateral extrusion of the Eastern Alps to the east from a regime of extension to a regime of compression causing tectonically-driven uplift at the orogen margins (Robl et al., in press).

In view of the overwhelming literature on the Western Alps, the much more active part of the orogen — the Eastern Alps — is often neglected. In this paper we analyze the morphology of rivers in the Eastern Alps to test whether the active tectonics of this part of the orogen is reflected in the morphology of the drainages. We study the channel profiles and drainage basins of major rivers in proximal versus distal positions with respect to the last glacial maximum (LGM) using a stream power approach. By comparing those we aim to separate signatures in the channel morphologies that are caused by glacial processes from those that are tectonically induced. In particular, we investigate the Danube, Drava, Adige and Rhine rivers and their tributaries. We will show that most of the obvious departures from morphological equilibrium may be related to glacial features, but there is also evidence for recent uplift at the very east of the Eastern Alps.

2. The drainage systems of the Eastern Alps

The drainage system of the Eastern Alps is characterised by a west–east trending drainage divide following more less the highest peaks of the mountain range (Fig. 1). This watershed separates the Inn, Salzach and Enns catchments north of the range from the Drava–Mur drainage system south of the divide. As both drainages north and south of the Alpine watershed are tributaries of the Danube River, almost the entire realm of the Eastern Alps is discharged by this drainage system and the Black Sea represents a common base level to much of the range. Only two major rivers respond to different base levels: The very south western part of the Eastern Alps is drained by the Adige River that discharges into the Adriatic Sea. The Adriatic Sea represents a largely independent base level as its sea level was dramatically different during the Messinian at 5 Ma. Secondly, the western most part of the Eastern Alps is discharged by the north draining Rhine system that is controlled by the massive base level lowering along the active Rhine graben (Cloetingh et al., 2006). This is known to have caused a radical reorganization of the north European drainage pattern (Peters and van Balen, 2007; Berendsen and Stouthamer, 2001). This current drainage network is the consequence of an evolution throughout the Miocene.

2.1. Drainage evolution through the Miocene

The development of the drainage system in the Eastern Alps is clearly related to the tectonic evolution of the mountain range. Frisch et al. (1998), Kuhlemann et al. (2006) and Kuhlemann (2007) suggest

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Fig. 1. Drainage systems and topography of the Eastern Alps. (a) The drainage system of the Eastern Alps on top of a topographic map. Green is Danube (Donau), brown is Drava (Drau) catchment (also draining into the Danube). The Adige (Etsch) River system is in purple. Labeled cities correspond to those shown on Figs. 2 and 3. Airplane symbols indicate the position and view direction of the photographs shown in Fig. 8. The blue shaded area indicates the extent of the last glacial maximum after van Husen (1987). (b) Topographic map of the Eastern Alps color coded for elevation between 300 m (black) and 1300 m (white). Thick black lines show drainage divides between the Rhine, Danube, Elbe and rivers draining into the Adriatic Sea. Thin black lines separate individual catchments of important tributaries. Important wind gaps are marked by white and red triangles. Red triangles are described in some detail in this study. A: Achental, S: Saalach Valley, B: Bad Mitterndorf, LP: Liesing–Palten Valley, PB: Passo Brennero (Brenner Pass), PR: Passo Resina (Reschen Pass). (c) Map showing the major units and fault systems of the investigated area.

that most of the Eastern Alps drained northward until about 20 Ma when young uplift and exhumation of the Tauern Window began. Much of this young uplift history is recorded by the Augenstein surface (Frisch et al., 2001), but the paleoaltimetry and exposure dating of this unique pebble deposit on the Alpine Karst plateau is still in its infancy. Around 13 Ma a division between north and south draining rivers began with formation of the paleo-courses for Inn, Salzach and Enns (Kuhlemann, 2007). The detrital record from the sediment fans of the northern Molasse documents a series of departures from the present day courses of these rivers (Kuhlemann et al., 2002; Kuhlemann, 2007) as well as of those flowing east and south: For example, according to Dunkl et al. (2006) and Frisch et al. (1998), the Mur is likely to have drained — together with the Mürz — across the Semmering pass towards the north-east, changing its course to its present day orientation (by reversing the flow direction of the Mürz) only in the last few million years.

The drainage evolution of the last 5 Ma is not very well known. The extent of the LGM in the Eastern Alps is well documented by van Husen (1987), but it is barely known how many of the courses of todays rivers in the Eastern Alps were changed by the glaciation periods during the Pleistocene. Kuhlemann et al. (2002) have documented a sudden rise of sediment influx in the Molasse Basin at and after 4 Ma, and Székely (2001) has performed the first modern analysis of the DEM of the Eastern Alps, but burial or exposure dating of young surfaces, wind gaps or terrace risers is still practically absent so that much of the youngest part of the drainage evolution remains unknown.

2.2. The drainages today

The Danube River drains most of the Eastern Alps with tributaries on the north side (Inn, Enns) and south side (Drava) of the Eastern Alps (Fig. 1a, b). The main channel of the Danube — not glaciated during the LGM — originates in the Black Forrest (Schwarzwald) and drains several hundred kilometres in north-east direction crossing the Alpine foreland (Fig. 2a). When reaching the Bohemian Massif, the river turns its course by about 50° in south-east direction following the spur of the Bohemian Massif. Here the Danube drains several times in deep, narrow gorges (e.g. Passau, Krems) in bed rock channels of high grade metamorphic rocks and granites of the Bohemian Massif. From the city of Krems downstream the Danube River drains through the Molasse Zone, the Vienna — and the Pannonian Basins and breaks through the Carpathians until the river confluences into the Black Sea.

On the northern side of the Eastern Alps the main tributaries to the Danube are the Inn (Fig. 2b), Salzach (Fig. 3b) and Enns (Fig. 3a) rivers. Except for the Enns below its knee-shaped bend, the channel segments draining the Eastern Alps of these rivers were covered by ice during the LGM (Fig. 1a). The main channels of these rivers follow a major sinistral strike-slip fault zone systems (Fig. 1c) that are related to the Miocene lateral extrusion of the Alps to the east (Ratschbacher et al., 1991a,b; Wang and Neubauer, 1998).

Along the Inn River, the Inntal fault system is still active and there is some evidence for recent activity along the Salzachtal–Ennstal fault zone (SEMP) indicated by rare seismic events and deformation of unconsolidated fluvial gravels (Neubauer et al., 2007). The Salzach and Enns rivers follow this orogen parallel lineament for more than 100 km before abruptly changing their course from west–east to south–north (Fig. 1a). In the south–north draining sections, both rivers enter deep gorges where they break through the Northern Calcareous Alps into the Alpine foreland (Stüwe and Sandiford, 1994). Interestingly, the easternmost major tributary to the Enns, the Salza River, drains in east–west direction and therefore reverse to the overall topographic gradient of the Eastern Alps. At the end of its course the Salzach River discharges into the Inn River, while the Inn and Enns form important tributaries of the Danube with confluence points in the northern Alpine foreland.

