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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

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Abstract

The development of topography is mainly dependent on the interplay of uplift and erosion, which are in turn 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 km²-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 km². 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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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 particularly 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 are 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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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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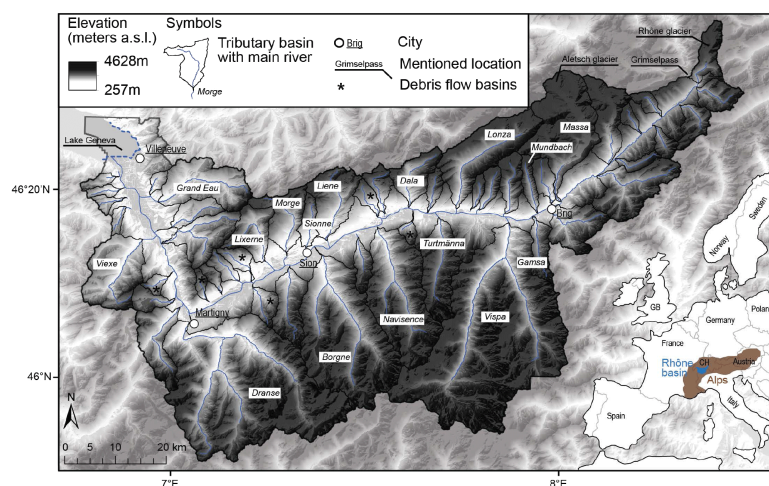


Figure 1. Location map of the study area showing the main Rhône River and 55 main tributary streams ($> 10 \text{ km}^2$) that are analysed in this study. Tributaries where sediment transport has mainly been accomplished by debris flows and torrential floods are labelled with a star.

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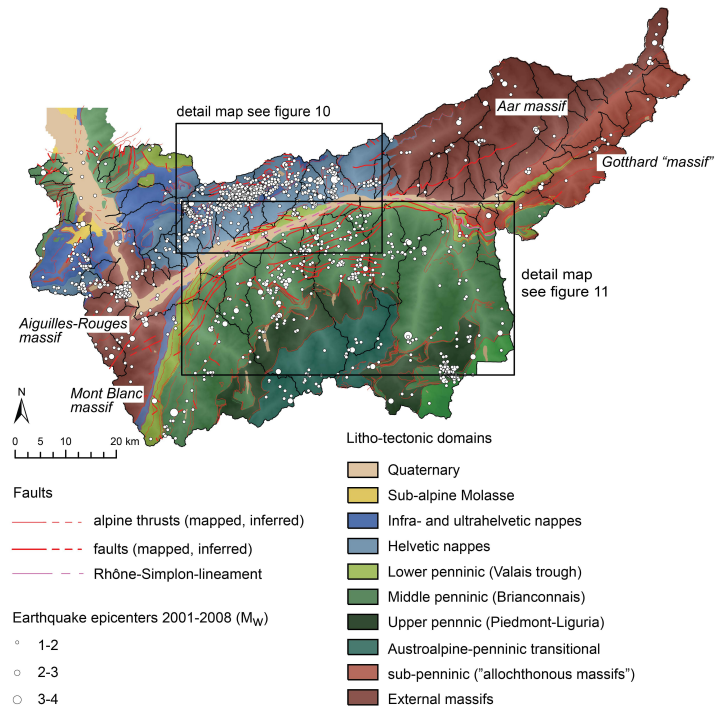
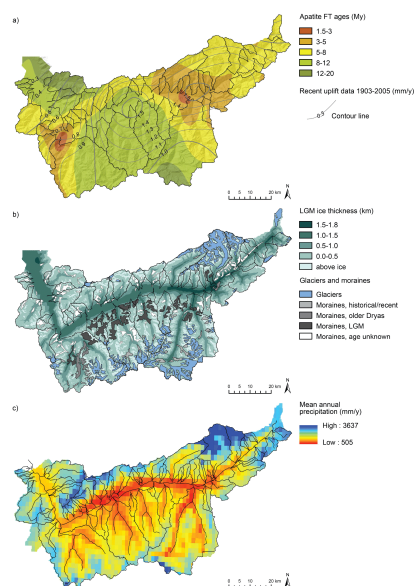


Figure 2. Simplified litho-tectonic map of the study area showing the major paleogeographic domains, the Helvetic nappes (blue), the Penninic nappes (green) and the External massifs (red) and the major structural features (data compilation from swisstopo[®] geological map 1 : 500 000, Swiss Earthquake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

