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Patterns of landscape form in the upper Rhône basin, Central Swiss Alps, predominantly show lithologic controls despite multiple glaciations and variations in rock uplift rates

L. A. Stutenbecker[1], A. Costa[2], and F. Schlunegger[1]

[1]Institut für Geologie, Universität Bern, Baltzerstrasse 1+3, 3012 Bern, Switzerland
[2]Institut für Umweltingenieurwissenschaften, ETH Zürich, Stefano-Franscini-Platz 3, 8093 Zürich, Switzerland

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Correspondence to: L. A. Stutenbecker (laura.stutenbecker@geo.unibe.ch)

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Abstract

The development of topography is mainly dependent on the interplay of uplift and erosion, which are in term controlled by various factors including climate, glaciers, lithology, seismic activity and short-term variables such as anthropogenic impact. While most studies have focused on the role of tectonics and climate on the landscape form and underlying processes, less attention has been paid on exploring the controls of lithology on erosion. The Central European Alps are characterized by a large spatial variability in exposed lithologies and as such offer an ideal laboratory to investigate the lithological controls on erosion and landscape form. Here, we focus on the ca. 5400 km^2-large upper Rhône basin situated in the Central Swiss Alps to explore how the lithological architecture of the bedrock conditions the Alpine landscape. To this extent, we extract geomorphological parameters along the channels of ca. 50 tributary basins, whose catchments are located in either granitic basement rocks (External massifs), oceanic meta-sedimentary and ophiolitic rocks (Penninic nappes) or fine-grained continental-margin sediments (Helvetic nappes). The analysis of longitudinal river profiles show that all tributary rivers within the Rhône basin are in topographic transient state as testified by mainly convex or concave-convex longitudinal stream channel profiles with several knickpoints of either tectonic or glacial origin. In addition, although the entire Rhône basin shows a strong glacial inheritance (and is still partly glaciated) and some of the highest uplift rates recently measured in the Alps, the river network has responded differently to those perturbations as revealed by the morphometric data. In particular, tributary basins in the Helvetic nappes are the most equilibrated (concave river profiles, overall lower elevations, less steep slope gradients and lowest hypsometric integrals), while the tributaries located in the External massifs are least equilibrated, where streams yield strong convex long profiles, and where the tributary basins have the highest hypsometric integral and reveal the steepest hillslopes. We interpret this pattern to reflect differences in response times of the fluvial erosion in tributary streams

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towards glacial and tectonic perturbations, where the corresponding lengths strongly depend on the lithology and therefore on the bedrock erodibility.

1 Introduction

The topographies of the world's mountains have been formed by rock uplift, which were usually initiated by lithospheric processes such as convergence, collision and crustal thickening (England and Molnar, 1990). However, topographic growth on Earth is not indefinite, but limited by erosional feedback mechanisms. Once threshold topography has been reached, any further uplift will be balanced by denudation, and this concept is known as topographic steady-state (Adams, 1980; Stüwe et al., 1994; Willett and Brandon, 2002). In order to understand this interplay, it is thus crucial to explore the mechanisms controlling erosion in an area. In this context, several studies have illustrated that denudation is highly variable in space and time, and that it depends on a large number of variables, such as climate, glaciation, tectonics, lithology and topography. For example, climate and denudation are coupled in such way that a general wetter climate with high orographic rainfall increases fluvial erosion and the related sediment flux (e.g. Willett, 1999; Willett et al., 2006; Chittenden et al., 2013). Glacial erosion was found to be even more efficient than fluvial erosion through relatively high slip rates and high basal shear stresses, and also through subglacial water pressure gradients (e.g. Hallett et al., 1996; Montgomery, 2002; Norton et al., 2010a, b; Spotila et al., 2004; Shuster et al., 2005; Valla et al., 2011). This seems to be especially valid for the Quaternary period, when multiple glacial advances and retreats formed the mountainous landscapes in many orogens (e.g. Kelly et al., 2004). In contrast, other authors have reported that the tectonic control on denudation has been more pronounced than a climatic one. For example, periods of accelerated uplift in the Alps, recorded by mineral cooling ages (Michalski and Soom, 1990; Vernon et al., 2008; Fox et al., 2015), coincide with a generally higher sediment flux into the foreland basin (Kuhlemann et al., 2002; Schlunegger et al., 2001), consistent with Baran et al. (2014) who compiled data

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about large-scale patterns of erosion in the Alps. Wittmann et al. (2007) measured Holocene erosion rates in Alpine river sediments, which correlate very well with measured uplift rates, suggesting that vertical rock movement is mainly caused by isostatic compensation of removed material (Champagnac et al., 2009). In thematically related studies, several authors concluded that erosion rates directly correlate with geomorphological variables like slope gradients and relief that can be extracted from digital elevation models (Granger et al., 1996; Schaller et al., 2001; Montgomery and Brandon, 2002). Furthermore, lithology is another controlling factor, since soft lithologies like marls are eroded much easier than hard lithologies such as granites or gneisses (e.g. Korup and Schlunegger, 2009; Kühni and Pfiffner, 2001; Morel et al., 2003; Norton et al., 2010b; Cruz Nunes et al., 2015). However, compared to other driving forces conditioning a landscape such as rock uplift, glaciations and precipitation, much less attention has been paid on exploring how the lithological architecture of a landscape in general, and the nature of the bedrock lithology, drives surface erosion.

The European Alps have been studied intensely regarding the coupling of surface and crustal processes paired with glacial conditioning on erosion (e.g. Persaud and Pfiffner, 2004; Gudmundsson, 1994; Champagnac et al., 2007; Schlunegger and Hinderer, 2001; Cederbom et al., 2011; Norton et al., 2010b; Schlunegger and Norton, 2013). However, the spatial and temporal variability of uplift, climate, glacial cover, lithology and topography throughout the orogen complicates an integrated understanding of the erosional patterns and the Alpine sediment budget. Nevertheless, because of the large variations in bedrock lithology in the Alps, it is possible to explore whether differences in landscape properties mainly reflect the response to these driving forces (uplift, climate etc.), or alternatively whether the landscape properties reveal a distinct pattern where similar characteristics are mainly grouped around identical lithologies, which will be documented in this paper. Here, we focus on the upper Rhône basin in south-western Switzerland, which is the largest inner-alpine drainage system with a total catchment size of over 5000 km^2. The Rhône basin was covered by some of the thickest Alpine glaciers throughout the Quaternary (Kelly et al., 2004) and recently

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experiences some of the highest uplift rates in the Alps (Kahle et al., 1997; Schlatter et al., 2005). We explore the geomorphological response of the landscape towards this strong glacial and tectonic conditioning by analysing the geomorphology of about 50 tributary rivers feeding the Rhône River between its source, which is the glacier next to the Grimselpass, and its terminus, defined here by the delta at Lake Geneva (Fig. 1). We complement our geomorphic data with published large-scale geological, glacial and exhumation data in order to attain a large-scale understanding of the predominant processes controlling the Rhône River sediment budget over multiple time scales. We find distinct spatial differences in the response of fluvial erosion to glacial and tectonic forcings, which are mainly related to lithotectonic architecture. This suggests that underlying lithology has exerted a fundamental control on erosion and the resulting landscape form.

2 Geological setting

2.1 Geology

The study area covers the entire upper Rhône basin between the Rhône glacier and Lake Geneva in the central Swiss Alps (Fig. 1).

The bedrock of the upper Rhône basin comprises the major tectonic units of the western Alpine orogen (e.g. Froitzheim et al., 1996; Schmid et al., 2004). Along its ca. 160 km long course from its source next to the Grimselpass at over 2000 m a.s.l. towards the delta on Lake Geneva at ca. 370 m a.s.l., ca. 50 major tributary streams with sources in either Penninic, Helvetic nappes or crystalline basement rocks derived from the European continental and oceanic lithosphere (Schmid et al., 2004) discharge their material to the Rhône River. The related lithologies are oceanic metasedimentary and ophiolitic rocks exposed in the Penninic nappes covering 52 % of the total Rhône watershed. These units are mostly drained by tributaries south of the main Rhône valley (Fig. 2). Variscan crystalline rocks of the European basement (granites, gneisses and

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schists) of the Aar, Aiguilles-Rouges and Mont-Blanc External massifs, exposed both on the eastern and western sides of the Rhône valley, contribute to 22 % of the bedrock underlying the Rhône basin. Calcareous metasedimentary rocks of the European continental margin are exposed in the Helvetic and Ultrahelvetic nappes north of the main Rhône valley and make up ca. 16 % of the total watershed. Finally, minor proportions of the Rhône watershed are made of unconsolidated Quaternary (6 %) and Oligocene Molasse (1 %) units as well as the "sub-penninic" basement nappes of the Gotthard massif (3 %).