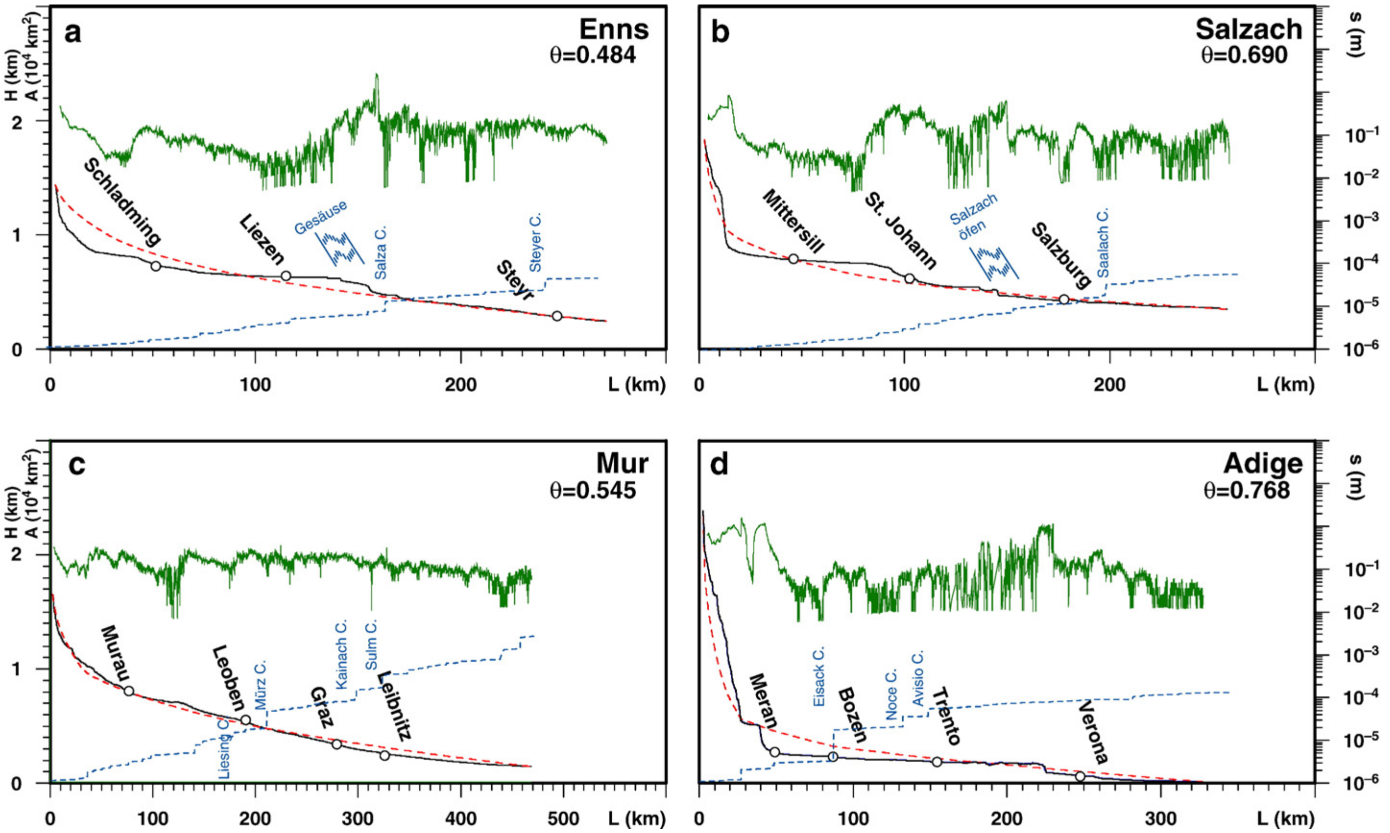


Fig. 3. Channel profiles of the Enns, Salzach, Mur and Adige rivers. For details of individual curves see Fig. 2.

Similar to the drainages north the principal divide of the Eastern Alps, the main channels on the southern side of the range follow predominantly major fault systems. The Drava drainage system follows largely the Periadriatic fault zone (separating the Adriatic from the European plate) in the Pustertal–Gailtal segment (Fig. 1a, c). Tributaries like the Möll and Lavant follow conjugate sets of dextral faults (Mölltal fault and Lavanttal fault, respectively). East of Villach both Drava (Fig. 2c) and Mur (Fig. 3c) flow in valleys never subject to glacial erosion. At the confluence with the Lavant River, the Drava River follows the dextral Lavanttal fault for about 15 km before exiting this prominent valley again to enter the narrow gorge between the Pohorje and the Koralpe. Further north, the Mur drainage system follows a distinct WSW–ENE oriented sinistral fault system: the Mur–Mürz fault system. While the Mur River drains within this lineament along the mean topographic gradient, the Mürz River follows the same valley in reverse direction. Immediately downstream the confluence point of the two rivers, the Mur turns south forming a T-shaped river segment. Similar to the Enns and Salzach in the north, the lower reaches of the Mur drain along a narrow valley bordered by steep limestone faces before entering the Pannonian Basin.

In contrast to other important rivers of the Eastern Alps, the main channel of the Adige (Fig. 3d) does not follow an orogen scale fault system. Similar to other drainages that discharge into the Adriatic Sea, the valleys are deeply incised even within high mountainous regions, showing steep channel gradients in the headwaters and extremely small channel gradients downstream. All these observations are consistent with the base level low stand during the Messinian, which was responsible for increased incision rates (Willett et al., 2006) and accelerated reorganization of the drainage patterns previously established in the Miocene. Relics of this reorganization process are wind gaps, or an extreme misbalance between valley size and river discharge that will be discussed further below.

Numerous wind gaps are dispersed over the Eastern Alps (Fig. 1b). At least some of them show evidence for the reorganisation of the drainage pattern as will be discussed below. Although the existence of these wind gaps have been discovered decades ago, the timing and the driving force for the river reorganisation is not well understood. North of the Alpine divide, the most prominent wind gaps are the Achensee north of the Inn River, the Saalach valley and Lake Zell north of the Salzach and Bad Mitterndorf north of the Enns River (labelled on Fig. 1b). Wind gaps that connect valleys south and north of the principal divide could give evidence that former rivers crossed the present day main ridge of the Eastern Alps as suggested by Frisch et al. (1998). Such wind gaps can be observed in the eastern part of the range at the Schoberpass (Liesing–Palten valley) as well as in the western part at the Brenner (Passo di Brennero) and at the Reschenpass (Passo di Resina). South of the Alpine divide wind gaps between the Mur and Drava and between the Drava and Sava drainage are observed.

3. Data and model

Rivers in morphological equilibrium (at constant uplift rate and uniform bed rock properties), show concave longitudinal channel profiles where the channel slope decreases with increasing discharge of the river. Deviations from such ideal channel profiles may give evidence for several independent processes including: (1) spatial variations in the uplift rate of the region (e.g. Wobus et al., 2006), (2) feedback between incision and uplift rate (e.g. Robl et al., 2008), (3) activity of faults in the recent past (Robl et al., in press), (4) changes in the base level (e.g. Willett et al., 2006) and (5) sudden changes of the river discharge caused by capturing events (e.g. Stüwe et al., in press). In order to test for such deviations channel profiles derived from digital elevation models may be compared with numerically modelled channel profiles. Both the derivation of channels from DEMs and the numerical modelling of predicted equilibrium channel profiles is not trivial and needs some consideration.

Our data analysis is based on version 2 of the SRTM3 data set with a resolution of the digital elevation model of 3 arc sec. Voids in the data set were filled following a minimum surface approach by solving the Poisson equation with the surface heights at the border of the voids as boundary values. Following this approach only a small number of additional closed basins (basins without an outlet) is introduced into the digital elevation model. Further on closed basins are filled until every point of the data set is characterized by a unique flow direction that allows the creation of a flow grid. Upstream drainage areas, river networks and drainage divides are calculated by a recursive approach, starting at the outlets (lowest points) at the geographic limits of the area and following the flow grid upstream to the ridges (highest points) of the DEM. The channel profiles shown on Figs. 2 and 3 are calculated by defining the coordinates of the river spring and successively following the flow grid to the outlet. A median filter with 1 km wavelength is applied to the channel profiles to reduce the noise of the raw data. This wavelength turned out to be a good compromise between reducing noise and preserving as much information as possible (Figs. 2 and 3). The filtered river profiles are exclusively monotonous curves (going only downwards) and are therefore the most practicable channel profiles that can be used for further modelling.

Our modelling of channel profiles is based on the most commonly used model to describe detachment limited bedrock channel erosion (e.g. Howard, 1980; Hergarten, 2002). This is generally described in terms of stream power s being a function of channel gradient $\mathrm{d}H/\mathrm{d}L$ and upstream drainage area A (as a proxy for water flux in the river):

$$s = \left(-\frac{dH}{dL}\right)A^{\theta} \tag{1}$$

Erosion rate is then usually considered to be proportional to s (Wobus et al., 2006) or to s^2 (Hergarten, 2002). This model is based on an empirical study of longitudinal river profiles, where Hack (1957) observed that the channel gradient is inversely proportional to the upstream drainage area of the river to the power of an exponent θ, called the concavity index (Flint, 1974). The concavity index controls the shape of steady state channel profiles and becomes therefore a crucial factor in modelling equilibrium channel profiles. The range of θ was determined between 0.25 and 0.6 from logarithmic plots of basin area against slope (Hack, 1957; Tucker and Whipple, 2002 for a review). There is also some debate about the influence of the channel width on θ (Finnegan et al., 2005) and on the question if alluvial processes need to be considered in the numerical modelling of most channels. Here, we follow initially the most simple approach and — when discussing stream power — we assume $\theta = 0.5$ so that stream power has the units of metres.