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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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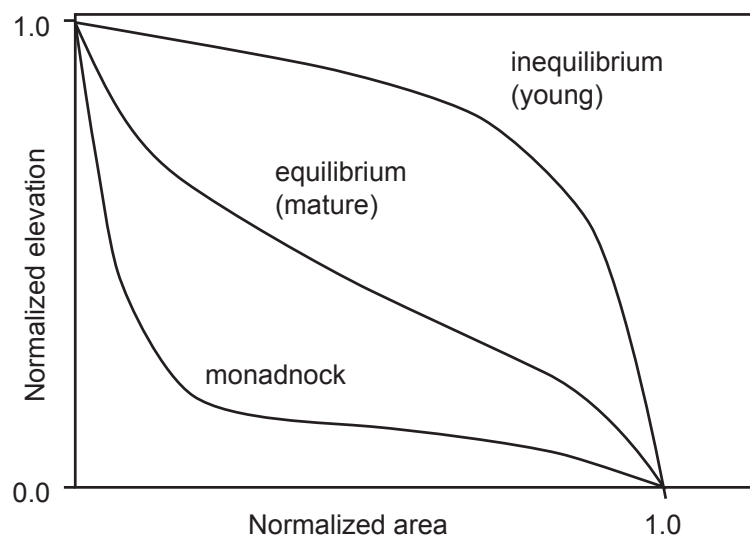


Figure 4. Scheme after Strahler (1952) showing the hypsometric curves of basins in monadnock phase (low HI), equilibrium (intermediate HI) and inequilibrium stage (high HI).

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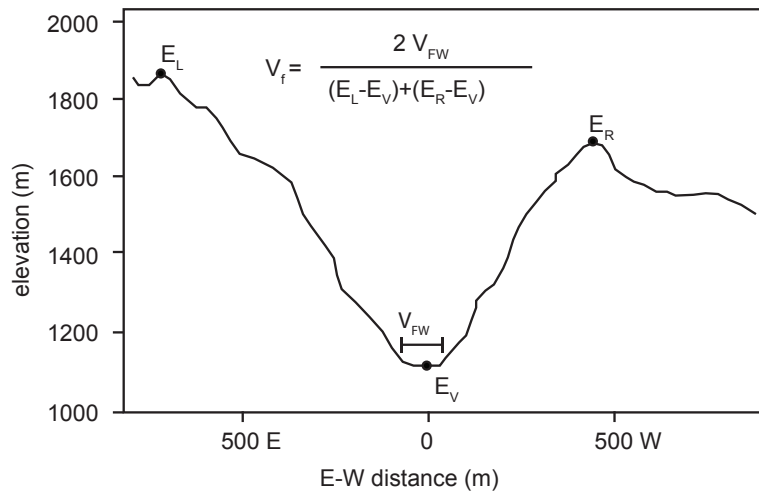


Figure 5. Concept of the valley height-width ratio that characterizes the general valley shape and can be used to distinguish v-shaped (low V_f) from U-shaped (high V_f) valley cross sections. E_V : elevation at the valley bottom. E_L : elevation at the left valley crest. E_R : elevation at the right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

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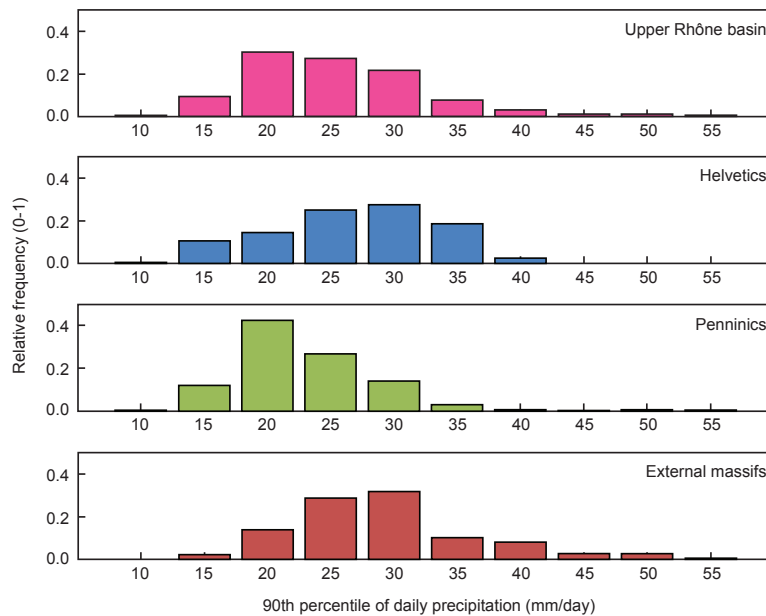


Figure 6. Spatial frequency distribution of the annual 90th percentiles of total daily precipitation over the entire upper Rhône basin (first from top), over the Helvetic nappes (second from top), over the Penninic nappes (third from top), and over the External massifs area (fourth from top).