2.2 Tectonics

Structurally, the Rhône basin is dominated by the Rhône-Simplon fault system, which accommodated orogenic extension mainly through dextral strike-slip movements since early Miocene times (Schlunegger and Willett, 1999; Egli and Mancktelow, 2013). Seward and Mancktelow (1994) suggested that faulting also had a normal fault slip component, which played an important role in the younger exhumation history of the area. Actually, the fault is not only the boundary between two different paleogeographic domains, but also separates two terrains with significantly different exhumations histories (Michalski and Soom, 1990; Schlunegger and Willett, 1999; Vernon et al., 2008; and references within, Fig. 3a). In particular, south of this fault in in the Penninic domain, apatite fission-track ages range between 8 and 20 million years, while related ages are around 5–12 million north of the fault in the Aar massif and the overlying Helvetic nappes. The External massifs such as the Aar and the Mont Blanc massif have been exhumed in Neogene times up to 8 km in ≤ 15 Ma (Pfiffner et al., 1997b) and therefore show the youngest exhumation ages of ca. 1.5–5 Ma (Michalski and Soom, 1990).

Recent uplift rates derived from GPS bedrock measurements and geodetic surveys (Kahle et al., 1997; Schlatter et al., 2005) in the Rhône basin are some of the highest recorded throughout the Alpine orogen, possibly caused by a combination of ongoing collisional processes (Persaud and Pfiffner, 2004), erosional (Champagnac et al., 2009) and glacial unloading (Gudmundsson, 1994). Uplift rates are highest in the eastern part of the study area ($1.5\,\mathrm{mm\,a^{-1}}$) and decrease to $< 0.3\,\mathrm{mm\,a^{-1}}$ towards Lake Geneva.

Main seismic activity is focused on the area north of the Rhône River within the Helvetic domains and corresponds mostly with strike-slip movement along faults (Fig. 2, Maurer et al., 1997; Deichmann et al., 2002). Faults in the Rhône basin are generally oriented along the main strike direction and parallel to the Rhône River (NE–SW). Another cluster of earthquakes, which is associated with normal faulting, occurs at intermediate elevations within the Penninic nappes south of the Rhône River (Maurer et al., 1997).

2.3 Glaciation

During the Quaternary, the landscape of the Rhône valley has been shaped and carved by multiple glaciations (Ivy-Ochs et al., 2008; Valla et al., 2011). In this context, the entire basin was covered by an up to 1.5 km-thick ice sheet especially during the Last Glacial Maximum (18–24 ky ago, Kelly et al., 2004). At the eastern border of the Rhône valley, two separate ice domes formed the ice divide of the Rhône and the Rhine headwaters (Florineth and Schlüchter, 1998). From there, the ice flew within the valleys (including the Rhône valley) down to the foreland in the north, and the ice thicknesses decreased radially towards the West.

Until recently, the Rhône valley has hosted some of the thickest Alpine glaciers like the Rhône or the Aletsch glacier. Today, ca. 9 % of the whole upper Rhône watershed is still glaciated, and most of the glaciers are situated in the East and Southeast of the basin (Fig. 3b). Their distribution within the three main litho-tectonic units is very distinct with glacial covers ranging from a maximum of 17.7 % in the External massifs, 12.5 % in the Penninic units and only 1.5 % in the Helvetic nappes. Individual tributary basins like the Massa basin (Fig. 1) are even glaciated up to 50 %, whereas others are completely ice-free. Numerous morphological features like oversteepened head scarps, wide, U-shaped, deeply carved trunk valleys and hanging tributary rivers in-

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cluding oversteepened inner gorges reflect the landscape's strong glacial inheritance (Norton et al., 2010a, b; Valla et al., 2011).

3 Methodology

Tectonic, climatic and glacial forcings and their interplay operating at different scales through space and time can be identified by the perturbation they have caused in the landscape, by the landscape's response and related morphologic measures suggestive for extents at which re-equilibrations to those perturbations have proceeded. In this context, precipitation patterns and geomorphological parameters such as river longitudinal profiles, river cross sections and their height-width-ratios, as well as catchment-wide hypsometric and slope distributions are frequently used to determine the landscape's condition (e.g., Wobus et al., 2006; Brocklehurst and Whipple, 2004; Robl et al., 2015), which we adapt in this study.

3.1 Precipitation pattern

The spatial distribution of precipitation in the current climate is shown in the form of total annual precipitation (Fig. 3c) and high intensity rainfall represented by annual 90 % of total daily precipitation. Computations were based on the RhiresD product of the Swiss Federal Office of Meteorology and Climatology MeteoSwiss (Schwarb, 2000). RhiresD is a gridded daily precipitation dataset covering the Swiss territory with a spatial resolution of $\sim 2 \times 2$ km from 1961 to present. The effective resolution of the dataset is coarser than the grid spacing, on the order of 15–20 km or larger, which is suitable for climatological analysis at the basin scale. Computations were conducted directly on the native grid and consecutively distributed over a 250×250 m grid by proximal interpolation. Precipitation amount and 90 % of total daily precipitation are calculated on annual basis and averaged over the 52 year period 1961–2012. Quantiles

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are computed only for wet days, assuming a threshold of 1 mm day^{-1} for distinguishing wet and dry days.

3.2 River longitudinal profiles

Several studies on river profiles in tectonically active regions have shown that the fluvial network draining an orogen reacts to perturbations by channel reorganization, formation and migration of knickzones and increasing the depth of incision (Whipple and Tucker, 1999; Snyder et al., 2000, 2003; Wobus et al., 2006). Where the rate of surface uplift (or base level lowering) exceeds the denudation rate, river profiles tend to adapt convex-up longitudinal profiles. Furthermore, as a result of a spatially variable uplift downstream a river, the channel can develop multiple knickzones, associated by abrupt changes in its steepness (Wobus et al., 2006). Through time, however, rivers will equilibrate the perturbation through headward retreat and vertical incision, thereby striving towards attaining a topographic steady state.

3.3 Hypsometry

Besides qualitative information about the shape of a river's profile, catchment-wide hypsometry is a measure for the distribution of elevations within a basin that can be linked to the maturity of the landscape (Strahler, 1952). Progressing erosion will lower the overall landscape's topography and the resulting hypsometric distribution will be skewed towards lower elevations. However, the presence or absence of distinct hypsometric maxima may indicate the occurrence of perturbations related to tectonic, climatic or glacial conditions yielding in the preservation, or the removal, of certain elevation ranges (Brozović et al., 1997; Brocklehurst and Whipple, 2002, 2004; Montgomery et al., 2001). In this context, hypsometric distributions of several catchments, illustrated by the hypsometric curve, are commonly used datasets displaying normalized elevations on the ordinate and normalized cumulative area above the corresponding elevation on the abscissa (Fig. 4). Furthermore, Strahler (1952) introduced the hyp-

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sometric integral (HI) as a proxy to infer the topographic state of a catchment. The related values are higher the more convex-up the hypsometric curves are (Fig. 4). Catchments with convex-up hypsometric curves and high HI are considered to be in a non-equilibrated state (after an external perturbation such as glaciation or surface uplift), whereas catchments with straight or concave-up hypsometric curves and low HI are more evolved and thus more equilibrated towards prevailing climate and tectonic conditions (Strahler, 1952). Likewise, river-bed hypsometry helps visualizing and comparing common patterns in the river profile and to evaluate the extent at which incision into the bedrock has proceeded. Accordingly, we calculated the HI for each watershed $> 10\,\text{km}^2$ using a bin size of 100 m suitable for hypsometric analyses through Eq. (1):

$$\text{HI} = \frac{H_{\text{mean}} - H_{\text{min}}}{H_{\text{max}} - H_{\text{min}}}, \tag{1}$$

where H_{mean}, H_{min} and H_{max} refer to the mean, minimum and maximum elevation of the basin.

We additionally performed hypsometric analyses on the main river channel, i.e. we extracted elevations only at the river-bed and plotted them in histograms.

3.4 Hillslope angles

Hillslopes represent the coupling element between mountain summits and the draining river system. Their gradients, distribution and cover are critical parameters for sediment transfer processes and have been found to depend mostly on rock mass strength (e.g. Schmidt and Montgomery, 1995; Whipple and Tucker, 1999; Kühni and Pfiffner, 2001). In high mountain ranges such as the Himalayas, hillslopes at threshold conditions and beyond (i.e., oversteepened) are widespread, and are commonly related to high denudation rates and rapid river incision responding to active tectonics (Burbank et al., 1996; Ouimet et al., 2009). However, if denudation exceeds bedrock uplift, progressing hillslope erosion will decrease the overall slope gradients to values that may be below threshold conditions (Kühni and Pfiffner, 2001; Ouimet et al., 2009). Consequently, in easily erodible lithologies this “equilibrium” will be reached earlier than in more resistant lithologies. In order to test the relation between lithology and slope, we extracted slope gradients for each catchment and for the three main litho-tectonic domains.