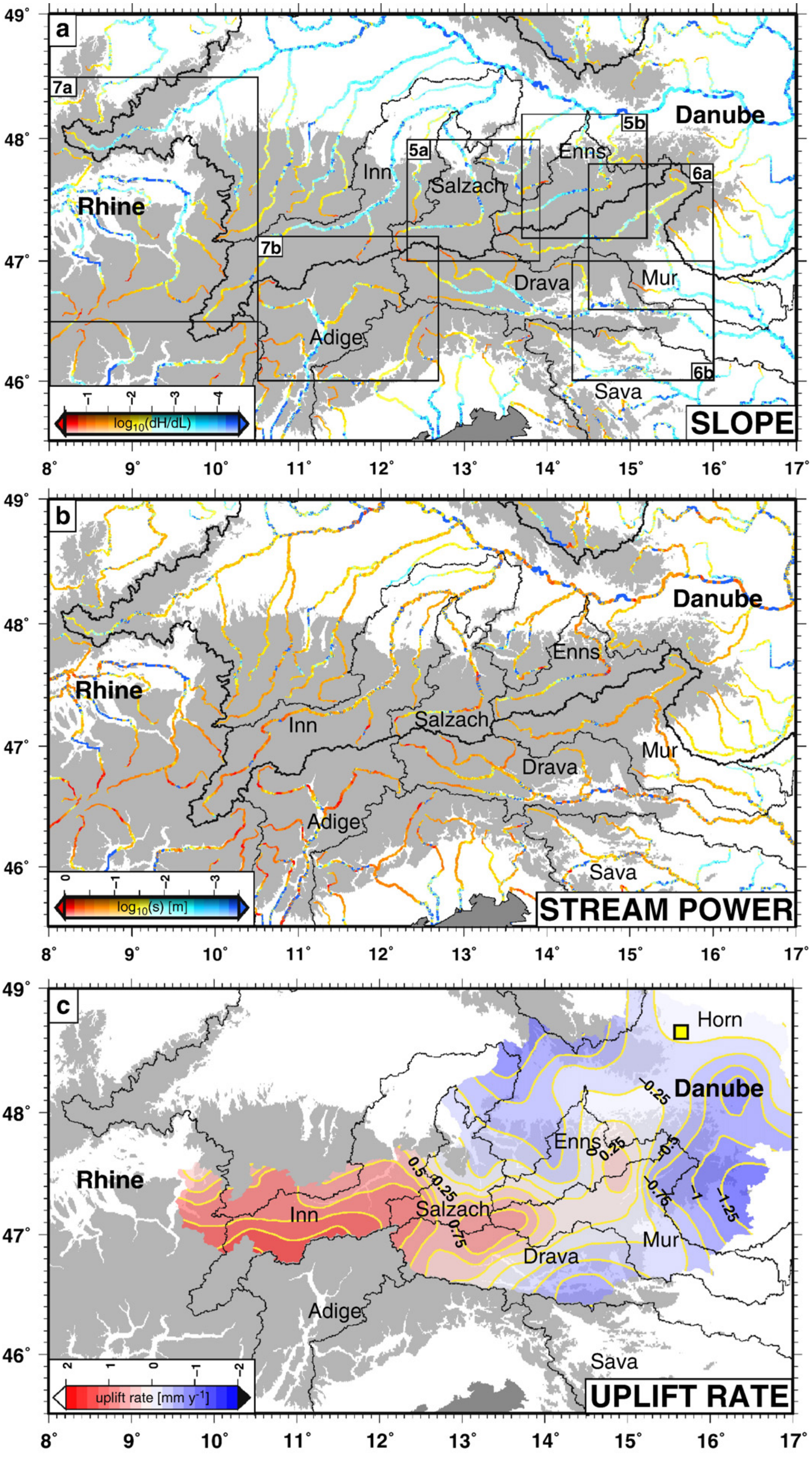
For a comparison between observed and theoretical longitudinal river profiles we have modelled equilibrium channel profiles in which erosion rate is constant at every point of the channel assuming constant uplift rate and homogeneous erodibility. Differences between observed and modelled channel profiles can then be interpreted in terms of tectonic disturbances or lithological variations. In geomorphic equilibrium, stream power is a constant along the entire channel (s = constant) and Eq. (1) may be reformulated to:

$$\left(\frac{dH}{dL}\right) \propto -A^{-\theta} \tag{2}$$

Eq. (2) was solved numerically using a backward (i.e., in upstream direction) finite difference scheme taking into account the area–distance relationships shown as dashed blue lines in Figs. 2 and 3. The concavity index θ was determined by performing a least square best fit to the observed channel gradients as extracted from the DEM.

4. Analysis of the channel profiles

The Danube River drains the entire northern side of the Eastern Alps and forms therefore an obvious starting point for our analysis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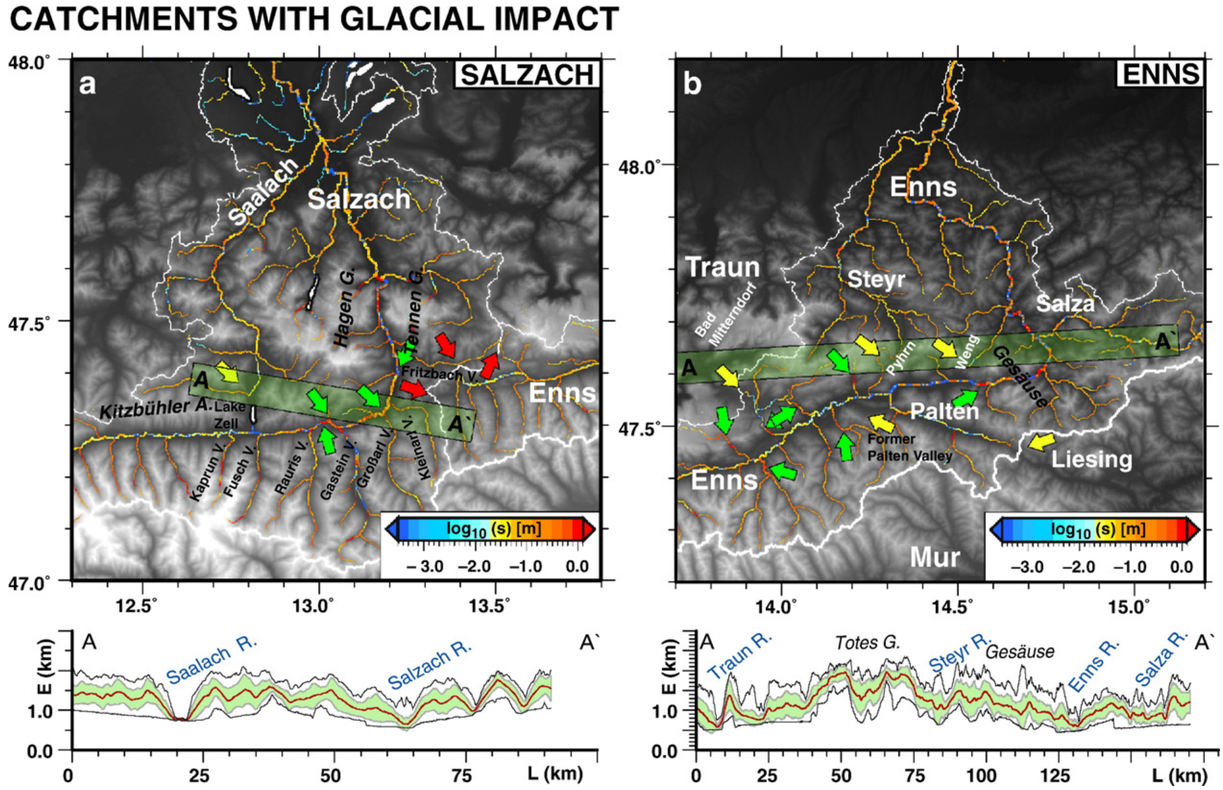

Fig. 5. Maps showing the stream power of two selected key areas representing catchments with glacial impact shown in Fig. 4a. Red, green and yellow arrows indicate the direction of the drainage divide migration, pronounced knick points and prominent wind gaps, respectively. Green transparent bars indicate the position, direction and width of swath profiles shown below.

(Fig. 2a). Its longitudinal channel profile shows some distinct knick points. One of them is located downstream of Donaueschingen, approximately at the position of the Danube sink, where the Danube River loses the bulk of water into karst sink holes. This water appears again as a spring of the Rhine River diverting its destiny from the Black Sea to the North Sea (Knop, 1878; Hötzl, 1996). The sudden water loss determines a discontinuity in the erosion of the river and thus the knick point. A second knick point is located below the Inn confluence (Fig. 2a). There — in the section between Passau and Krems — the Danube follows the spur of the Bohemian Massif and is characterised by an increased channel slope. From Bratislava downstream the channel gradients become very small, as the Danube is crossing the Pannonian Basin. The channel profile of the entire river section shown in Fig. 2a is best fit by a modelled channel for a concavity index of $\theta=0.355$ (not shown on Fig. 2a). This is substantially lower than typical values for concavity indices (e.g. Hack, 1957) and also does not provide a good optical fit of the observed profile. It arises from the fitting across all knick points. By splitting up the channel profile into three segments, separated by the two knick points, the best fit concavity indices of the segment A and segment B ($\theta=0.577$ and $\theta=0.469$ for segments A and B respectively; shown as dashed red lines on Fig. 2a) are very close to the best fit concavity index of $\theta=1/2$ (see Tucker and Whipple, 2002 for a review). Segment A can still not be fit very well as the upper most part of the Danube catchment has recently lost drainage area due to capture of the headwaters by the Rhine (Berendsen and Stouthamer, 2001). This is also reflected in the decreased values for stream power (green line) for segment A. However, segment B (using $\theta=0.469$) can now be fit very well to the measured profile between Donaueschingen and Passau indicating geomorphic equilibrium with constant uplift rate of this section. This may also be seen in the relatively constant stream power (green line) of this segment. In segment C the best fit concavity index is $\theta=1.049$ which is much higher than any values for θ observed for equilibrium channels around the world. This is because the upper part of segment C (between Passau and Vienna) is characterised by an elevated channel gradient where the Danube follows the spur of the Bohemian Massif in deep gorges.

The upper reach of the river Inn (Fig. 2b) is characterised by several knick points. However, downstream of Landeck (segment B) the channel does not show dramatic disturbances and appears well equilibrated. This segment fits perfectly with $\theta=0.496$, being very close to the Alpine concavity index. The good fit suggests that the uplift rate within this segment is constant. Segment A consists of a steep channel with a more or less constant slope for about 50 km and several smaller knick points. The increased channel gradients of segment A also cause elevated stream power, but in general it can be seen that the stream power fluctuates highly in segment A and is rather constant in segment B.

The Enns and Salzach rivers (Fig. 3a,b) show similar characteristics, including steep headwaters, low channel gradients separated by distinct knick points in the segments that follow the Miocene faults. Both rivers also show strong variations in stream power along the channel. For example, the Enns has a distinct knick point along the Ennstal fault near Schladming and its stream power decreases by one order of magnitude along the Miocene fault. After draining about 70 km to 100 km to the east parallel to the orogen, both Enns and Salzach turn their course abruptly towards the north. At this point the channels steepen again (downstream of Liezen and upstream of St

Fig. 4. Maps showing the (a) channel slope and (b) stream power of all rivers with an upstream drainage area greater than 1000 km^2. The frames shown in (a), show the key areas discussed in detail in Figs. 5–7. (c) shows geodetically measured uplift rates relative to the city of Horn (BEV, 1991; Ruess and Höggerl, 2002). Grey shaded background shows the area of the Eastern Alps that is higher than 600 m in surface elevation.

