Reply to interactive comment from JD Jansen

First, we would like to thank J.D. Jansen for his constructive and very careful review. We incorporated his specific comments and technical points without further questioning and changed the manuscript accordingly. Apart from these specific comments, the referee's main request was to restructure the manuscript in a way that would allow more specific hypothesis testing on the role of the other possible control factors besides lithology (precipitation, uplift, glacial forcing). In this context, the referee challenged our qualitative analysis and asked for a more quantitative approach, which we have done.

We now base our analyses on previous studies where uplift (long- and short-term), glacial inheritance, precipitation and erosional resistance of the underlying bedrock have been invoked to explain the landscape's characteristics, expressed through variables including e.g., mean elevation, hypsometry, relief, hillslope gradients and convexities of stream profiles. We test these relationships through correlation and statistical analyses, and we conclude that among driving parameters, variations in erodibility, which we have measured based on the erodibility map of the Swiss Alps by Kühni & Pfiffner (2001), explain most of the morphometric variations that we can observe within the Rhône basin.

In particular, in order to achieve this, we proceeded in three steps:

1) We quantified erodibility, amount and intensity of precipitation, glacial inheritance and uplift for each basin by extracting mean annual precipitation values, the average daily 90th percentile of precipitation, LGM ice thickness, recent surface uplift, long-term uplift (based on apatite fission-track ages) and erodibility from the dataset of our original manuscript. We extracted these values for each basin.
   Instead of lithology, we now use the more specific erodibility, which we based on three erodibility classes based on the erodibility map of Kühni & Pfiffner (2001).
2) We then summarized quantitative values for five topographic variables (mean elevation, hypsometry, relief, hillslope gradients, convexity of the river long profiles). We tabulate these topographic variables in an additional table for each tributary basin to make our analyses more transparent.
3) For each of the five controlling variables and mechanisms described in 1), we plot all five topographic attributes outlined in 2) as boxplots. This allows the reader to see that there are significant topographic differences between the three erodibility classes and also within the three defined uplift/exhumation classes. For LGM thickness and precipitation, the correlation to the landscapes' metrics is less pronounced. Then, we run a linear discriminant function analysis to explore whether the tributary basins are classified correctly on the base of the five topographic attributes. We found that erodibility serves best to group the tributary basins according to their morphometric variables outlined in 1).

We hope this summary of quantitative data, and the statistical testing of the relationship between observed attributes (topographic measures) and explanatory variables (controlling factors) will convince the referee.
In the following, we will answer to all other comments. The reviewer's comment is marked in grey with a "R:", while our answer is marked in black with an "A:".

R: [1062:11] 'Lithological architecture' is not examined in this study; I suggest replacing this phrase with 'lithology'.
A: Done

R: [1062:21] Specify which perturbations are being referred to here: tectonic, glacial or both? A: Both, we have specified that. And is it possible that some perturbations have their origins outside a given litho-tectonic unit? A: Yes indeed, we have specified these (e.g., large-scale uplift, but this will not change the conclusions of our work).

R: [1063:7-10] 'Threshold topography' is a rather theoretical concept that has undergone some development over the last 20 y, as has 'topographic steady state'. It would be useful to clarify the meaning of both these terms especially with regards to hillslope morphology and the mechanisms at play. This explanation should link forward to [1069:13].
A: Done.

R: [1063:11-13] This so-called 'coupling' between climate and denudation is complicated to the extent that one might question whether it really exists in any direct way. Perhaps refining the example would help: e.g. 'increased orographic precipitation can drive higher river discharges that in turn tend to enhance rates of fluvial channel incision'.
A: Done

R: [1063:22] This binary-style of argument (climate vs tectonics) is not very useful and we all should be striving to get beyond it. Climate and tectonics encompass a whole suite of mechanisms that operate over different temporal and spatial scales. Writing in these overly general terms doesn't add much.
A: Indeed, we did not intend to oppose climate and tectonics here. We apologize for the misleading term "in contrast" and modified the text accordingly.