3.5 Valley height-width ratio

The valley height–width ratio (V_f) is a relatively straightforward measure for valley shapes derived from the valley cross section (Bull and McFadden, 1977; Bellin et al., 2014). It is the ratio between the width of the valley bottom and the height of the valley flanks and thus can be expressed by Eq. (2):

$$V_f = \frac{2V_{FW}}{(E_L - E_V) + (E_R - E_V)}, \quad (2)$$

where E_V, E_L and E_R are the elevations of the valley bottom, the left and the right valley flank, respectively, and V_{FW} refers to the width of the valley bottom (Fig. 5). In V-shaped valleys, V_f is smaller compared to valleys with a pronounced U-shape. Usually, low V_f values and V-shapes are interpreted to be the result of active fluvial incision (mostly as a result to active tectonics), whereas high V_f values and U-shapes occur in settings with wide valley bottoms such as in tectonically inactive or glaciated reaches (Pérez-Peña et al., 2010; Bellin et al., 2014) We extracted V_f values along the tributary rivers at four locations each (excluding sections with hydropower dams and water reservoirs), usually after ca. 20, 40, 60 and 80 % of the river length in order to track changes in the valley shape.

All extracted geomorphological parameters including elevation, slope gradients, catchments' sizes and river profiles were extracted with standard hydrological tools in ArcGIS© and with the Matlab© based TopoToolbox published by Schwanghart and Kuhn (2010). The base map for all analyses was the 2 m-resolution digital elevation model swissALTI$^{3\text{-}D}$ provided by swisstopo©.

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4 Results and interpretation

4.1 Precipitation pattern

Within the upper Rhône basin, annual precipitation is characterized by a rather high variability in space, ranging from less than 500 mm year^{-1} along the Rhône Valley to more than 2500 mm year^{-1} at very high elevations (Fig. 3c). This spatial pattern most likely reflects orographic effects where inner low elevations are sheltered valleys and thus receive little precipitation, while the annual amount of precipitation is much larger at higher altitudes. Spatial precipitation gradients are relatively low (Fig. 3c). With respect to precipitation-driven erosion processes, it is thus not possible to identify significant distinctions in erosion potential among tributary catchments. This is also confirmed when comparing the frequency distribution of very high intensity daily rainfalls at the basin scale for the External massifs, Penninic nappes and Helvetic nappes (Fig. 6). Indeed, the annual 90 % of total daily precipitation do not show relevant differences in frequency between the three domains and the entire basin (Fig. 6). Median values of these heavy daily rainfalls range from 22 mm day^{-1} in the Penninic nappes, to 27 and 28 mm day^{-1} in the Helvetic nappes and the External Massifs, respectively. The spatial variability of high intensity precipitation within each lithological unit is similar, showing interquartile ranges in the order of 7–9 mm day^{-1} in all lithological units. This suggests that gradients of rainfall erosivities are limited to the vertical dimension driven by orographic forcing, and that all analysed upper Rhône lithologies have experienced similar rainfall amounts (and extremes) on the average.

4.2 River profiles

All analysed tributary channels show features that are characteristic of external perturbations including oversteepened head scarps, several knickpoints and highly convex or concave-convex shapes (Fig. 7), indicating that all tributary channels in the Rhône

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basin are in a topographic transient state. Based on these features, river channels can be categorized into three distinct groups:

1. Streams with mostly convex-shaped longitudinal profiles, multiple topographic steps specially in the upstream stream segment and broad, U-shaped valley cross sections.

2. Deeply incised, canyon-like, mostly concave-shaped channels with typically V-shaped valley cross sections.

3. Concave-convex channels with several knickzones, steep channel heads, flat middle stream segments and steep knickzones towards the junction with the Rhône River.

Interestingly, the three groups are situated in different litho-tectonic domains: channels of group 1 are mostly found in the External massifs, while streams of groups 2 and 3 are found in catchments draining Helvetic and Penninic nappes, respectively. Recent glaciation in the watershed seems not to play a significant role for the shape of the profile, as rivers from the same litho-tectonic unit, but with different recent glacial cover, show similar profiles (Fig. 7).

This categorization is furthermore supported by distinct river bed hypsometric distributions (Fig. 8). Histograms of rivers draining Helvetic units usually show a maximum in lower elevations towards the junction with the Rhône River and a general decrease in elevation frequency towards the head of the river. These lower stream segments are incised deeply into the bedrock and form narrow canyons (Fig. 9), indicating that these inner gorges have been formed by fluvial incision. Major knickpoints in these rivers occur mainly in the upper stream segments and are frequently located along faults (Fig. 10).

In contrast, the hypsometric maxima of streams within the External massifs are present at intermediate elevations, from where the relative frequencies decrease in both the down- and upstream directions. This is also reflected by the generally convex curvatures of the river profiles, where the middle segments are usually the flattest

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parts. The lower stream segments are not incised towards the junction with the Rhône River and form hanging tributaries with prominent knickpoints that are often associated with waterfalls (Fig. 9).

Channels situated in the Penninic units usually show hypsometric maxima at elevations of ca. 1500–2000 m a.s.l. and second maxima at lower elevations (around 800 m) towards the junction with the Rhône. The maxima at higher elevations correspond to the flat reaches in the middle stream segments where channel floors are covered by gravel (Fig. 11). These flat reaches usually show U-shaped valley cross sections and occur upstream of terminal moraines (Fig. 3b), indicating that these flat reaches were shaped by glaciers. At elevations between 1000 and 1500 m, the flat segments end in a knickzone and are juxtaposed by steep zones (minimum in hypsometric curve, Fig. 8) farther downstream. These segments, that are generally oversteepened (Norton et al., 2010b), connect the hanging glacial valley with the Rhône trunk stream by an elevation drop of up to 1000 m. The second hypsometric maxima around 600–800 m of elevation (Fig. 8) are particular pronounced in the Vispa and Farne Rivers, and less evident in the Turtmänna and Gamsa Rivers. This can be explained by different extents of the floodplain located between the tributary outlet and the junction with the main Rhône River. The Vispa and Farne Rivers have relatively long portions of their river channel running through the floodplain at 600–800 m of elevation, whereas these segments area relatively shorter for the Turtmänna and Gamsa Rivers, and thus less pronounced in the hypsometry.

4.3 Catchment hypsometry

The hypsometric curves of basins within both the Penninic units and the External massifs show convex-up shapes (Fig. 12). The histograms show more or less normal distributions with a maximum at intermediate elevations and decreasing altitude frequencies towards higher and lower elevations (Fig. 13). In contrast, the hypsometric curves of catchments in the Helvetic unit are slightly less convex, and the histograms are clearly skewed towards lower elevations.

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The hypsometric integrals (HI) calculated for all watersheds > 10 km^2 size range from 0.28 to 0.7. Summing up the HI of all catchments within each litho-tectonic unit yields averages of 0.37, 0.43 and 0.47 for the Helvetic and the Penninic units, and External massifs, respectively (Fig. 14). Within the standard deviation, the HI of Penninic units and External massifs are similar, while the average HI of the Helvetic units is smaller.

For the Helvetic and Penninic watersheds we found a linear relationship between watershed size and HI, where smaller watersheds usually have higher HI than larger ones (Fig. 14). Also for both litho-tectonic units, we found a cluster of small catchments with slightly lower HI than expected from the linear relationship. Those catchments host without exceptions steep, torrential rivers, where sediment transport has mainly been accomplished by debris-flow processes or concentrated flows like the Illgraben (Schlunegger et al., 2009) or the Torrents de St.-Barthélémy. In the External massifs (Fig. 14), the two largest catchments (Massa and Lonza Rivers) have very high HI, suggesting a non-linear relationship.

4.4 Hillslope gradients

The hillslope gradients extracted for the Externals massifs show an overall normal distribution with a modal value of 28° (Fig. 15). A minor peak in slope gradients < 10° is probably related to the high glacial coverage in this litho-tectonic domain (see Sect. 2.3). Glaciers on the DEM appear as flat regions with slope angles below 5° and therefore bias the slope distributions (Burbank et al., 1996). The slope gradients within the Penninic units follow a normal distribution with a modal value of 25°, whereas the histogram for the Helvetic nappes is clearly asymmetric and skewed towards flatter slopes and has a modal value of only 20° (Fig. 15).