Johann for Enns and Salzach, respectively) and break in deep gorges through the Northern Calcareous Alps to the Alpine foreland. In the knee-shaped bends of the rivers as well as within the gorges, stream power rises rapidly to a maximum indicating an out of equilibrium state and a possibly very young age of these bends.

The channel profile of the river Mur (Fig. 3c) behaves ideal in the headwaters, featuring a knick point some 50 km downstream of Murau where it passes the terminal moraine of the last glacial maximum. The river has no remarkable deviations from an equilibrium channel profile from there on. Not even the sudden change of the flow direction at the confluence with the Mürz River or the transition from the Alps into the Pannonian Basin near Graz leads to an appreciable deviation from an equilibrium channel profile. In brief, the Mur River appears to be equilibrated so that modelled (assuming constant uplift rate) and measured channel profiles largely coincide. Also, the best fit concavity index of $\theta=0.545$ is near the representative value for rivers in equilibrium (e.g. Tucker and Whipple, 2002). The equilibrium state of the Mur is also reflected in a fairly constant stream power along the river, with the only major deviation being near the terminal moraine of the Mur glacier during the LGM and somewhat elevated stream power values near the confluence with the Mürz.

The Drava River (Fig. 2c) does not show any major knick points. However, there is a several hundred kilometres long linear channel segment suggesting a non-equilibrium state of the Drava River. The channel profile of the Drava River is obviously not ideal in terms of the equilibrium model assuming constant uplift applied here. The channel segment of the headwater (segment A) shows downstream steepening leading to a negative best fit concavity index for this channel segment ($\theta=-0.517$) and therefore a significant downstream rise of the stream power. Channel segment B is characterised by a fairly linear constant channel gradient over several hundred kilometres, so that the coincidence between modelled and measured channel profiles is rather weak. The stream power within this segment is noisy and gives no clear signal partly due to several power stations in this segment. A small knick point is located where the Drava flows for 15 km along the Lavanttal fault. Downstream of segment B, the channel becomes concave and the noise level of the stream power is considerably reduced. Interestingly, the point of the transition between a linear and a concave channel profile is exactly located in Maribor where the Drava River leaves the narrow gorge of the Pohorje Range and enters the Pannonian Basin.

The channel profile of the Adige River (Fig. 3d) is fairly different to all other rivers discussed here. The headwaters are extremely steep, but characterised by a constant slope over about 50 km and a pronounced step-shaped knick point some 10 km upstream of Meran. Downstream of Meran channel slopes are extremely small and rather constant for about 200 km, where the slopes slightly increase after a knick point some 50 km upstream of Verona. The stream power shows large values for the headwater segment and two small maxima in the low channel gradient segment related to knick points. However the high level of noise does not allow an interpretation of stream power for the last 50 km. The large difference between observed and modelled channel profile and the large fluctuations in stream power clearly indicate that this river is not in geomorphic equilibrium. The causes for this may either lie in (i) highly variable uplift rates along the channel, (ii) the impact of glaciations or (iii) may be related to base level change for example during the Messinian in the Adriatic Sea. Variations in lithology are excluded here, because lithological

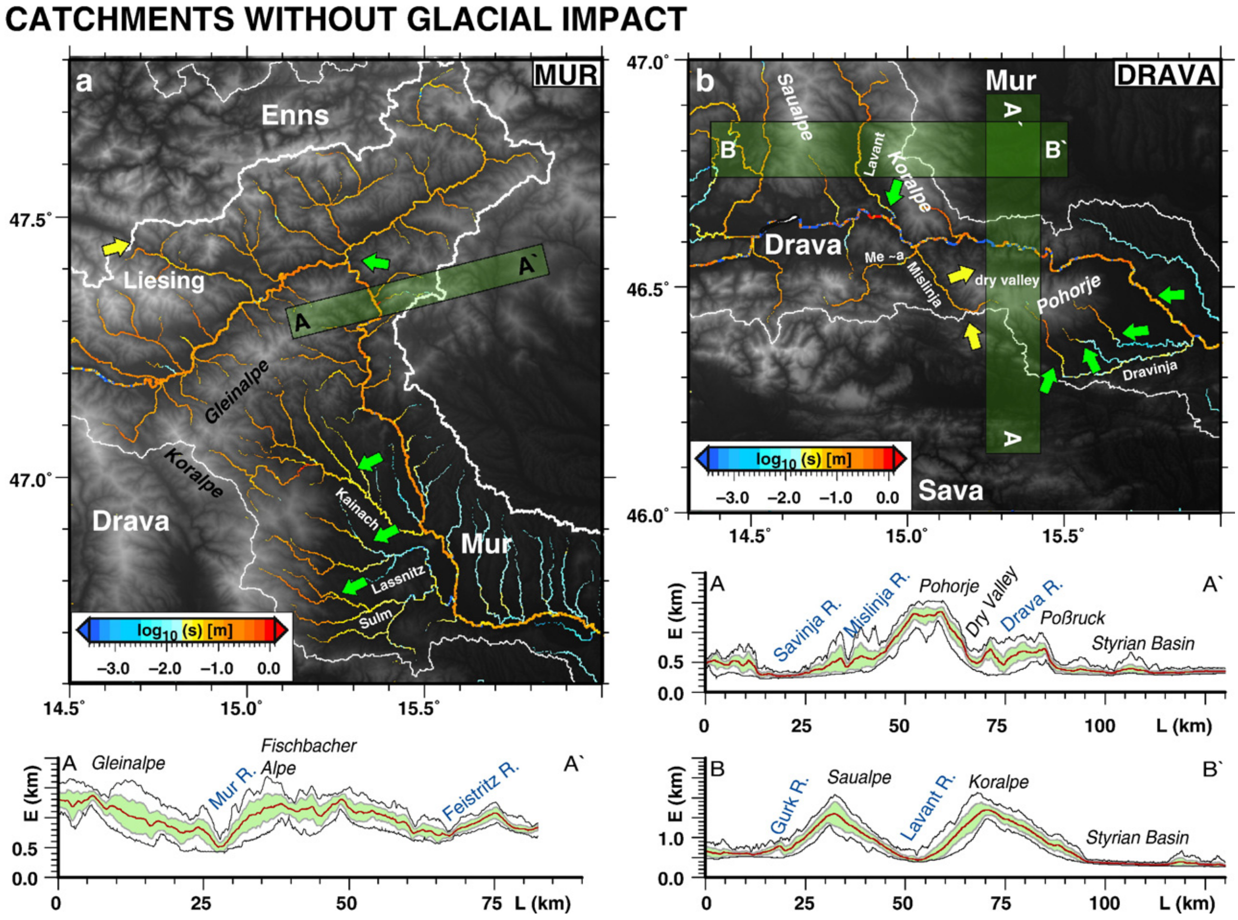

Fig. 6. Maps showing the stream power of two selected key areas showing features of catchments without glacial impact as indicated in Fig. 4a. The indent of arrows and green transparent bars are explained in Fig. 5.

transitions do not appear to influence any of the other major rivers discussed here. The causes may be constrained by considering stream power aerially in the next section.

5. Properties of the drainage network

The comparison of measured channel profiles from the Eastern Alps with modelled equilibrium channel profiles assuming constant uplift rate and erodibility has shown that some of the major rivers in the Eastern Alps appear to be in morphological equilibrium along most of their channel (e.g. Mur). Others are characterised by channel segments out of equilibrium (e.g. Danube River, possibly because of variable uplift rates or lithological variation) and some have a conspicuous maximum in stream power along knee-shaped bends in their course (i.e. Salzach, Enns and — to a small extent — the Mur at the confluence with the Mürz). Finally, there are some rivers for which a stream power approach fails completely to describe the observed channel profiles (e.g. Adige River). These observations in the main channels do not yet allow interpreting the cause of the disturbance in the stream power and the channel gradients. To infer these it is necessary to extend the analysis of stream power to all major tributaries. We have therefore calculated the stream power for all major rivers and their tributaries in the Eastern Alps (Fig. 4). From this map, six key regions were selected that represent three different settings with respect to their morphological evolution: (i) catchments within the region covered by ice during the last glacial maximum (Salzach, Enns; Fig. 5a,b), (ii) catchments never covered by ice (Mur, Drava; Fig. 6a,b) and (iii) catchments subject to base levels different from the Black Sea (Rhine, Adige; Fig. 7a,b). These maps are now discussed in connection with the extent of glaciation shown in Fig. 1a and the geodetically measured uplift rate shown in Fig. 4c.

As a whole, it may be seen that the highest slopes of most rivers are indeed found in the headwaters, while large drainage areas correspond to segments of low channel gradients (Fig. 4). Head waters within the high topography regions are generally steeper than the headwaters of rivers with an origin in the forelands. The maps for stream power and channel slope also show that the highest values are found in the western central part of the Eastern Alps and decrease in east direction. This observation corresponds with the determined spatial variations of the uplift rates for the Eastern Alps and the Alpine foreland where highest uplift rates coincide very well with regions of highest stream power (Fig. 4c). Measured uplift rates are in the range of $1.5\ \mathrm{mm\ a^{-1}}$ in the western and central part of the Eastern Alps and about $-1.5\ \mathrm{mm\ a^{-1}}$ in the Pannonian Basin relative to the city of Horn (BEV, 1991; Ruess and Höggerl, 2002).