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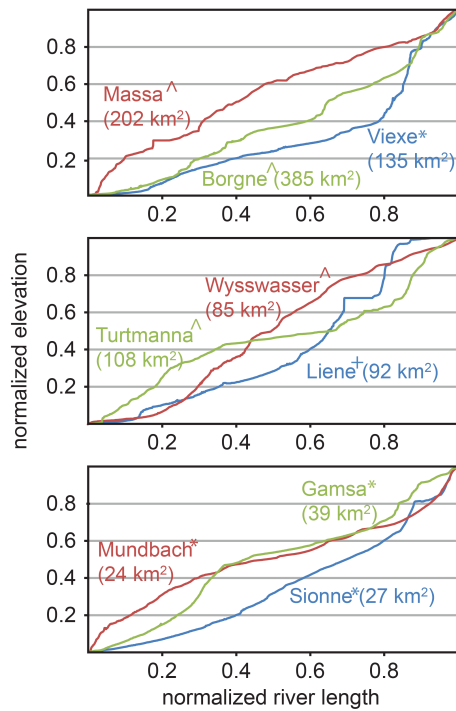


Figure 7. Examples of extracted river profiles from channels located in the External massifs (red), the Penninic units (green) and the Helvetic nappes (blue). Examples of each litho-tectonic unit are given in three different catchment sizes (from top to bottom). The recent glacial cover is expressed 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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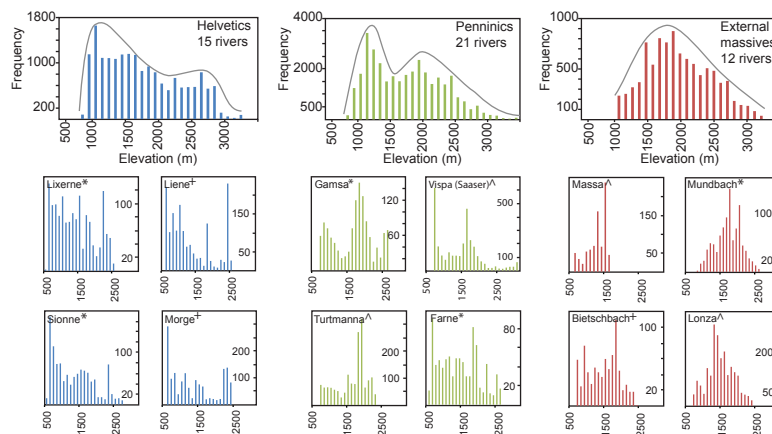


Figure 8. Distribution of elevations of the river bed for channels within the Helvetic nappes, Penninic units and the External massifs. On top, a combined histogram for each unit is given (for 15, 21 and 12 rivers, respectively). Below, four examples from single rivers of different sizes are displayed. 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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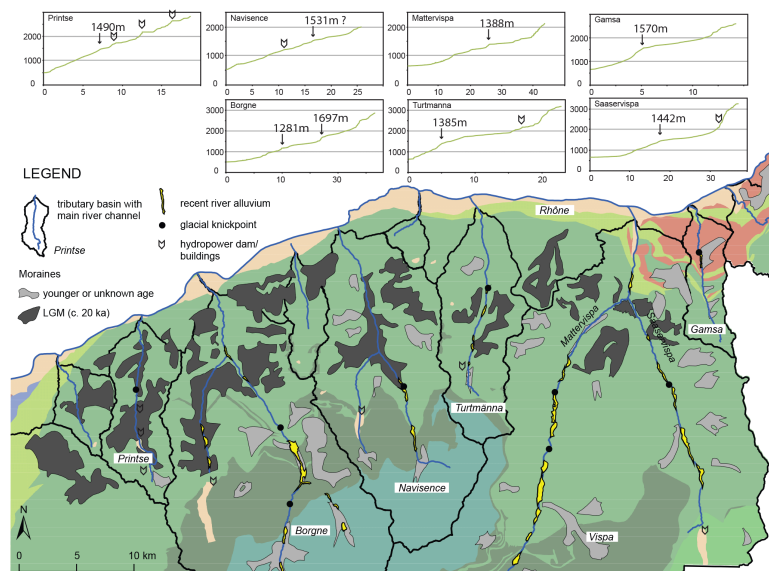


Figure 11. Detail map of watersheds located within the Penninic units south of the Rhône River (for location within Rhône basin, see Fig. 2). Major knickpoints separating convex and concave river stream segments are often located at elevations around 1500m. Recent river gravels are frequent upstream 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.