4.5 Valley height-width ratio

We observe a general decrease in V_f in all the analysed tributary rivers from their headwaters to the outlets. The headwaters, either recently glaciated or glacially conditioned

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in the past, often show a pronounced U-shaped valley cross section, whereas the outlets of the rivers often form narrow, deeply incised canyons (Fig. 16). However, V_f values are generally lower (average = 0.22) for streams located in the Helvetic nappes than for those draining the External massifs (average = 0.39). Rivers in the Penninic nappes show stronger variations in this variable, but have usually V_f values around 0.26. Furthermore, the valleys in the Helvetic nappes (and also in parts of the Penninic nappes) show low V_f values and narrow V-shapes already approximately half-way down the stream. In contrast, valleys in the External massifs show higher V_f values along the entire stream, and V_f is decreasing rapidly only at the basin outlet (Fig. 17). This suggests that incision has proceeded farther upstream in the Helvetic and (most of the) Penninic nappes, whereas it has only affected the stream outlets in the External massifs.

5 Discussion and implications

The geomorphological analysis performed in the upper Rhône basin showed that geomorphological parameters are highly variable between different tributary basins. The origin of this variability seems to be related to differences between the main lithotectonic units the basins are located in. In particular, there appears to be a difference in the landscape's maturity between the basins located in the External massifs, the Penninic and the Helvetic nappes. Highly convex river profiles, high hypsometric integrals and higher hillslope gradients as they appear in the External massifs point to an overall low maturity and a high bedrock strength, particularly when considering the steep hillslopes (Kühni and Pfiffner, 2001). In contrast, concave river profiles, lower hypsometric integrals and lower hillslope gradients as observed in the Helvetic nappes indicate a higher maturity and a much lower bedrock strength, also in view of the low hillslope angles (Kühni and Pfiffner, 2011). As shown before, this appears to be largely independent from the basin size. The differences in inferred landscape maturity are also recorded by morphometric properties at smaller scales. In particular, in the Helvetic units, rivers have deeply incised into the bedrock and have accomplished more or less

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concave river profiles. The valleys are V-shaped almost along their entire length, testifying the occurrence of strong fluvial erosion, except for the headwaters, where cirque glaciers formed a wide U-shape. Prominent knickpoints are mainly located at faults, indicating that faulting during most recent times may play a role in the development of those river profiles (Maurer et al., 1997; Ustaszewski et al., 2007).

In the Penninic units, concave-convex river profiles with a flat plateau around elevations of 1000–2000 m followed by steep knickzones farther downstream are frequently observed. As can be seen on the 1 : 25 000 geological maps of the area, these flat reaches are usually covered by gravel deposits (Fig. 11) and can therefore be considered to be zones of deposition, or sediment bypass, with no fluvial downcutting. In contrast, downstream of these plateaus and the steep knickzones, the rivers are situated in V-shaped inner gorges and have incised into deposits that are mostly made up of terminal moraines of LGM glaciers (Fig. 3b). Furthermore, the elevations of the knickpoints (around 1500 m) correspond to the regional LGM positions of the equilibrium line altitude (ELA) (Ivy-Ochs et al., 2008), indicating that the typical steep-flat-steep morphology of the rivers profiles could be of glacial origin. The flat plateau is also marked by minima in the river hypsometric distributions (Fig. 8). Similar morphologies have been described by Korup and Montgomery (2008) in the Himalayan region, where steep knickzones in rivers draining the Tibetan Plateau correspond with the regional LGM ELA positions. Interestingly, slope-by-elevation analyses at the scale of the entire Alpine orogen (Kühni and Pfiffner, 2001; Hergarten et al., 2010; Robl et al., 2015) found an increase of hillslope gradients up to elevations of ca. 1500 m, followed by a decrease of this variable around 1500–2000 m elevation. In the same context, Robl et al. (2015) used “glacial buzz-saw” mechanisms to explain this orogen-wide pattern. In summary, the basins situated in the Penninic nappes record strong morphometric evidence for glacial carving during the LGM and possibly earlier glaciations to have conditioned the shape of the current landscape.

In the External massifs, tributary basins usually also show glacially inherited morphologies like U-shaped valley cross sections and wide cirque-glacier headwaters,

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but their river profiles are highly convex. Evidence for deep incision in these basins is mostly absent, except for the Massa River (Fig. 9), which formed a steep canyon into its granitoid bedrock. A mechanism, which could explain this feature is largely unknown, but could be related to erosion by overpressured subglacial meltwater during glacial times (Dürst Stucki et al., 2012; Jansen et al., 2014). The hypsometric analysis for the basins situated in the External massifs showed that high elevations are more frequent here than in the Helvetic or Penninic units. Considering the comparatively young Neogene exhumation of the External massifs (Fig. 3a), the resulting surface uplift pulse could possibly explain the frequency of high elevations in these areas (Kühni and Pfiffner, 2001) as well as the high convexity in the river profiles (Snyder et al., 2000).

Altogether, it seems that the difference in the landscape shape between the tributary basins records a large spatial variability of glacial sculpting and tectonically driven uplift. However, the most dominant glaciation of the LGM affected the entire Rhône basin in equal measures with thick ice sheets located in all tributary valleys. Recent glaciation is more variable with most of the glaciers located in the Aar massif and in the highest regions of the Penninic units, but we did not observe a difference in the geomorphologic properties between recently glaciated and non-glaciated basins within the same litho-tectonic unit (Figs. 7, 8, 14 and 17). In the same sense, the uplift pattern shows a stronger spatial variability that is mostly related to the younger exhumation history north of the Rhône-Simplon–Lineament compared to the Penninic units south of it. Nevertheless, this spatial difference in uplift fails to explain the remarkable geomorphological difference we observed between the Helvetic nappes and the External massifs, which have a similar tectonic evolution, as the Helvetic nappes are the sedimentary cover perched on European basement rocks.

A possible mechanism to explain these differences is offered by surface erosion and sediment transport in response to precipitation, where the amount of precipitation affects streamflow and sediment transport capacity, while heavy precipitation intensity contributes to hillslope erosion. The sequence of rainfall events in time influences soil

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moisture, infiltration/saturation and, as a consequence, runoff and potential sediment mobilization. The analysis of the basin scale precipitation, averaged over the 52 year period 1961–2012, reveals that catchments located in the three main litho-tectonic units have experienced a similar rainfall pattern in the recent past. In contrast, there is a high variability in total precipitation and heavy daily rainfalls as a function of elevation. The orographic effect drives the spatial distribution of precipitation with values increasing consistently from the valley bottoms to the drainage divide. The frequency of 90 % of daily precipitation is similar for the External massifs, Penninic and Helvetic nappes, indicating that high intensity rainfall events, potentially important for soil detachment and erosion, are comparable among the three lithological units. Note that although our climatic record is limited (52 years) compared with time scales typical of landscape evolution, it is possible to state that due to the size, the location and the topography of the upper Rhône basin, precipitation can be considered very similar between the studied lithologies. The consequence is that, even if climatic conditions might have affected topography and undergone significant changes over large time scales, the climate forcing cannot alone explain the observed different geomorphological structures of the ca. 50 analysed tributary basins.

Similarly, neither glacial coverage (both at present and during previous glaciations such as the LGM) nor tectonically driven uplift seems to have a spatial variability significant enough to explain the current geomorphological difference we observed within the upper Rhône basin. We therefore interpret that the different levels of glacial or tectonic conditioning preserved in the present landscape are not predominantly related to variable forcing extents of these processes, but rather to a different responses of the basins towards these drivers. It is worth noticing that the main forcing mechanisms we identified above for the three main litho-tectonic units operate on different time scales, with exhumation being a long-term (My), glaciation an intermediate-term (several ky), and seismic activity along faults being a short-term mechanism. Accordingly, basins in the Helvetic units do not record a strong conditioning caused by glaciation or long-term tectonically driven uplift and related exhumation, although they have been affected by

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both in a similar extent as the other litho-tectonic units. In contrast, they show perturbations in their river profiles that are caused by short-term tectonic perturbations, mainly by strike-slip movement along active lineaments, which apparently have operated on the shortest timescales. This indicates that these basins have already equilibrated to intermediate- and long-term perturbation caused by past glaciation and exhumation. In contrast, the landscape in the External massifs still largely record the effects of glacial as well as long-term tectonic driving forces, which suggests a relatively long response time towards these perturbations. The basins in the Penninic nappes yield evidence for perturbations by glacial processes during LGM times, suggesting that their response times lie somewhere in-between on an intermediate level.