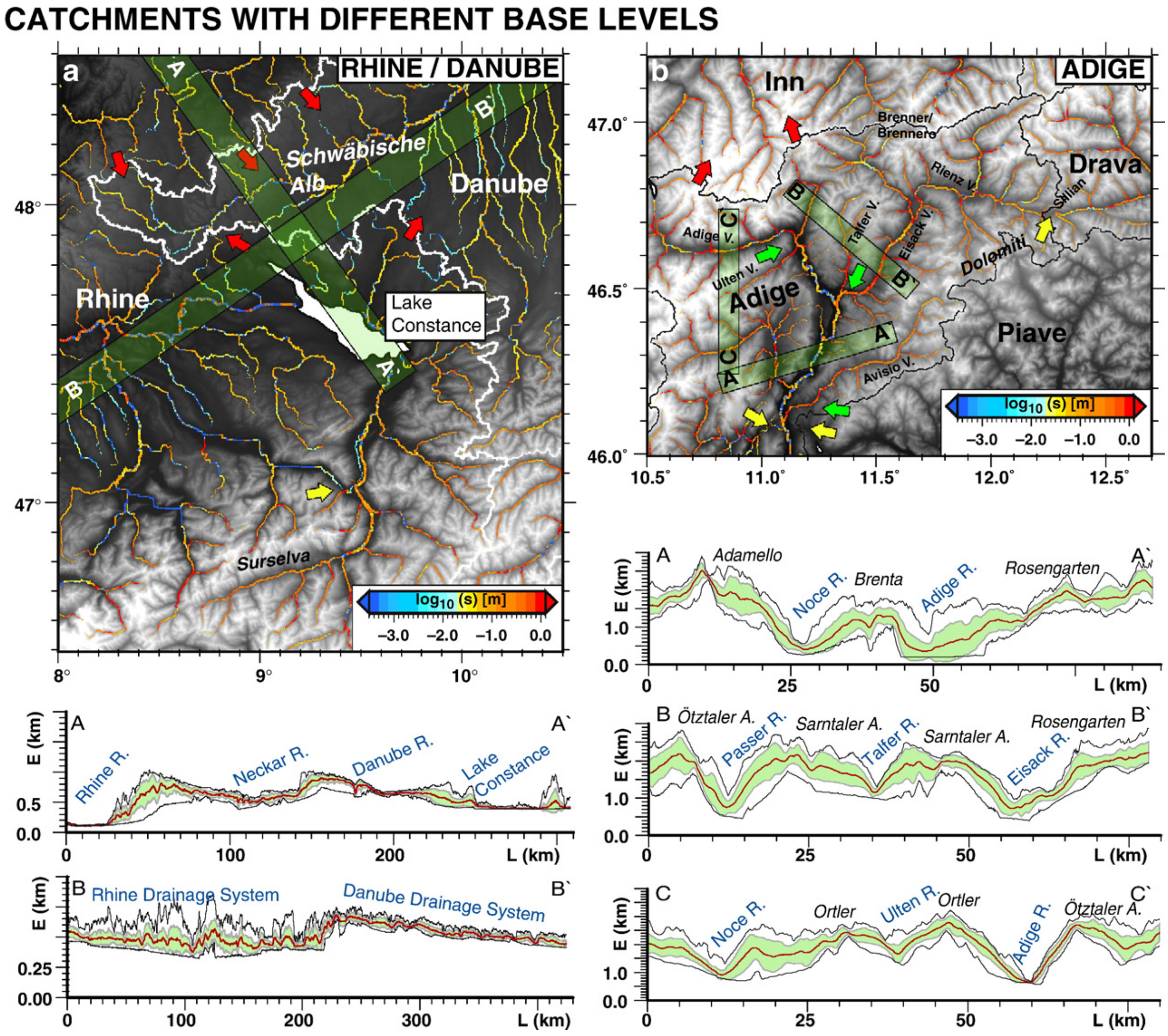

Fig. 7. Maps showing stream power of two selected key areas of catchments with different base levels as shown in Fig. 4a. The indent of arrows and green transparent bars are explained in Fig. 5.

5.1. Catchments in regions covered by ice during the LGM

The Salzach and Enns capture all the representative features of rivers in close connection with the major fault zones related to the tectonic evolution of the Eastern Alps. Both rivers respond to the constant base level of the Danube and both rivers were largely ice covered during the LGM (Fig. 1a). The rivers follow broad valleys and are now filled with sediments.

The morphology of the Salzach River channel and its knick points may be interpreted by investigating its southern tributaries. These have very different characteristics west and east of Lake Zell in the Saalach wind gap (Figs. 5a and 8d). West of the Lake Zell, they are characterised by very high stream power values in their headwaters (where the tributaries flow in glacial bowls) and lower stream power values near the confluence to the Salzach (where the channels are controlled by fluvial bed rock incision in gorges). At Lake Zell, there is a

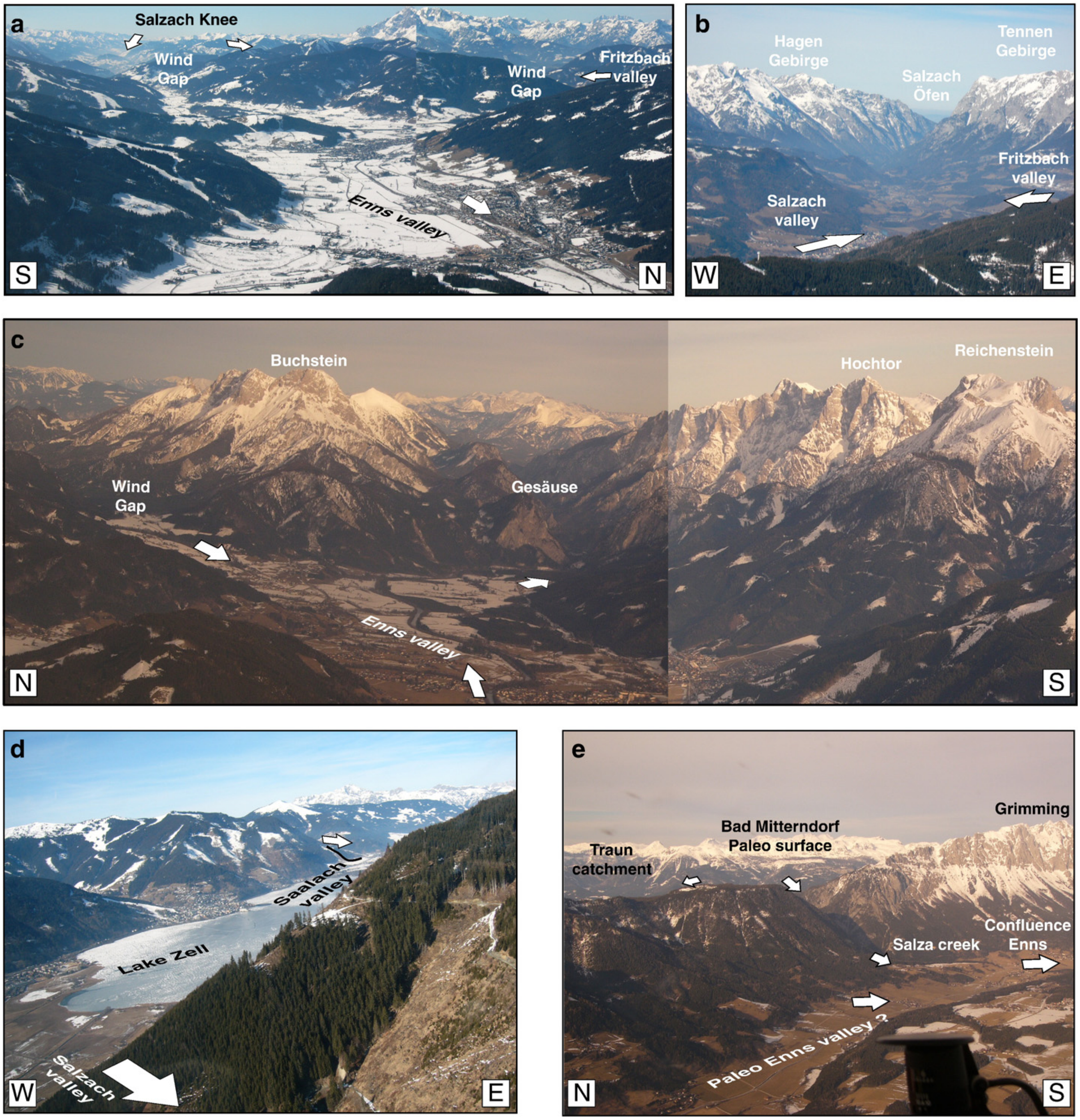

Fig. 8. Oblique aerial photographs of some key features of the rivers discussed here. The exact position and view direction is shown on Fig. 1a. (a) The Salzach–Enns junction. The major east–west trending valley in the left part of the picture is a major Miocene sinistral fault system. The Salzach bend near St Johann is in the center of the picture behind the low lying hills. (b) The Salzach River entering a deep gorge by crossing the Northern Calcareous Alps (NCA) in north direction. (c) The Enns entering the Gesäuse gorge by crossing the NCA looking east from above Liezen. (d) Lake Zell located in the pronounced wind gap of the Saalach valley. (e) The paleo Enns valley bypassing the Grimming.

sudden change from high to low stream power values of the tributaries at their confluence point to the Salzach River. Also, the tributaries east of Lake Zell show an increase in channel length from west to east.