R: [1063:24-27] The point that mineral cooling ages record periods of accelerated uplift, which coincide with higher sediment flux into the foreland is completely circular. How is this an argument for tectonic control on denudation? The cooling history might be equally well explained by the onset of a wetter or colder or stormier climate. Please rephrase this point.
A: We are aware of the controversy concerning this point. However, besides a possible climatic driver, there have been studies, which related the 5 Ma increase of uplift (and erosion) to deep-crustal processes such as slab unloading. We added four more relevant works for clarification (Lyon-Caen & Molnar 1989, Schmid et al. 1996, Pfiffner et al. 1997, Sue et al. 2007)

R: [1064:8] It is fair to say that lithology (or more correctly, rock mass strength as it affects erodibility) has received too little attention. It might be useful to state why this is . . . probably because substrate erodibility is a difficult property to quantify and it has a complicated relationship to lithology. I suggest that the authors acquaint themselves with the key early work: Hack 1957, USGS-294-B.
A: That is probably a valid explanation why lithology was not considered in many studies. Especially on a sub-basin scale it is indeed a complicated task to do, if one considers soil cover, the strike and dip of strata, schistosity, fracture density and so on. But for our scale of investigation we think it is rather straightforward to state that there should be a significant difference between the erodibility of carbonates and granites. Furthermore, we added the erodibility map published by Kühni & Pfiffner (2001), which is valid on a larger scale, and is based on the geological and geotechnical maps of Switzerland (Niggli & de Quervain, 1936), and calibrated with a smaller-scale erodibility map by Jäckli (1957). We acknowledge that we have not given sufficient credit to these papers and have improved the revised text accordingly.

R: [1067:3] Seismic activity recorded over what time interval, 2001-08 as shown in Fig. 2? Not a big sample, is it?
A: That is true. Displaying the entire set of available data (250-2008) would just lead to a complete overload in this figure, but the main conclusion doesn't change much. Seismic activity is focused in the zones described. However, we will add the entire dataset to the appendix in a separate figure.

R: [1067:22-24] Far more important that the current spatial distribution of ice cover are the differences that have occurred over the last several glacial cycles; i.e. the timescale over which the valley long profiles and general landscape has been shaped. What can be said about how the proportion of ice cover has varied between the litho-tectonic units over this time scale? As discussed later [1078:14] the LGM glaciation engulfed the entire Rhône basin with thick ice in every tributary.
A: We addresses this point by adding the LGM ice thickness (mean values per tributary basin) into the statistical test described above.

R: [1068:15-16] Please describe 'annual 90
A: It is the 90th percentile of daily precipitation computed over each single year of the data record and afterwards averaged over the 52 years record. The terms "annual" and "total daily precipitation" were added referring to how values are computed. But we realized it could be confusing, therefore we changed it in "90th percentile of daily precipitation on annual basis".

R: [1069:5] 'Channel reorganisation' means?
A: We actually mean 'reorganization of the channel network' through migration, abandonment and cannibalization of channels like described in Willet et al. (2014). We added this reference here and rephrase the text.

R: [1069:7-9] This is not strictly correct and depends upon the spatial pattern of erosion. Please clarify this statement and give some reference of support. A: Done. Change 'adapt' to 'adopt'. A: Done

R: [1069:13] Hillslope adjustment is central to the notion of 'topographic steady state' and should really be acknowledged here (cf. note above).
A: Done

R: [1069:17] Such Davisian terms as 'maturity' and 'youth' do not serve any useful function in modern quantitative geomorphology. It was fine for Strahler, he was still operating in a largely Davisian paradigm (pre-Hack), but not today. A: We modified this part. Replace 'progressing' with 'progressive'. A: Done