The response time of a fluvial network is highly dependent on the lithology and its erodibility (Whipple and Tucker, 1999; Snyder et al., 2000), and rivers located in lithologies with low mechanical strengths (such as the Helvetic thrust nappes, Kühni and Pfiffner, 2001) have been found to reach graded stream profiles after a perturbation within 100 000 years or less (Snyder et al., 2000). In our study area, the difference between the easy erodible limestone lithologies of the Helvetic nappes and the comparable resistant granitic lithologies in the External massifs is therefore likely to control the landscape's maturity.

6 Conclusions

The upper Rhône basin has been affected by variable uplift and multiple glaciations, which had a measureable geomorphological impact onto the landscape. We used standard geomorphological tools including river profile, hypsometric, slope and valley cross-section analyses to conclude on the topographic state of this high Alpine landscape. We identified partially oversteepened hillslopes, knickpoints, convex river long profiles, deeply incised v-shaped canyons related to fluvial incision, and hypsometric distributions indicating that the landscape is in an immature, and not yet equilibrated state. However, we found that the river network has responded differently to those

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perturbations, and the spatial difference corresponds very well with the lithological architecture of the bedrock underlying the streams. We found that tributary basins in the Helvetic nappes that are mainly made up of limestones and marls, are the most equilibrated ones (concave river profiles, deep fluvial incision, overall lower elevations and slope gradients), while the tributaries located in the External massifs where granite and gneiss constitute the major lithologies are least equilibrated, which is expressed by convex river profiles, the highest elevations and the steepest slope gradients. In the Penninic nappes, we found morphometric evidence for a strong glacial conditioning related to the last glacial maximum. However, neither the LGM ice extent nor the precipitation pattern show a spatial variability that is large enough to explain why the Penninic units did preserve the glacial geomorphology, and the Helvetic nappes did not.

The observed differences identified by several geomorphological tools correspond well with the distribution of lithologies with different erodibilities within the basin. We therefore conclude that the lithology and erodibility of the bedrock plays a major control on the lengths of the response times for rivers to attain graded longitudinal profiles after glacial and tectonic perturbations.

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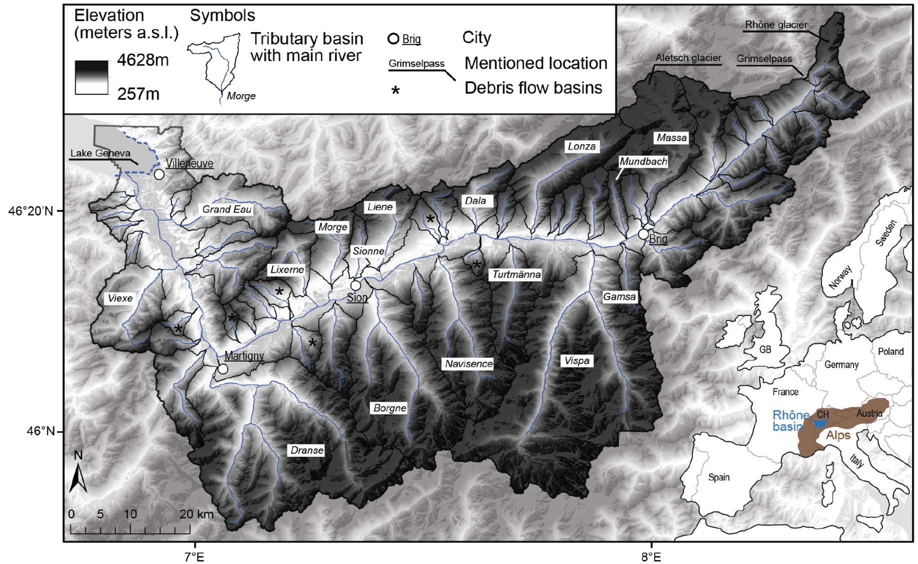

Figure 1. Location map of the study area showing the main Rhône River and 55 main tributary streams (> 10 km^2) that are analysed in this study. Tributaries where sediment transport has mainly been accomplished by debris flows and torrential floods are labelled with a star.

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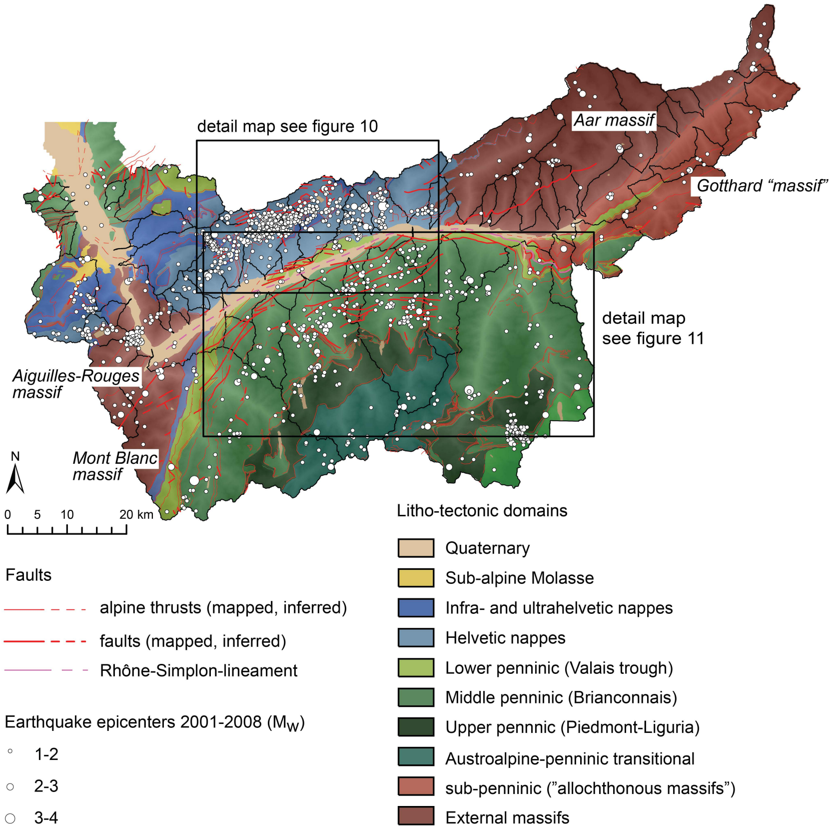

Figure 2. Simplified litho-tectonic map of the study area showing the major paleogeographic domains, the Helvetic nappes (blue), the Penninic nappes (green) and the External massifs (red) and the major structural features (data compilation from swisstopo© geological map 1 : 500 000, Swiss Earthquake Catalogue).

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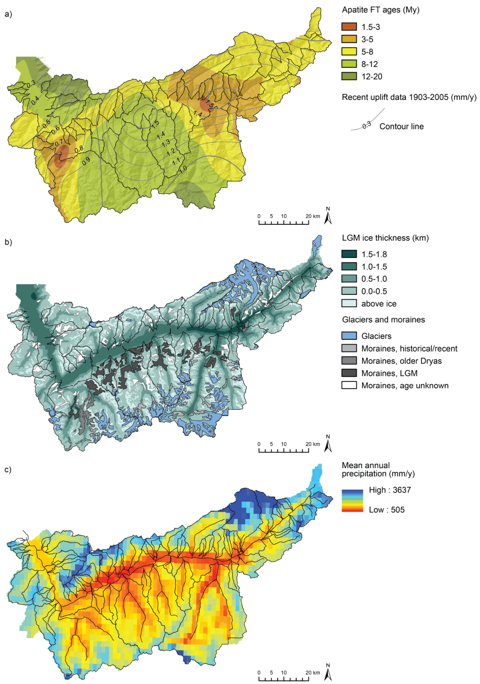

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Figure 3. (a) Interpolated exhumation ages based on apatite fission-track dating (Vernon et al., 2008) show youngest ages both in the East and the West, which correspond to the External massif tectonic unit and oldest ages south of the Rhône River located in the Penninic nappes. Contour lines of recent uplift (Schlatter et al., 2005) in contrast show two maxima in the eastern and the central part of the basin and gradual decrease of uplift rate towards the West. **(b)** Map showing the maximum glacial extent during the Last Glacial Maximum (from Kelly et al., 2004) and the recent distribution of moraine deposits and glaciers. Today, glaciers are mainly located in the East and the Southeast of the study area, whereas moraine deposits can be found in the whole study area, with the highest concentrations south of the Rhône River. **(c)** Spatial distribution of total annual precipitation averaged over the period 1961–2012. Rainfall amounts increases with elevation due to orographic effects.