We interpret this difference between the tributaries west and east of Lake Zell to be related to the wind gap of the Saalach at Lake Zell itself. There, the topographic barrier between the Saalach and the Salzach valley is only some few meters and the channel beds consist of unconsolidated glacial gravel (Vorstossschotter). A swath profile across the Saalach — and the Salzach valleys shows that the base level of the Saalach — and Salzach River is similar. In fact, the Saalach valley is conspicuously larger than the Salzach valley suggesting it previously hosted the Salzach River. We suggest therefore that the Salzach once drained northwards along the Saalach channel and that its present day course east of Lake Zell is a very young feature. As we will show below that the catchments that were ice free during the glaciations have no comparable features we propose that this change in the course of the Salzach is as young as the LGM.

This interpretation is consistent with the major knick point of the Salzach River some 20 km downstream of Lake Zell. There, the stream power of the Salzach River is increased by about two orders of magnitude across the knick point (Figs. 3b and 5a). We relate the origin of this knick point to a change of the Salzach course from flowing through the Saalach wind gap to its present day course. The sudden increase of discharge caused by this recent capture event may explain the significantly elevated stream power downstream the capture point, causes higher erosion rates and a lowering of the Salzach base level. As such, the knick point in the Salzach is caused by a capture event rather than by tectonics. This interpretation is consistent with location of knick points in tributaries to the Salzach: Knick points formed during a single event migrate rapidly upstream at a constant vertical rate. Knick points in the Salzach tributaries draining the Großarl and Gastein valleys are on the same elevation as that in the Salzach main channel. This suggests that they all relate to the knick point forming event in the main channel.

Near the knee-shaped bend of the Salzach River (Fig. 8a,b), there are at least three wind gaps that connect the Salzach and Enns catchments. One wind gap connects the Kleinarl valley with the Enns valley, two other connect the Fritzbach valley with the Enns valley (red arrows on Fig. 5). The Klainarl valley probably once formed the head waters of the west flowing Salzach between St Johann and Zell. Today, the stream power at the side of the Salzach drainage area is significantly higher than in the Enns drainage area and the topographic barriers, especially for the Fritzbach wind gap (Fig. 8a), are only some tens of meters, it is very likely that the Salzach River will take over the headwater tributaries of the Enns River.

Similar to the Salzach, the Enns River is characterised by very low stream power values in the orogen parallel segment along the SEMP fault system and a stream power increase by 2 orders of magnitude in the Gesäuse and downstream (Fig. 5b). Interestingly, the Enns valley glacier reached as far as the Gesäuse and covered the entire low stream power segment of the Enns but not the segment downstream the Gesäuse characterised by high stream power values (Fig. 1a). All major tributaries south and north of the main channel between the two kick points at Schladming and the Gesäuse are characterised by very high stream power near the confluence points to the Enns River.

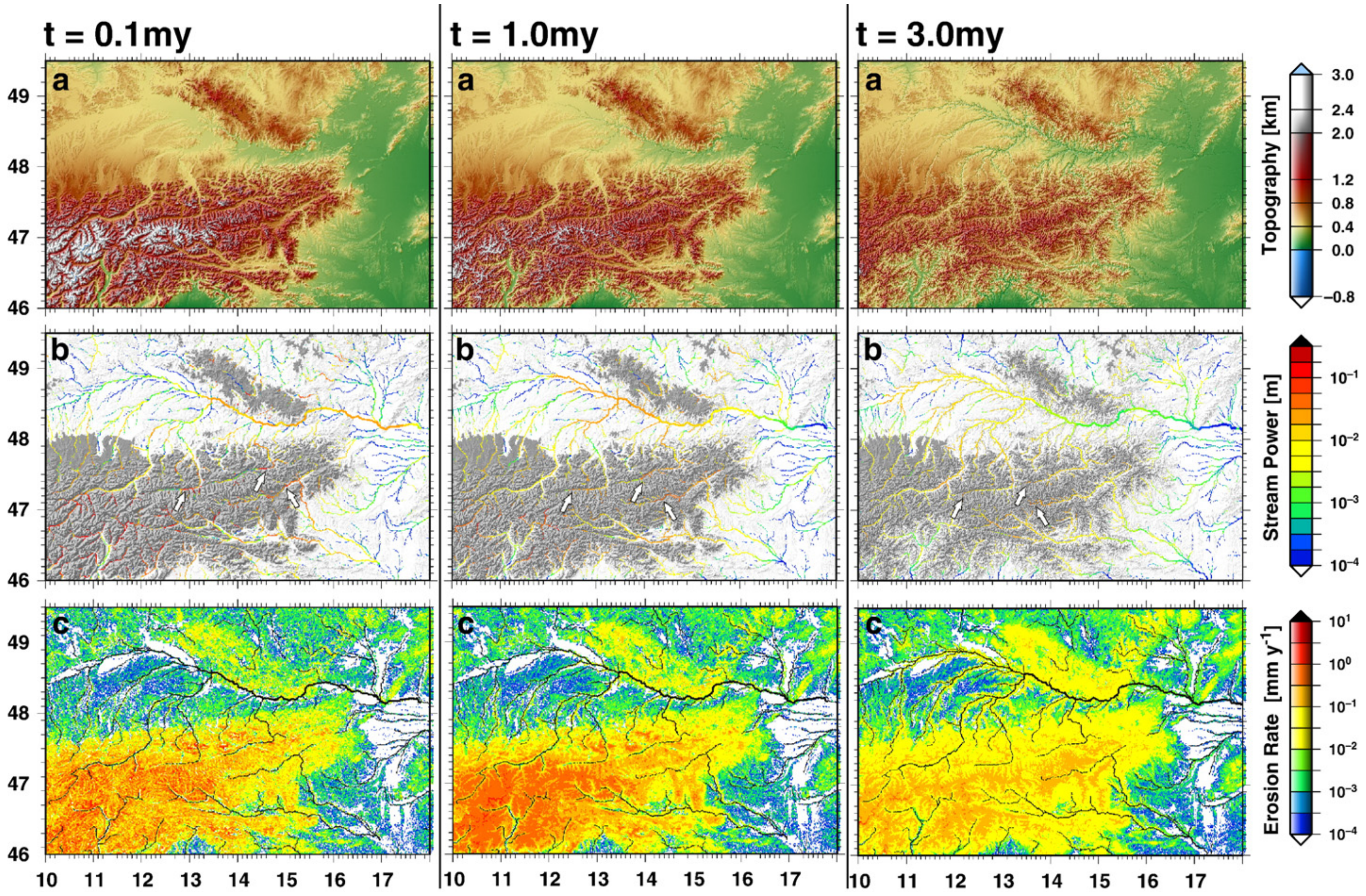

Fig. 9. Three time steps of a time dependent model evolution illustrating the decay of topography and waning erosion rates caused by relaxing landscape. The model evolution is run over about 3 Ma using Eq. (3) with $E = 100\ \text{km}^{-1}\text{a}^{-1}$. The erosion rate in this model scales linearly with time, so that E and time are inversely proportional (i.e. double E and half time are identical). (a) topography, (b) stream power of drainages with an upstream drainage area larger than 100 km^2. White arrows indicate segments of high stream power in the Enns, Salzach and Mur. (c) erosion rate.

On the north side along this segment at least two different distinct levels of paleo surfaces can be observed (van Husen, 1981) (Fig. 8e). Tributaries of the Enns River draining within these paleo surfaces between Bad Mitterndorf and Pyhrn some 200 m to 300 m above the recent base level show very low stream power values. However, at the southern front of these paleo surfaces the channels show high channel gradients and elevated stream power values at the steep slope to the Enns valley.

Several distinct wind gaps with levels in the range of 100 m above the present Enns bed raise the question whether the course of the Enns River was rearranged in the latest past. The massive wind gap at Weng is much wider than the current channel through the Gesäuse suggesting that the Enns drained there at some stage and was replaced to the current course at recent times (Fig. 8c). A more dramatic change in the drainage pattern is needed by assuming that the wind gaps at the Pyhrn and at Bad Mitterndorf once hosted the main channel(s) of this drainage basin. A major part of the current Enns tributaries would have drained into the Steyr and Traun River, respectively. Another evidence for such a completely different drainage pattern is given by the former Palten valley (Fig. 5b, the yellow arrow indicates the former flow direction) that entered the Enns valley in an atypical acute angle some kilometres east of Liezen suggesting that the flow direction of the Enns River at least east of this point was reverse.