R: [1069:19-23] It's clear that glacial erosion might be focused at specific elevations reflected in hypsometry, but not so concerning tectonic or climatic controls. Please rephrase. Since Strahler there have been several important studies of hypsometry that are not acknowledged here. Given that hypsometry is rather central to this study I suggest the authors consider studies that have examined, for instance, the importance of catchment shape on the H curve, the scale-dependence of HI in transient vs steady state settings, the effects of lithology etc., as discussed in Willgoose Hancock (1998, ESPL), Hurtrez et al. (1999, ESPL), and Cheng et al. 2012, Geomorphology).
A: We have improved this section to the extent that it is in line with the major scope of this paper. However, we emphasize that hypsometry is only one of five variables that we consider here, therefore we decided to address these points/papers only to the extent that they are of relevance for our study.

R: [1069:1] What does 'topographic state of a catchment' mean?
A: We rephrased this part.

R: [1069:3-8] 'Lithological controls' occurs in the MS title, yet there seems to be no explicit analysis of the well known influence of lithology on hypsometry. I suggest the authors reframe this oblique approach in favour of a study setup that tests directly the influence of lithology on topography, landscape response etc.
A: We hope we addressed this point with our new approach, please see first sections.

R: [1069:11] How are these topographic properties actually measured and what are the measurement uncertainties?
A: We now described this more specifically in the methodology chapter.

R: [1070:21-22] Again, what threshold mechanism is being invoked here: internal friction within the hillslope? If so, how does a hillslope develop beyond its threshold? An oversteepened slope means? Overhang? The use of these terms has developed somewhat since Burbank et al. (1996) and it would be useful for the authors to reflect on these developments (see for instance Korup Weidinger 2011, GSL).
A: These relationships has been discussed and addressed by Norton et al. (2010, Geology) who also focussed on the Alps. We basically applied their concepts and categorization, and improved the text accordingly.

R: [1070:24] The idea of rates of denudation exceeding rock uplift in an orogenic setting is an interesting one. How would this happen exactly and at what scale? This is indeed an interesting point and has been addressed by previous studies, but apparently no final conclusion has been found. We thought that it is beyond the scope of our paper to solve these relationships in a proper way for the Rhône basin and have therefore decided not to enter into this discussion. Replace 'progressing' with 'progressive'.
A: We have replaced the terms as suggested.

R: [1071:2] The preceding text implies a connection between threshold slopes and rock mass strength, but here lithology seems to be standing in as a proxy for the latter. What is the relationship between lithology and rock mass strength in the study area and how has this relationship been determined beyond simple qualitative generalisations?
A: We addressed this point mainly by introducing the erodibility map of the Swiss Alps by Kühni & Pfiffner (2001, Geomorphology), which is based on an older geo-technical map of Switzerland (Niggli & de Quervain, 1936). We clarified that we used their erodibility classes as a base for our categorization.

R: [1071:11] How is valley width measured and what are the uncertainties involved? Uncertainties associated with the topographic analyses seem to have been ignored. Are they negligible? The relevant assumptions folded within the ArcGIS and TopoToolboxdriven analyses could be presented in brief supplementary note.
A: In the light of the new structure of the paper we decided to eliminate the valley width measurements, since they could not convince both reviewers. Also, this variable does not offer an added value to the revised version of the manuscript.

R: [1072:5-8] The algorithm used to interpolate the precipitation data into a grid-based dataset presumably involves a strong topographic component. I suggest some comment on how this might affect their analysis of orographic precipitation patterns.
A: As suggested by the reviewer, the interpolation scheme accounts for the strong relation between elevation and precipitation. The spatially distributed product of MeteoSwiss actually reflects the altitudinal gradients that characterize precipitation in mountainous regions (Schwarb, 2000). We wanted to focus on the fact that it is not possible to identify any specific spatial pattern in the precipitation field, but the one related to elevation, which is expected.

R: [1072:9] Precipitation-driven erosion processes sound like rain-splash to me, whereas presumably fluvial erosion is meant. Fig. 3 needs to needs to be enlarged.
A: With "precipitation-driven erosion processes" we intend to consider both the direct effect of rain-slpash and the indirect effect of increased fluvial erosion due to rainfall events (higher discharge and higher transport capacity).