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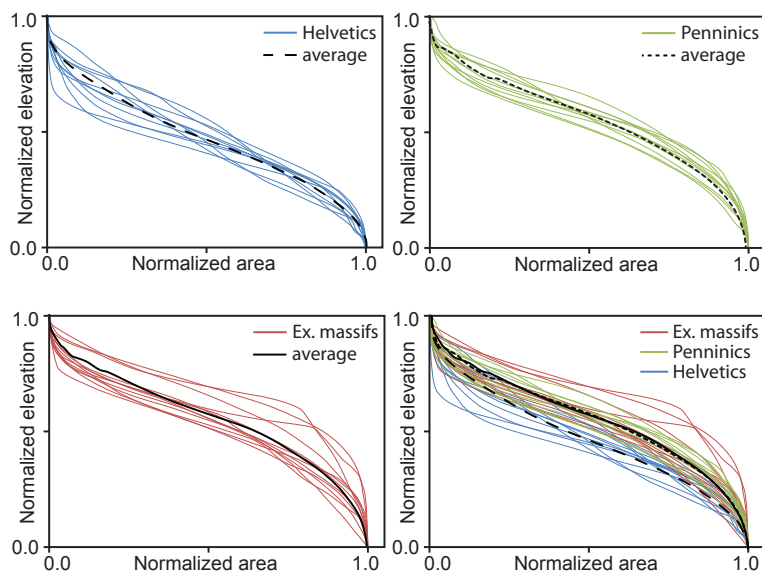


Figure 12. Curves of basin hypsometry within the three litho-tectonic units show that basins located in the Helvetic nappes have more convex curves than basins in the Penninic nappes or External massifs.

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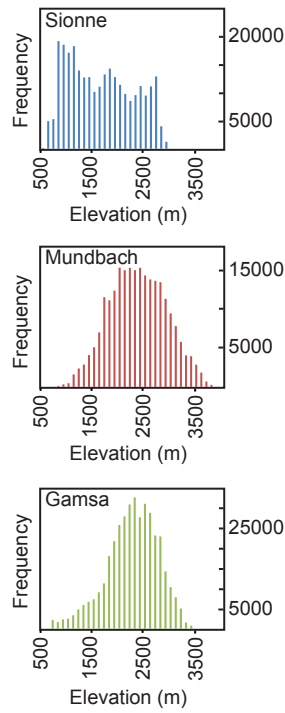


Figure 13. Hypsometric histograms of three examples from the Helvetic, Penninic and External massif catchments show more or less normal distribution for the basins in the Penninic nappes and the External massifs. In contrast, the histograms are shifted towards lower elevations for the basin located in the Helvetic nappes. All displayed basins are rather small tributary basins (24–38 km²) that are not glaciated.

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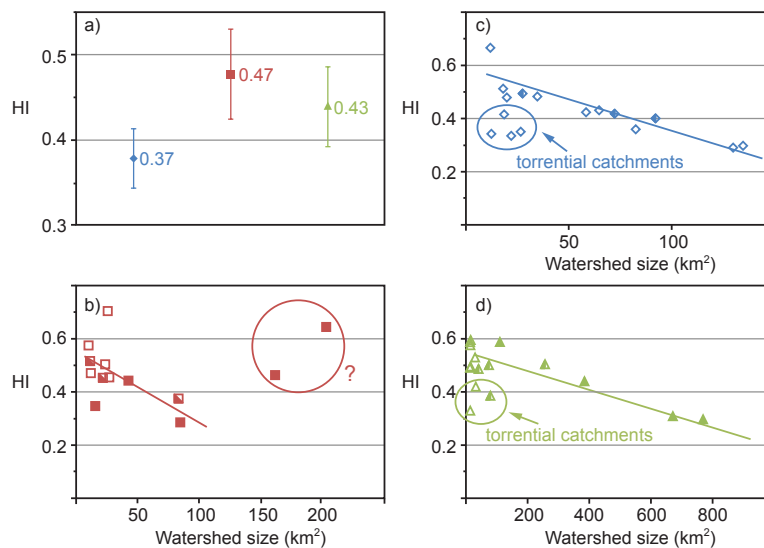


Figure 14. Plots of the mean hypsometric integral HI for each litho-tectonic unit **(a)**, and of HI for each tributary river against the watershed size in the External massifs **(b)**, the Helvetic **(c)** and the Penninic **(d)** units.