Summing up all feature from the Enns catchment we suggest that the Enns valley glacier was responsible for a base level lowering of 100–200 m in the current main valley. This caused a massive reorganisation of the drainage system. Tributaries on the southern side of the main channel are therefore characterised by elevated stream power values near the confluence with the main channel. The same characteristic is shown by the tributaries on the northern side of the current Enns valley. As these knick points did not migrate significantly upstream the timing of this base level lowering can be constrained to the LGM. However, these tributaries show very low channel gradients as long as they drain within paleo surfaces. We therefore propose that the headwaters of these tributaries within the paleo surfaces have been captured (by reversing the flow direction) by head ward cutting creeks that drain along the step that emerged between the former and the current Enns valley after the deglaciation. This would explain the watershed between Enns and Traun crossing the valley of Bad Mitterndorf and the watershed between the Steyr and the Enns at the Pyhrn wind gap. Therefore it is very likely that tributaries of the Enns River originally were part of the Traun and the Steyr drainage systems. In contrast, the very low stream power in the orogen parallel segment, and the appearance of limnic sediments would rather be an evidence for jamming the valley by post-glacial mass movements in the Gesäuse region (van Husen, 1979).

5.2. Catchments never covered by ice

Two major catchments of the Eastern Alps were ice free during the LGM: The Drava below Völkermarkt and the Mur below Murau. As such, these two rivers have a unique position in the entire Alpine orogen as their morphological evolution is unmasked by glacial erosion possibly preserving Miocene morphological features. Both rivers flow across some major structures known to be active within the last 5 Ma: The seismically still active sinistral Mur–Mürz fault system and the dextral Lavanttal fault system.

As shown by the channel profiles, the main channel of the Mur River is very well equilibrated (Figs. 3c and 6a). The stream power is fairly constant along the main channel but shows a small maximum at the T-shaped river segment at the confluence with the river Mürz. Interestingly Mur and Mürz follow the same lineament but in opposite direction, so that the Mürz River drains against the mean topographic gradient of the orogen. Although the stream power of the main channel of the Mur River is rather constant, the stream power of the tributaries in the Gleinalpe and Koralpe region show large systematic variations (Fig. 6a). All tributaries are characterised by decreasing stream power from the mountainous region of the Koralpe in direction to the Pannonian Basin.

This gradual transition from high stream power values in the western part to low stream power values in direction to the Pannonian Basin may be interpreted by the transition between the Alpine area with high uplift rates to the Pannonian Basin with low uplift rates and therefore strong evidence for recent uplift in this region. T-shaped river segments as the one at the confluence between the Mur River and the Mürz River are frequently observed in orogens around the world. Large orogen parallel rivers are uplifted and captured by head ward cutting rivers that in general drain along the recently developed topographic gradients (e.g. Robl et al., 2008). It is very likely that the Mur originally drained in east direction into the Vienna Basin to the Danube, but was captured during the uplift of the eastern part of the Eastern Alps. The channel segment east of the capture point changed the flow direction and became the Mürz tributary. This is confirmed by rock provenance data at the eastern border of the Eastern Alps (Dunkl et al., 2006) and can also be seen as evidence for recent uplift at the eastern border of the Eastern Alps.

At the south eastern border of the Eastern Alps the Drava drainage systems was also ice free below Völkermarkt (Figs. 6b and 2c). The main channel shows highly variable values for stream power, mainly caused by a numerous hydropower stations all along its course. After the confluence with the Lavant River, the Drava follows the fault system for about 20 km. Interestingly, the length over which the river follows the fault is consistent with the displacement along the Lavanttal fault (Linzer et al., 2002). Then, instead of further following this valley, the Drava River again changes its course by 90°, draining from this point on in east direction and entering the Pohorje Range. At this location two rivers join the Drava: the Meža and the Mislinja rivers. The Mislinja River has its source at the southern flank of the Pohorje Range, drains in west direction along the Drava-Sava drainage divide and reaches the prolongation of the Lavant valley at a distinct wind gap. Here the Mislinja River follows the valley in north direction until the confluence with the Drava. On the south eastern flank of the Pohorje Range several tributaries of the Dravinja River show the same stream power pattern than observed on the east side of the Koralpe. The Drava itself crosses the Pohorje Range in several deeply incised gorges. Within the Pohorje Range, about 5 km to 10 km south, about 200 m to 300 m above the current base level and parallel to the recent channel of the Drava River, a dry valley indicates the former course of the Drava River (Sölva et al., 2005). Although this dry valley trends west–east, recent creeks on the north side of the Pohorje Range drain south to north deeply incising the former Drava channel. A south–north oriented swath profile starts in the Sava drainage area and reaches a pronounced topographic low surrounded by steep crests and drained by the Savinja River before reaching the Pohorje Range. The flanks of the range are steep but the central part forms a several square kilometre large plateau.

Summarising all features we suggest that the Drava River is older than the activity of the Lavanttal fault and that it was displaced by it which is consistent with the offset along the Lavanttal fault. We further interpret the radial drainage and stream power pattern around the Pohorje Range in terms of young uplift and propose that the Drava River was antecedent. The interpretation of originally low topography in this region is consistent with the properties of the former Drava valley which is wide and shallow. As a consequence of the uplift of the Pohorje Range the Drava River was also uplifted and captured by steep north draining channels that followed the newly formed topographic gradient. This led ultimately to a shift of the Drava course in north direction. The stream power of the Pohorje Range is most likely related to decreasing uplift rates from the centre of the range to the Pannonian Basin. The shift of the Drava channel on the north side of the range in north direction as well as the decreasing stream power from the southern side of the Pohorje in direction to the Pannonian Basin suggest that the Pohorje represents a dome like structure with elevated uplift rates compared to the vicinity. The fact that the central parts of the range is characterised by a plateau like landscape and out of morphological equilibrium gives evidence that the uplift of the range is a recent feature.

5.3. Catchments with base levels different from the Black Sea

The upper Rhine and the Adige present the only two rivers of the Eastern Alps that respond to different base levels from the Danube, namely the Rhine graben and the Adriatic Sea, respectively. Both base levels have seen substantial fluctuations within the last 5–6 Ma as the Adriatic Sea level was up to 1500 m lower during the Messinian (e.g. Clauzon et al., 1996) and the seismically active Rhine graben was characterised by significant subsidence (Cloetingh et al., 2006). Because both of these base levels were potentially different from that of the Danube, it is likely that the Adige and Rhine eroded more rapidly than the Danube catchments and thereby enlarging their drainage areas and shifting their drainage divides into other catchments.

For the watershed between the Danube and the Rhine catchment, the stream power of the tributaries to the Rhine is significantly higher than that of tributaries to the Danube (Fig. 7a). As a consequence, the Rhine drainages system will successively grow (and has in the past) at the expense of the Danube by capturing its uppermost tributaries (Fig. 7a; red arrows). This may also be seen in the highly lobate shape of the divide between these two rivers. This process was driven by base level lowering during the opening the Rhine graben, but may also be related to the recent uplift of the Danube channel especially along the spur of the Bohemian Massif indicated by channel segments of elevated stream power (Fig. 2a). Swath profiles across the drainage divide of the Rhine and Danube rivers show evidence for the latest evolution of the drainage system and the tectonic causes. A swath profile from the Rhine graben to the Lake Constance is dominated by the asymmetric topography with steep flanks in northwest direction and a gentle decrease of surface elevation in the opposite direction (Fig. 7a, A–A'). In detail it can be seen that the base level of the Rhine valley is several hundred meters below the base level of the Danube. Even the Neckar River, captured by the Rhine in Pliocene times (Berendsen and Stouthamer, 2001), has significant lower base level than the Danube. The channel of the Danube River is located on a topographic high, as the region around the Lake Constance is distinctly deeper than the Danube main channel. A 2nd profile B–B' running north of Lake Constance and parallel to the alpine front shows clearly differences in the base level between the two drainage systems but also in the roughness of the topography.

At the southwestern border of the Eastern Alps, the drainage system of the Adige River is generally characterised by a higher mean value for stream power compared to the surrounding drainage systems (Figs. 7b and 3d). This corresponds very well with a maximum in the uplift rates determined for the Eastern Alps (Fig. 4c). The main channel of the Adige is deeply incised until Meran. Below Meran, channel gradient and stream power of the Adige main channel is much smaller (Fig. 3d). Importantly, it is smaller than that of most of its tributaries like the Eisack River. Segments showing maxima in stream power are systematically located near the confluence point of the tributaries with the Adige River (e.g. Ulten, Talfer, Avisio) while the headwaters of these tributaries are characterised by stream power values lowered by one order of magnitude. The extreme incision of the Adige River and their tributaries can best be observed by swath profiles that show differences in the surface elevation of more than 3000 m within a distance of few kilometres across the valleys.

The observation of low stream power values in the main channel and high stream power in the tributaries near confluences is similar to the Salzach- and Enns rivers where we interpret this feature as the consequence of lowering of the main channels during the LGM. For rivers sharing the Mediterranean Sea as common base level the question on the impact of the Messinian salinity crisis arises as deeply incised bed rock channels several hundred meters below the current sea level were common in these drainages about 5 Ma ago (e.g. Foeken et al., 2006). Although the Messinian salinity crisis coined the drainage system in the Southern Alps and probably shifted the principle drainage divide in north direction, there is no signal left in the stream power pattern. Evidence for a watershed migration is given by morphological aspects like the pronounced wind gap in Sillian where the Drava and Rienz River follow a common valley, but drain in opposite directions. Even stronger evidence is given by rock provenance data that clearly show that the Inn drainage system originally encompasses the region of the Periadriatic fault system (Frisch et al., 1998; Kuhlemann, 2007).