R: [1072:14-21] Some consideration of measurement uncertainties would be welcome here and is necessary in order to make such interpretations.
A: This part has been modified in the revised manuscript. However, we consider important to provide the reviewers with an overview of the accuracy of the RhiresD product, used in the present analysis. The accuracy depends both on the accuracy of the underlying local measurements (measurement errors) and on the capability of the interpolation algorithm to reproduce precipitation in

areas that are not covered by measurement stations. The systematic error in Switzerland, which is mainly due to wind-induced gauge under-catch, was estimated to range from about 4% at lower elevations during summer to even more than 40% at higher elevations during winter (Sevruk, 1985). As indicated by MeteoSwiss in the product's documentation, the error of the interpolation scheme depends on the user's interpretation. If gridpoint values are considered as representative of local point estimates, the errors are considerable (standard error equal to a factor of 1.7 and 1.3 respectively for light and heavy precipitation). Whereas, if gridpoint values are considered as area-mean values, as in the case of the present work, the error is significantly smaller (in the order of 5-30% for mean values over 15x15 km^2 areas for intense precipitation events).

[1072:18-21] I suggest rephrasing this last sentence.
A: We modified this part.

R: [1072:23] It's not clear what is meant here by 'external perturbations', but would lithology also be expected to play a role in determining long profile shapes etc? Cf. my earlier comment concerning testing the role of lithology more explicitly.
A: These are the driving forces and related variables. We hope we covered this point in the restructured version.

R: [1073:1-2] These qualitative descriptions and by-eye assessments are needlessly imprecise when there are simple methods available to quantify profile concavity, _, including segments of LPs specifically due to lithological controls (see Duvall et al. 2004, JGR). I suggest the authors adopt a more quantitative approach. This will enable them to show the relationships more convincingly and avoid the vague statements given in 17-24.
A: We apologize. We used a more quantitative approach in the revised manuscript.

R: [1073:11-13] This seems a very inductive approach. I suggest restructuring into a more hypothesis driven setup.
A: This problem should be solved in our restructured version.

R: [1073:13-14] Recent glaciation means? As I note above, the point is to establish whether the proportion of ice cover has varied between the litho-tectonic units over the time scale that is relevant to the shaping of topography; i.e. probably since the MPT.
A: We have solved this by considering the LGM ice thickness.

R: [1074:9-10] Many of these flat reaches are very likely to be sediment fills backed up behind overdeepenings. The flatness is therefore probably a function of postglacial sedimentation, not glaciers.
A: see answer below.

R: [1074:16] Are these floodplain sections overdeepenings? Sediment-fills should ideally be excised from the hypsometric analysis because in some cases they can be hundreds of metres deep and therefore misrepresent or bias the elevation distributions in the hypsometry.
A: Unfortunately there is not detailed information about the sediment thickness in the tributary basins available yet. These data exist for the main Rhône valley, where the maximum thickness ranges between ~400 m in the upper part (between Brig and Sion) and up to 900 m in the lower part (between Sion and Martigny). We would assume it is less in the tributary basins, because the floodplains are smaller than in the main Rhône valley, and the valleys are in general narrower. But this would be definitely worth looking at. It is just too much for this paper since this requires geophysical surveys or drillings, which we don't have, unfortunately. However, since we have restructured the paper (see introductory comments above), the paper became a shift in the way of how we interpret the morphometric properties of the Rhône tributary basins. In context, the point raised by the reviewer became obsolete.

R: [1074:23-28] Again, such qualitative descriptions are misplaced and compromise much of the interpretations. It is not sufficient to show three ideal examples (Fig. 13) in support of the preferred interpretation. Fig. 13a does not look ‘more or less normal’ as described (line 24).
A: We modified this section accordingly.