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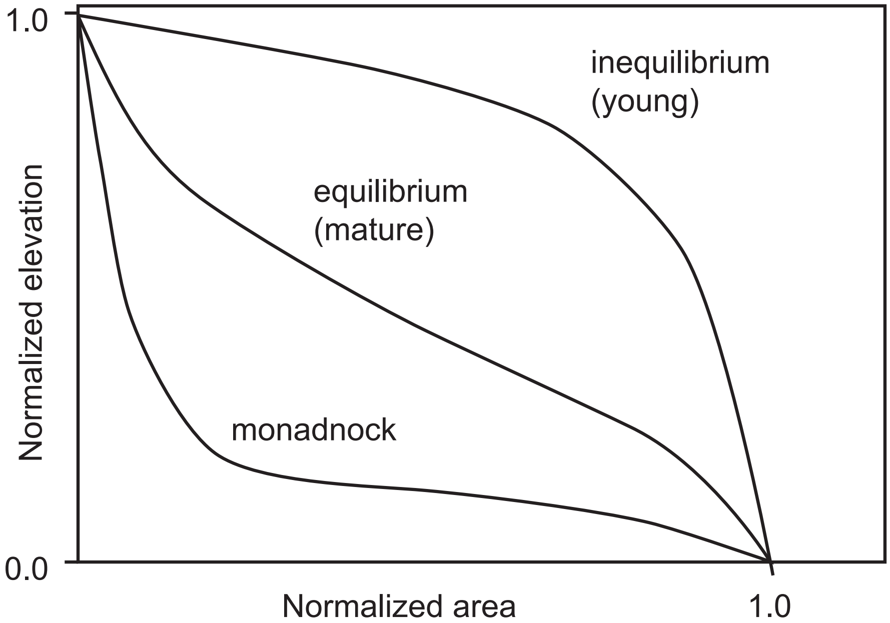

Figure 4. Scheme after Strahler (1952) showing the hypsometric curves of basins in monadnock phase (low HI), equilibrium (intermediate HI) and inequilibrium stage (high HI).

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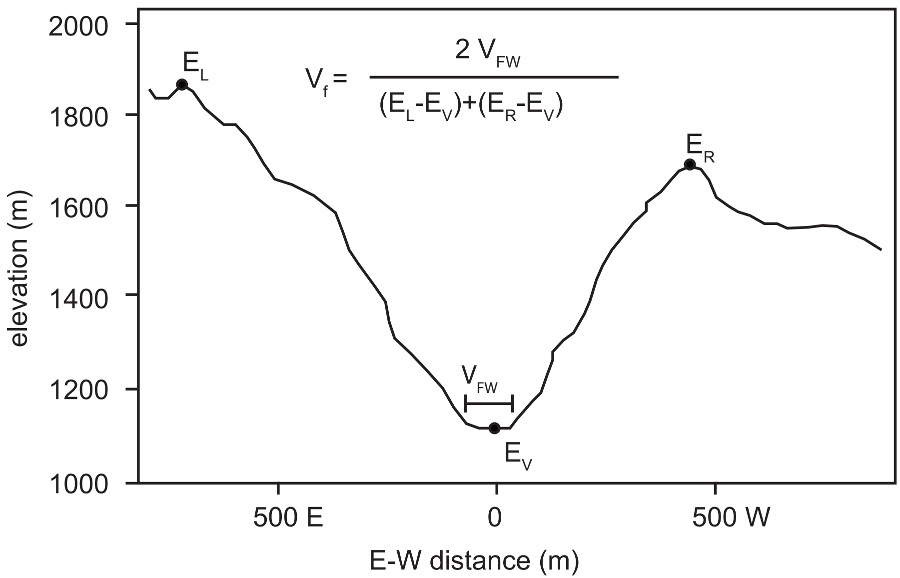

Figure 5. Concept of the valley height-width ratio that characterizes the general valley shape and can be used to distinguish v-shaped (low V_f) from U-shaped (high V_f) valley cross sections. E_V: elevation at the valley bottom. E_L: elevation at the left valley crest. E_R: elevation at the right valley crest. V_{FW}: width of the valley bottom.

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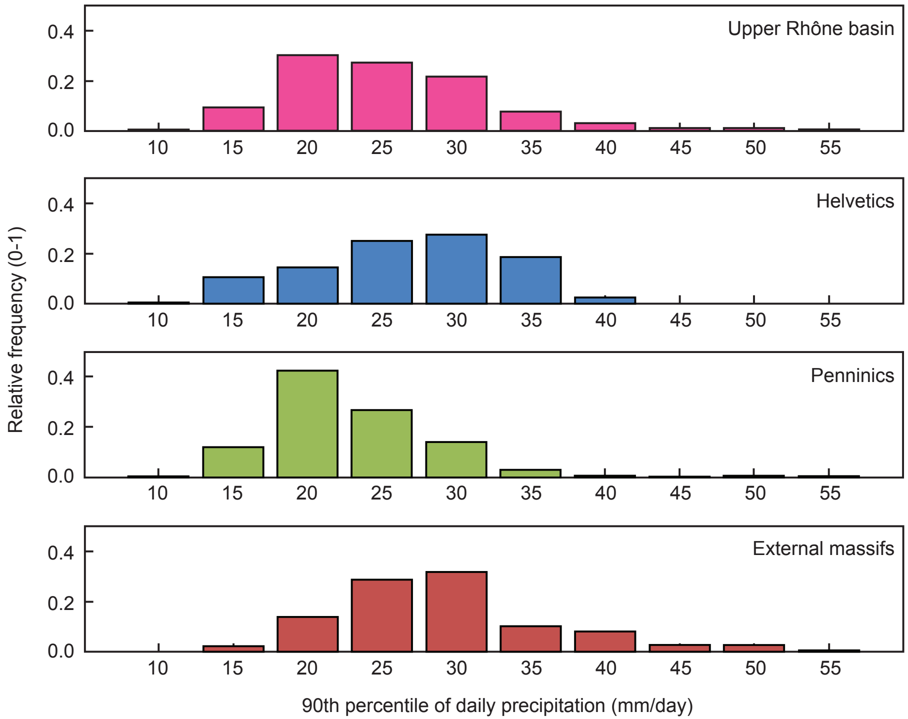

Figure 6. Spatial frequency distribution of the annual 90th percentiles of total daily precipitation over the entire upper Rhône basin (first from top), over the Helvetic nappes (second from top), over the Penninic nappes (third form top), and over the External massifs area (fourth from top).

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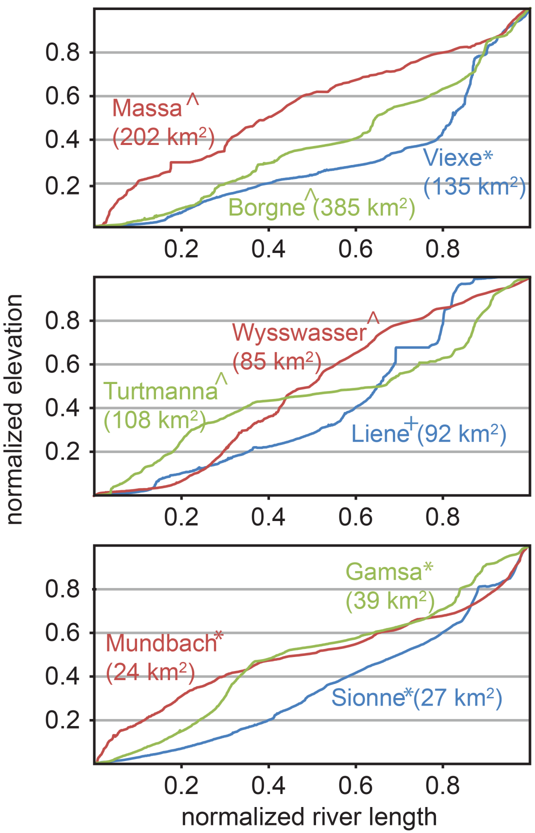

Figure 7. Examples of extracted river profiles from channels located in the External massifs (red), the Penninic units (green) and the Helvetic nappes (blue). Examples of each litho-tectonic unit are given in three different catchment sizes (from top to bottom). The recent glacial cover is expressed by a star (*) if between 0–2 % of the watershed area, by a cross (+) if between 2–10 %, and a triangle (Δ) if > 10 %.