6. Discussion

The analysis of the channel profiles and the stream power pattern of the Eastern Alps has shown that there is a substantial discrepancy between glaciated and not glaciated catchments during the LGM and catchments that are characterised by the influence of other base levels than the Danube. Catchments not covered by ice during the LGM show rather equilibrated channel profiles (e.g. Mur) with only their minor tributaries reflecting a broad uplift of the range. The displacement of the river Drava by the Lavanttal fault or the capture of the Mur–Mürz system by a south draining lower Mur appear not to be reflected in significant knick points. Only few localised observations testify of broad uplift: The several hundred kilometres long linear channel segment of the Drava River can well be interpreted in terms of recent tectonic activity. Strong gradients in the stream power of the Mur tributaries at the east side of the Koralpe Range and similar stream power pattern along tributaries of the Drava at the Pohorje Range are likely to show the response of the drainage system to strong and local gradients in the uplift rate.

As disturbance in channel profiles and stream power patterns are significantly more pronounced in catchments showing strong glacial impact, the difference between ice covered and ice free catchments may indicate that rather the latest glaciations disturbed the morphological equilibrium and not deformation along distinct fault zones. Here we interpret the appearance of knick points at the position were the Salzach (Salzachöfen) and Enns (Gesäuse) break through the northern oroganic front as a combination of glacial base level lowering and the differential uplift rates between foreland and orogen. This interpretation implies that the present day courses of these rivers and their knick points are extremely young features. This is testified through the time dependent evolution of disequilibrium features. For example, knick points that were created during a single event like capture events migrate subsequently upstream the river. The vertical rate of up river migration is comparable to the mean erosion rate so that 0.1–1 mm per year erosion rate implies that the knick points have migrated 100 m–1 km vertically in the last 1 Ma. For example, the elevation of the major knick points in Salzach and Enns only few tens of metres above the suggested capture points is consistent with these capture events having occurred in connection with the LGM. This hypothesis can be tested by modelling the time dependent evolution of the drainages into the future.

6.1. Temporal evolution of the drainage system

In order to test our hypothesis that most of the morphological features of main channels are unrelated to tectonics, we have designed a time dependent model for erosion. This model can be used to estimate orogen wide erosion rates, the rate of occurrence of capture events or the velocity of upstream migration of knick points. By comparing the forward prediction of these processes into the future with our suggested evolution of the recent past, we can test our hypothesis for the past. For our model we have assumed that the erosion rate is proportional to the square of stream power as defined in Eq. (1):

$$\frac{dH}{dt} = Es^2$$

Using $\theta = 0.5$ in Eq. (1) this corresponds to:

$$\frac{dH}{dt} = E\left(-\frac{dH}{dL}\right)^2 A \tag{3}$$

where E is a proportionality constant with the units of [$\mathrm{m}^{-1}\ \mathrm{s}^{-1}$] that can be interpreted as an erodibility. Other authors have assumed that erosion rate is linearly related to stream power but we follow here Hergarten (2002) and Stüwe et al. (in press) assuming a quadratic relationship for reasons explained there. For E we assume $E = 100\ \mathrm{km}^{-1}\ \mathrm{Ma}^{-1}$, so that the erosion rate of a $10^4\ \mathrm{km}^2$ sized catchment and a channel gradient of 100 vertical m per 100 km channel is 1 mm a^{-1}. This value for E was determined for Himalayan catchments (Robl et al., 2008) but seems also reasonable for the European Alps as erosion rates are in the same order of magnitude than measured uplift rates.

We have then interpolated a digital elevation model for the Eastern Alps onto a triangulated mesh with an average resolution of 0.16 km^2. To preserve the valleys we have applied a low pass filter with a wavelength of 1 km to the digital elevation model, so that the drainage system is not biased by artificial barriers caused by down sampling of the DEM to the resolution of the grid. This model is then evolved through time assuming zero uplift rate (Fig. 9). To get an estimate on the life time and migration rate of knick points and other deviations from the morphological equilibrium, three representative time slices are shown. The first time slice on Fig. 9 after 0.1 Ma is comparable to the duration of the last glaciations. The time slice after 3 Ma of erosion was chosen to predict whether the Messininan salinity crisis can still be observed as disturbance in the drainage system or not.

After about 0.1 Ma (representing the duration of the last glaciations) a significant part of the central Eastern Alps is still above 2000 m (Fig. 9). Dramatic changes in the topography can not be observed. The stream power pattern of major alpine rivers is similar to the pattern shown in Fig. 4b, with highest stream power segments in the central and western parts of the Eastern Alps and high stream power sections in the knee-shaped reaches of the Enns, Salzach and Mur River. A long segment of elevated stream power is also observed in the Danube River along the Bohemian Massif. By comparing the actual pattern of the stream power (Figs. 5–7) with the pattern after 0.1 Ma of erosion the high stream power segments have already migrated 100 vertical meters in the Enns and in the Salzach River. The pattern for the erosion rate and stream power coincides largely. Interestingly, the orogen parallel segments of the Salzach and Enns River that are characterised by very low erosion rates and stream power values are surrounded by regions of very high erosion rates, indicating that there is still strong morphological disequilibrium between large inner alpine valleys and smaller tributaries. The patchy pattern for the erosion rates especially in the central eastern Alps is caused by non-steady state channel profiles primarily caused by the impact of glaciations. Nevertheless a similar pattern can also be observed in the Bohemian Massif that was not glaciated in the recent past.

After about 1 Ma all alpine rivers have deeply incised their channels so that the topography starts to dissect. The decay of topography proceeds so that only narrow mountain crests remain above 2000 m. Segments of high stream power have migrated several tens (Salzach, Enns, Mur) to more than hundred kilometres (Danube) upstream leading to a subsequent base level lowering. Due to the ongoing decay of topography the average stream power in the main channels and larger tributaries is reduced. The originally patchy pattern of erosions rates has become more homogeneous as disturbances in the channels have moved upstream, have decayed and finally have left the drainage system. The highest erosion rates are still located in the central part of the Eastern Alps with maximum values exceeding 1 mm a^{-1}. Although the model runs were performed without uplift and topography was significantly removed during 1 Ma of erosion, the overall erosion rates increased as a consequence of base level lowering through knick point migration. Next to central parts of the Eastern Alps, this phenomenon can also be observed in the Bohemian Massif.

After 3 Ma of erosion, the dissection of the Eastern Alps has destroyed the major part of the mountainous domain so that the highest summits at the central mountain crest are below 2000 m. Segments of high stream power have more or less left the entire drainage system and can only be observed in the very headwaters of the major rivers. Starting from the Pannonian, the low base level is migrating along the Danube and reaches subsequently the upstream tributaries by establishing a new deeper base level. The erosion rates in the Eastern Alps do not exceed 0.5 mm a^{-1} and are now in the same order of magnitude than in the Bohemian Massif. Interestingly, the deep base level originated within the Pannonian Basin entered the Salzach River leading to a steeper channel and higher erosion rate at the lower reach.

From modelling the temporal evolution of the drainage system we propose that deviations introduced into the drainage system leave the main channels within less than 5 million years, so that we can not relate knick points and segments of high stream power to the Messinian salinity crisis. However, this does not necessarily mean that the Messinian reorganisation of the drainage system has been revoked. At least in a relaxing landscape the course of the major rivers remains fairly constant and even the drainage divides do not shift significantly, although the landscape morphology changes dramatically from a mountainous to a highly dissected hilly topography.

The occurrence of knick points and their rapid migration in catchments glaciated during the LGM and the equilibrated channels in catchments without glacial cover suggest that most of the disequilibrium features are young and rather related to glacial processes than to tectonics.

7. Conclusion

Our analysis of channel profiles and stream power of the major drainages of the Eastern Alps allows drawing the following conclusions:

(A) Over all, the regions of high stream power coincide largely with regions of highest topography and largest uplift rates (BEV, 1991; Ruess and Höggerl, 2002), while the northern and southern foreland as well as the Pannonian Basin are characterised by significantly lower stream power.

(B) Channel profiles of major rivers in the Eastern Alps show little evidence for tectonic disturbance. Most major knick points may be related to features of the last glacial maximum and only broad zones of uplift are recorded.

(C) As a result of base level lowering of the current main channels during the last glaciations a dramatic reorganisation of the Enns and Salzach drainage system occurred. Strong evidence for this is given by a variety of wind gaps, and knick points in the main channels and tributaries. The two prominent knick points in the Salzach — and Enns Rivers at the northern orogenic front represent most likely the collision driven uplift during the glaciations and the post-glacial rebound. The difference in level up — and downstream the knick points is consistent with an uplift rate of about 1 mm a^{-1} and a duration of the last glaciations of about 100 Ka.

(D) At the very east of the Eastern Alps (Koralpe), as well as in the Pohorje Range and in the Bohemian Massif there is strong evidence for late orogenic uplift. This is indicated by strong stream power variations along rivers in these regions.

(E) Base levels different to those of the Danube have a strong impact on the development and reorganisation of the east alpine drainage system. The low base level of the Rhine relative to the base level of the Danube causes a still ongoing watershed migration. This process may be intensified if the channel of the Danube River becomes lifted along the spur of the Bohemian Massif. Similar to the Rhine graben, the Messinian salinity crisis caused a reorganisation of the drainage system in the Adige catchment. However, as morphological disturbances leave the channels in less than 5 Ma there is no signal in the stream power pattern.

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