R: [1075:9] Is there a theoretical reason for a linear relationship? Some background is required here (the scale-related issues with hypsometry that are well studied by previous workers but not acknowledged here).
A: We did not want to state that there is always a linear relationship between the hypsometry and the basin-size. In the study area it was just noticeable that (1) there is a scaling dependency, and (2) that it seemed almost linear for some of the basins. We included the scaling dependency into the discussion now.

R: [1075:14] Why assume a non-linear relationship when there may simply be no scaling relationship?
A: see answer above.

R: [1075:19] Simply deleting the ice masses from the DEM would alleviate this pleading explanation.
A: Thanks for the advice, we excluded the glaciers from the DEM and updated the slope values accordingly.

R: [1076:2-11] Rather than plucking out some ideal examples in support (Fig. 16), I suggest a more quantitative treatment of the results would be more effective and more convincing.
A: We hope we have properly addressed this point in our restructured version.

R: [1076:13] What is presented here is essentially an analysis of digital elevation data, not a geomorphological analysis. That would entail exploring the relationships between forms and the processes responsible for them and I don’t agree that this MS does that.
A: We changed this expression accordingly.

R: [1076:15] This is an important point: what are the differences between the main lithotectonic units? Perhaps I missed it earlier but I cannot find where the authors explicitly state these. The lithological generalisations given in Section 2.1 are not really adequate. One key question might be: is the intra-unit variation in erodibility less than the inter-unit differences? If so, good, but the authors need to somehow demonstrate this to be the case.
A: See before [1071:2]. We addressed this point mainly by adapting the rock erodibility classes defined by Kühni & Pfiffner (2001, Geomorphology), who compiled an erodibility map based on an older geo-technical map of Switzerland (Niggli and de Quervain, 1936, and an updated version from the Federal Statistical Office). We clarified that we used their erodibility classes as a base for our classification.

R: [1076:16-24] This concept of ‘maturity’ is not useful in my view. For instance, how would one differentiate low-maturity in strong rocks from high-maturity in weak rocks? One would need information on the timing and source of the perturbations, neither of which seem to be available for this study area. The two properties obviously correlate; perhaps the authors might reflect on the ‘relaxation time’ concept instead (sensu Brunsden Thornes 1979, TIBG).
A: We have rewritten this section for clarification.

R: [1076:24] ‘As shown before, this. . .’. I am unclear what is being said here.
A: We rephrased this part.

R: [1077:2] The V-shaped valley morphology says more about the absence of glacial erosion than it does about the speed or strength of fluvial incision. V-shaped valleys can have incision rates < 2 m/Myr.
A: The V- and U-shaped valley form is excluded now from the paper.

R: [1077:13-16] The regional ELA refers to the elevation of the former ice surface, which stood many hundreds of metres above the valley floor. Why would knickpoint elevations match the ELA?
A: This comments is linked with the question of why knickpoints particularly in the tributary basins from the south (i.e., the Penninics) are linked with terminal moraines, which in turn coincide with the elevation of the LGM ELA (Ivy-Ochs et al., 2008). Our interpretations of these observations have originally been inspired by the work of Oliver Korup (Korup and Montgomery, 2008, Nature). However, as mentioned above, we have re-structured our paper with the consequence that this particular point does not need to be addressed in the revised version. Indeed, a full discussion of this yet to be solved problem would require a paper of its own that will be based on geophysical surveys.

R: [1077:20] What is a 'slope-by-elevation analysis'?
A: We refer here to the work by Robl et al. (2015), but we acknowledge that reviewer Jansen has not been convinced that this concept, although valid for the scale of an entire orogen (Robl et al., 2015), can be applied to the Rhône basin. We thus decided not to include these information in our paper.

R: [1077:17-19] I do not see why one would expect any difference to exist. The recent deglaciation limit is irrelevant to the long-term topographic development dealt with here.
A: We excluded the recent glaciation from the paper.