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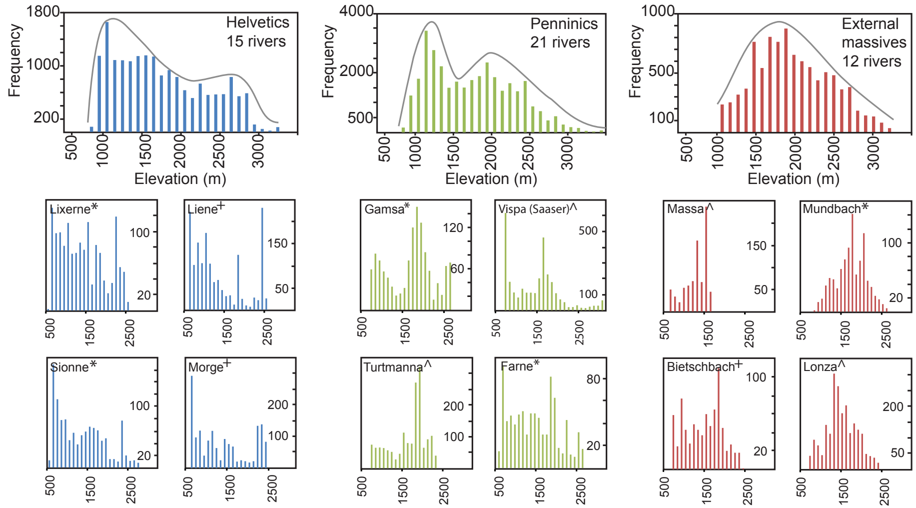

Figure 8. Distribution of elevations of the river bed for channels within the Helvetic nappes, Penninic units and the External massifs. On top, a combined histogram for each unit is given (for 15, 21 and 12 rivers, respectively). Below, four examples from single rivers of different sizes are displayed. The recent glacial cover is again expressed by a star (*) if between 0–2 % of the watershed area, by a cross (+) if between 2–10 %, and a triangle (Δ) if > 10 %.

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Figure 9. Photographs from the field, showing a deeply incised river mouth of a channel in the Helvetic nappes (left, Lixerne River) in contrast with a hanging tributary associated with a waterfall located in the External massif (middle, Bietschbach River). The picture on the right was taken in the Massa canyon, which is the only river located in the External massif that incised a narrow canyon into its bedrock (right, Massa River).

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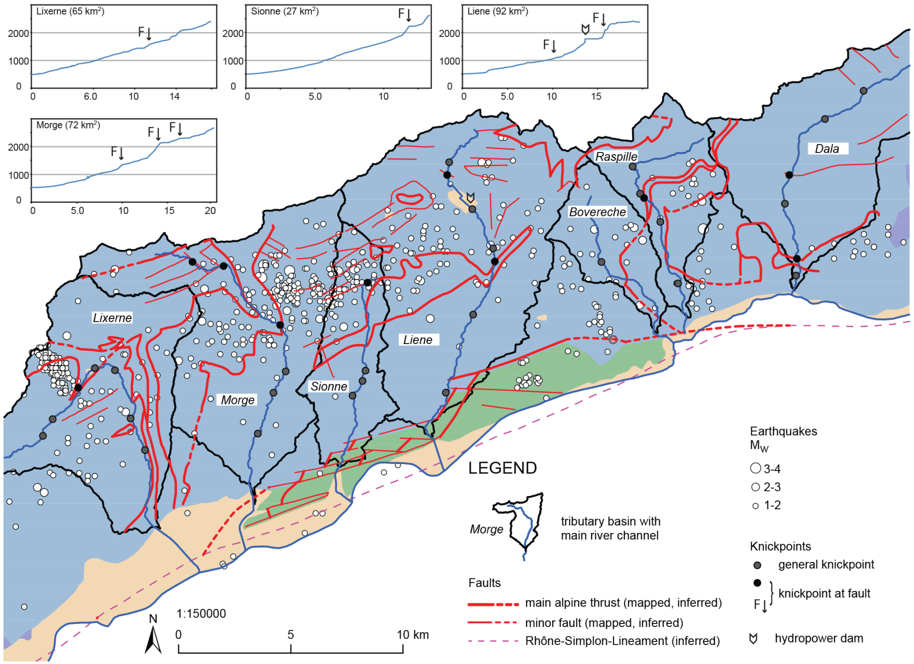

Figure 10. Detail map of watersheds located in the Helvetic nappes north of the Rhône River (for location within Rhône basin, see Fig. 2). Faults in this region (red) are associated with frequent, but relatively weak earthquakes (white dots), and knickpoints are frequently located at these faults (black dots). In the river profiles (small insets), the corresponding knickpoints are marked by arrows. Compiled from the swisstopo© geological map 1 : 500 000 and the Swiss Earthquake Catalogue.

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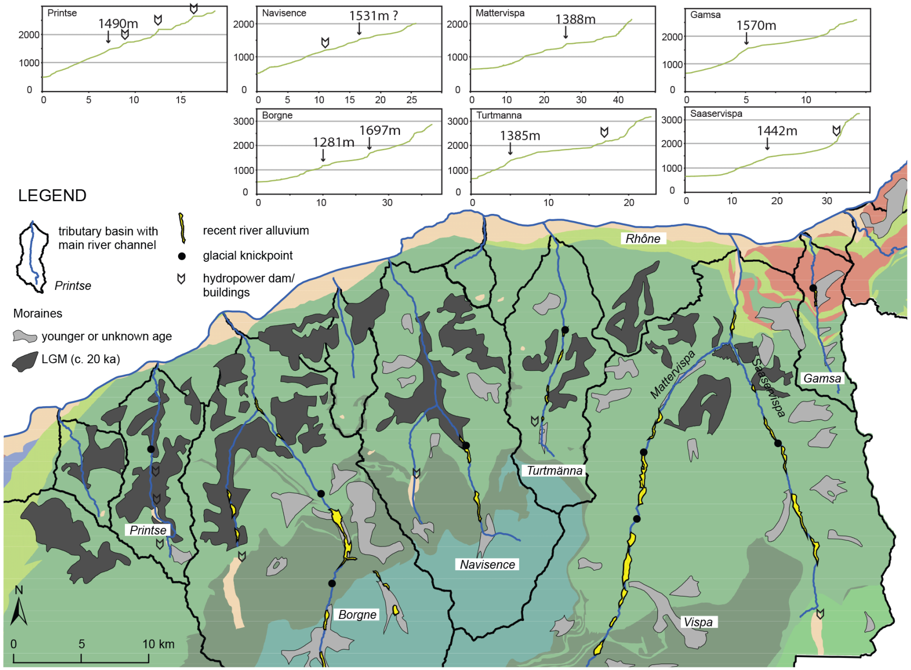

Figure 11. Detail map of watersheds located within the Penninic units south of the Rhône River (for location within Rhône basin, see Fig. 2). Major knickpoints separating convex and concave river stream segments are often located at elevations around 1500 m. Recent river gravels are frequent upstream the knickpoints covering the flat stream segment. Compiled from the swisstopo© geological atlas 1 : 25 000 of Switzerland and the swisstopo© geological map 1 : 500 000.

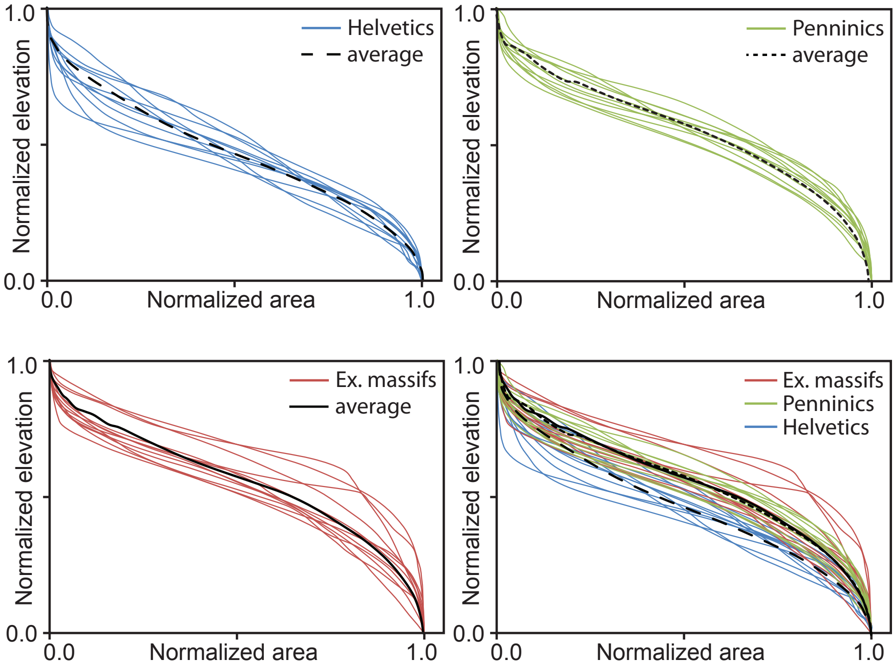

Figure 12. Curves of basin hypsometry within the three litho-tectonic units show that basins located in the Helvetic nappes have more convex curves than basins in the Penninic nappes or External massifs.