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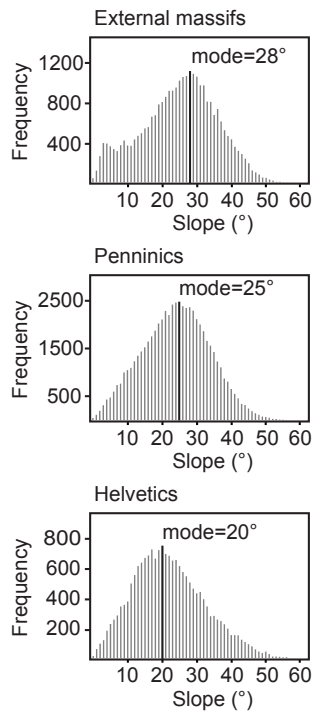


Figure 15. Frequency histograms with basin-wide slope gradients and modal values displayed for all watersheds within the Helvetic and Penninic nappes and the External massifs.

1103

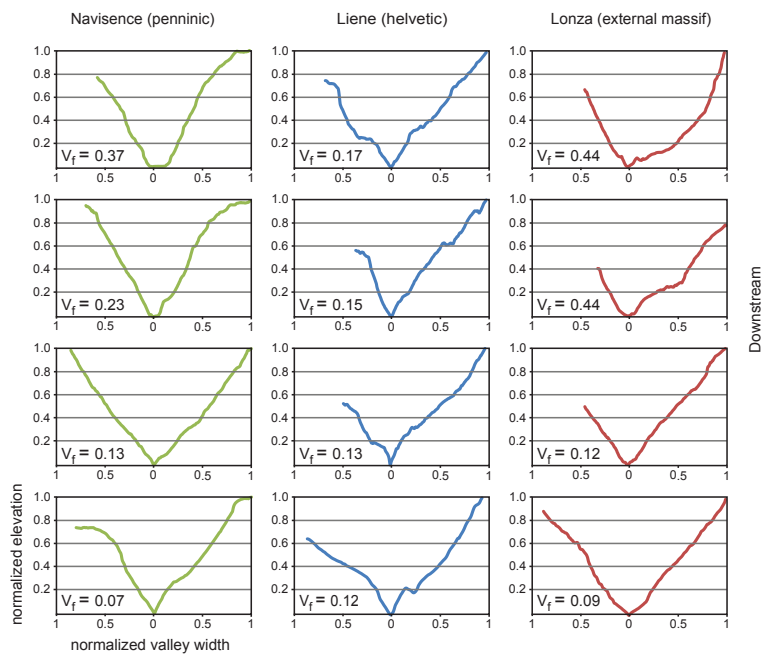


Figure 16. Normalized valley cross sections of three rivers within the Penninic nappes (left column), the Helvetic nappes (middle column) and the External massifs (right column). The cross sections were extracted at 4 locations downstream the river (from top to bottom).

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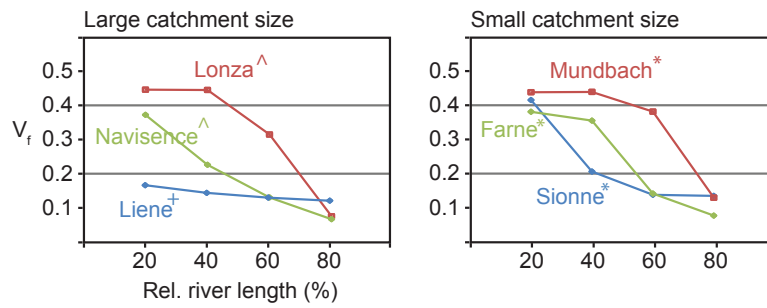


Figure 17. Calculated V_f values plotted against the position downstream the river (20, 40, 60 and 80% of the river length) show a general decrease towards the river outlet for all the rivers. However, at the same position (e.g. at 40%), the V_f value is much smaller in the river located in the Helvetic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