R: [1077:20] Not sure I follow the logic here. Heavy rainstorms might strip regolith from hillslopes but I question whether this would be evident in the large-scale hypsometry. Hillslope morphology is more a function of susceptibility to bedrock landsliding, which has an indirect relationship to precipitation, if any. I wonder whether there might be structural differences between the Helvetic nappes and the External massifs, such as fracture density. That's a term I would like to see in this MS.
A: We used precipitation as proxy for a climate variable operating on longer term. We fully agree that data on structural difference would be really helpful in this context, but this information is not available at the level of details required by the reviewer. However, it is, to some extent, contained in the erodibility map by Kühni and Pfiffner (2011).

R: [1078:7-10] Recent exhumation (rock uplift) does not necessarily drive surface uplift. Is this conflating rock uplift with surface uplift here?
A: Not necessarily, but for the study area several studies have linked the relatively recent exhumation to the development of the current surface topography (e.g., Maurer et al. 1997). However, we try to separate these two terms better.

R: [1079:24 to 1080:10] This section goes off in the wrong direction. Linking response/ relaxation times to time scale of causation is a flawed approach in my view. Exhumation is not really a 'forcing mechanism'; it is a long-term response measurable over long time spans. Yet bedrock landsliding, which is a rapid and short-term process might be the most important driver of exhumation on the slopes. Glaciation has also operated over several millions of years. Even though glacial advances span just a few tens of thousands of years, subglacial erosion is slow and incremental. Seismicity is short-term, but it has operated over long periods. This section needs to be thoroughly revisited.
A: Done. We have rephrased the section for clarification.

R: [1080:11-18] Here the authors finally get around to stating what should have framed the study from the outset: the hypothesis of lithological control on topographic development should be opening the Discussion, not only closing it. Moreover, the link to Snyder's (2000) conclusions needs quite a bit more bolstering; response time scales depend upon a whole range of climatic, topographic, and substrate factors. The authors could expand on this point.
A: We restructured the discussion accordingly.

R: [1081:1-] 'Lithological architecture' is not dealt with here: all the Figures are presenting morphometric data. The Conclusions listed are interesting, but forced. Some major revisions are necessary to have these lead more naturally from the empirical data.

A: We hope we addressed this problem with the new approach (see our first paragraphs).

R: [Fig. 12] What is ‘average’ here? Does it include or exclude the full dataset?
A: This figure is not part of the paper anymore.

R: [Fig. 14] Do these colours denote something? Please state what. Are these leastsquares regressions? Some more information would be very helpful.
A: This figure is not part of the paper anymore.

R: [Fig. 16] Are these examples chosen randomly?
A: This figure is not part of the paper anymore.

R: [Fig. 17] ‘Large’ and ‘small’ catchment means?
A: This figure is not part of the paper anymore.

3. Technical points [page:line]

R: [1062:3] Replace ‘term’ with ‘turn’.
A: Done

R: [1062:6] Replace ‘on’ with ‘to’.
A: Done

R: [1062:6] Replace ‘variability’ with ‘variation’.
A: Done

R: [1062:10] Delete ‘-large’.
A: Done

R: [1062:15-16] ‘analysis . . . shows’, or ‘analyses . . . show’.
A: Done

R: [1062:20] ‘and contains some of the highest’
A: Done

R: [1062:23] ‘less steep slopes and’
A: Done

R: [1063:17] ‘sliding rates’.
A: Done

R: [1064:13] ‘paid to’.
A: Done

R: [1064:15] ‘intensively’.
A: Done

R: [1064:21] Better to break up this 5-line sentence.
A: Done

R: [1066:16] ‘exhumation’.
A: Done

R: [1066:18] delete ‘in’.
A: Done

R: [1066:18-21] Rephrase to clarify ‘related ages’.