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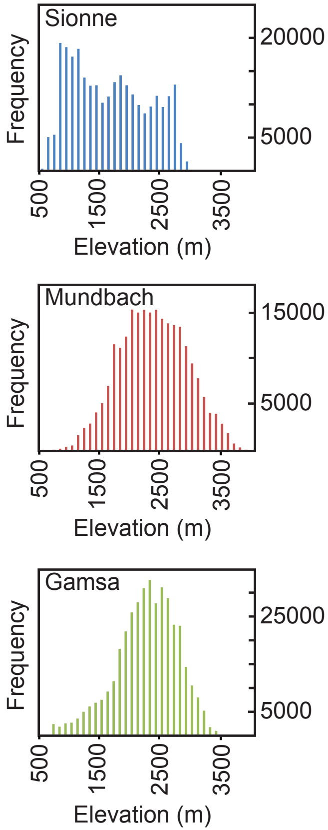

Figure 13. Hypsometric histograms of three examples from the Helvetic, Penninic and External massif catchments show more or less normal distribution for the basins in the Penninic nappes and the External massifs. In contrast, the histograms are shifted towards lower elevations for the basin located in the Helvetic nappes. All displayed basins are rather small tributary basins (24–38 km^2) that are not glaciated.

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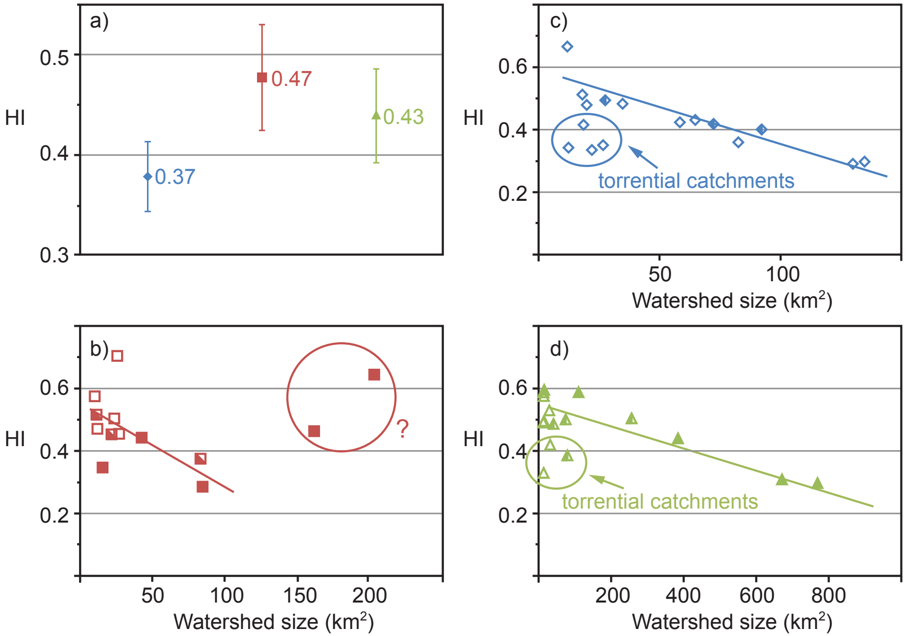

Figure 14. Plots of the mean hypsometric integral HI for each litho-tectonic unit **(a)**, and of HI for each tributary river against the watershed size in the External massifs **(b)**, the Helvetic **(c)** and the Penninic **(d)** units.

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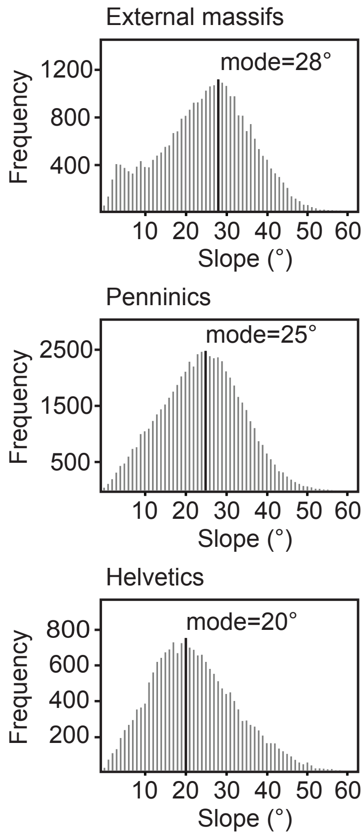

Figure 15. Frequency histograms with basin-wide slope gradients and modal values displayed for all watersheds within the Helvetic and Penninic nappes and the External massifs.

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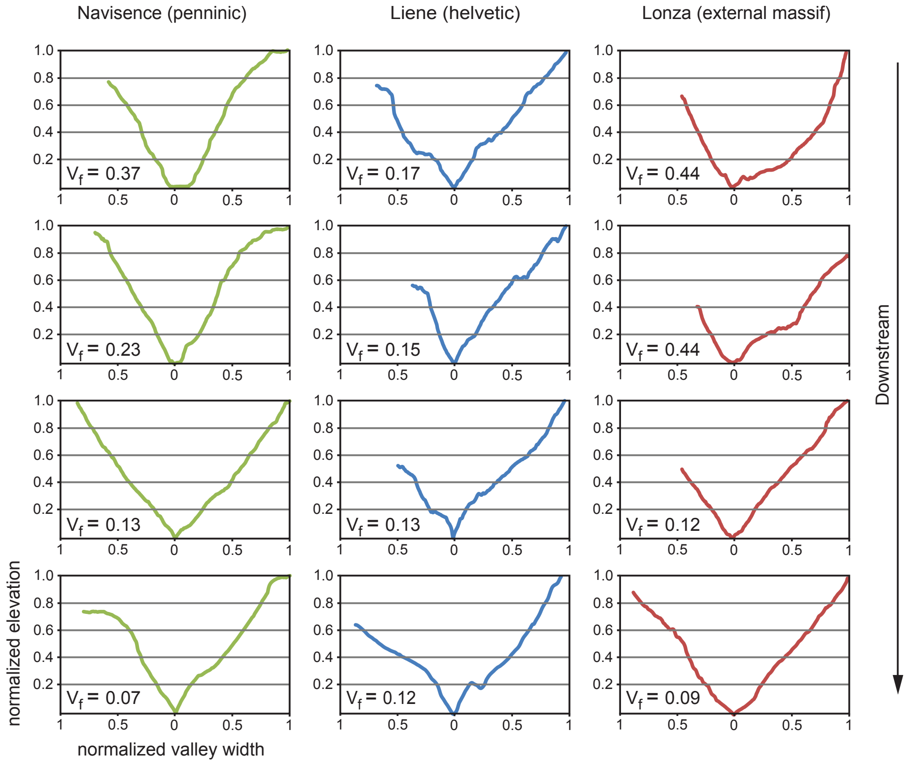

Figure 16. Normalized valley cross sections of three rivers within the Penninic nappes (left column), the Helvetic nappes (middle column) and the External massifs (right column). The cross sections were extracted at 4 locations downstream the river (from top to bottom).

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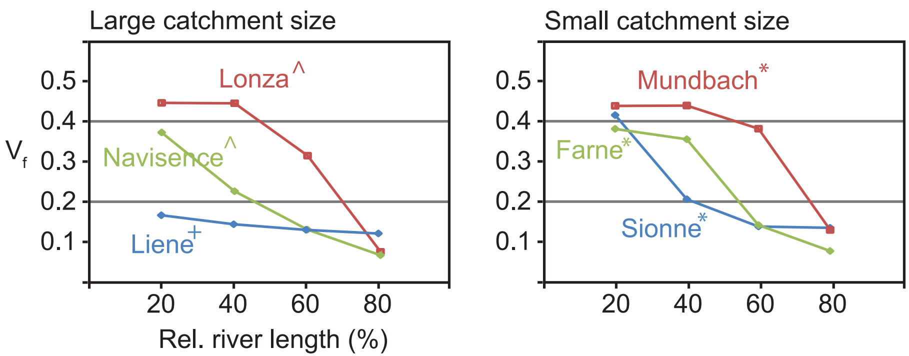

Figure 17. Calculated V_f values plotted against the position downstream the river (20, 40, 60 and 80 % of the river length) show a general decrease towards the river outlet for all the rivers. However, at the same position (e.g. at 40 %), the V_f value is much smaller in the river located in the Helvetic nappes than in the river in the External massif.

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