A: Done

R: [1066:24] Rephrase ‘GPS bedrock measurements’.
A: Done

R: [1067:16] Replace ‘flew’ with ‘drained’
A: Done

R: [1067:19-26] I suggest you tabulate this information, noting just the ranges here.
A: Done

R: [1068:4-12] Very long sentences are better broken up.
A: Done

R: [1068:24] ‘on an annual’.
A: Done

R: [1069:10] Remove ‘a river’, and ‘associated with’ is better.
A: Done

R: [1069:15] I suggest this first sentence be deleted.
A: Done

R: [1069:20] Replace ‘yielding in’ with ‘reflecting’.
A: Done

R: [1077:6] I suggest the term ‘low-slope reaches’ rather than ‘plateau’ here and below.
A: Done

R: [1078:4] Replace ‘overpressured’ with ‘pressurised’.
A: Done

R: [1080:16] ‘easily’.
A: Done

Reply to interactive comment from S. Brocklehurst

We would like to thank Simon Brocklehurst for his review of our manuscript. His main critical point is that the methods and results are presented in an uneven way and that the results are not convincing in the way they are presented. This overlaps partially with the critical points by J.D. Jansen. We hope that the incorporation of some statistical analysis and a generally more quantitative approach addresses this problem in a sufficient way.

We now base our analyses on previous studies where uplift (long- and short-term), glacial inheritance, precipitation and erosional resistance of the underlying bedrock have been invoked to explain the landscape's characteristics, expressed through variables including e.g., mean elevation, hypsometry, relief, hillslope gradients and convexities of stream profiles. We test these relationships through correlation and statistical analyses, and we conclude that among driving parameters, variations in erodibility, which we have measured based on the erodibility map of the Swiss Alps by Kühni & Pfiffner (2001), explain most of the morphometric variations that we can observe within the Rhône basin.

In particular, in order to achieve this, we proceeded in three steps:

1) We quantified erodibility, amount and intensity of precipitation, glacial inheritance and uplift for each basin by extracting mean annual precipitation values, the average daily 90th percentile of precipitation, LGM ice thickness, recent surface uplift, long-term uplift (based on apatite fission-track ages) and erodibility from the dataset of our original manuscript. We extracted these values for each basin.
   Instead of lithology, we now use the more specific erodibility, which we based on three erodibility classes based on the erodibility map of Kühni & Pfiffner (2001).
2) We then summarized quantitative values for five topographic variables (mean elevation, hypsometry, relief, hillslope gradients, convexity of the river long profiles). We tabulate these topographic variables in an additional table for each tributary basin to make our analyses more transparent.
3) For each of the five controlling variables and mechanisms described in 1), we plot all five topographic attributes outlined in 2) as boxplots. This allows the reader to see that there are significant topographic differences between the three erodibility classes and also within the three defined uplift/exhumation classes. For LGM thickness and precipitation, the correlation to the landscapes' metrics is less pronounced. Then, we run a linear discriminant function analysis to explore whether the tributary basins are classified correctly on the base of the five topographic attributes. We found that erodibility serves best to group the tributary basins according to their morphometric variables outlined in 1).

We hope that this new approach, which is less inductive and more quantitative, will convince the reviewer. In the following, we will answer to all other comments. The reviewer's comment is marked in grey with a "R:", and our answer is marked in black with an "A:".

R: - Section 2.1. Given the range of variables in play across the study area (e.g., the range in base level for each of the catchments, set by the Rhone), could the authors make more of directly comparing drainage basins entering the Rhone from opposite sides at similar points along the river?
A: Thank you for raising this point, which we considered as very valid. We thus tried to apply this suggestion, but found out that patterns from streams entering the Rhône River at the same elevation are indeed different between streams entering from the South and streams entering from the North. On the river profiles plot, in which we now included all profiles, we normalized the elevations.

R: - Section 3.1. The authors make frequent reference to the “annual 90% of total daily precipitation”, yet I never felt confident that I understood what this statistic meant (and how it related to the more familiar 90th percentile). Please could the authors explain with greater clarity?
A: It is the 90th percentile of daily precipitation computed over each single year of the data record and afterwards averaged over the 52 years record. The terms "annual" and "total daily precipitation" were added referring to how values are computed. But we realized it could be confusing, therefore we changed it in "90th percentile of daily precipitation on annual basis".

R: - Section 3.2. The section on river longitudinal profile methods is very brief. Yes, numerous authors have used similar methods, but the authors should still give a clear account of the methods they’re applied here (which links to the comment below, where alternative methods have been selected rather than longitudinal profile analysis, and to comments about the results section).
A: We have expanded this methodology part.

R: - Section 3.3. The account of the hypsometric curve could be clearer, and also doesn’t tell the whole story of how hypsometry might be influenced by glacial modification. River-bed hypsometry is given the briefest of mentions. Is this a technique that has been used widely elsewhere? To me it seems likely to tell a story similar to stream gradient, yet with significantly less resolution, so why introduce this new hypsometry approach? It seems confusing to be using hypsometry for both drainage basins overall, and just along the thalweg of the stream, and also to eschew established longitudinal profile analysis here
A: We have expanded this methodology part. As the river-bed hypsometry appears not to have convinced the reviewers, we excluded it from the paper, and only used the basin hypsometry.

R: - Section 3.4. I found it unclear what tests the authors were proposing to undertake based on the hillslope gradients.
A: We introduced this morphometric variable because it has been used in other studies as one of many other variables (e.g., hypsometry, relief etc.) to characterize the morphology of a basin (e.g. Korup et al., 2005). It can give information about land siding potential (and thus sediment transfer) and has been linked to rock mass strength, glacial and climatic modification and so on. We do see that our text was short on explanations and references. We have thus expanded our explanations.

R: - Section 3.5. How robust are measurements of Vfw? Is there any subjectivity here?
A: We decided not to use Vfw anymore, since it could not convince both reviewers, and for the new approach it would not add much.

R: - Section 4.1. Rather confusing comment that spatial precipitation gradients are low, yet precipitation varies from <500 mm/yr to >2,500 mm/yr. See comment above on “annual 90%”.
A: We apologize for the confusion. With spatial variability we here refer to the entire Rhône basin. The spatial variability within each basin is high because of the orographic effect, but since this effect is occurring everywhere, the difference between different basins is rather small.

R: - Section 4.2. “Oversteepened head scarps” are one of the features omitted from the longitudinal profile methods (see above). Please outline in the methods the basis of this approach. Also, I couldn’t find a clear illustration of the three groups of river channels; Figure 7 is not presented using this framework, so doesn’t match the text here. If the authors are going to argue that each of their three geologic domains corresponds more or less uniquely to a different longitudinal profile form, this case needs to be much more compelling. If Figure 7 is filled out with more longitudinal profiles, will they really disperse into three distinct groups?
A: We now included all river profiles in the same figure.

R: - Section 4.3. Given the broad overall range of hypsometric integrals, is there really a statistically significant distinction between the three litho-tectonic units?
A: We hope we properly addressed this problem with the boxplots.

R: - Section 4.5. What is meant by “have usually”?
A: We decided not to use Vfw anymore, since it could not convince both reviewers, and for the new approach it would not add much.

R: - Figure 5. Vfw as labelled doesn’t appear to be a specific, readily repeatable measure. How do you know exactly where this is? (See comment above)
A: We decided not to use Vfw anymore, since it could not convince both reviewers, and for the new approach it would not add much.

R: - Figure 7. Information about relief/elevation and gradient has been lost when longitudinal profiles are plotted normalised like this. Is this a problem? A: Not really if elevations are normalized to the point of entry into the Rhône valley, which we have now done. We apologize for the confusion. Also, no mention of groups 1, 2 and 3 here (see comment above). A: We modified this section.

R: - Figure 8. As discussed above, more detail on the hypsometry along the river bed would be good. Given the impressive resolution of the topographic data, is the river bed always 1 pixel wide? What’s the upstream end of the river bed? What differences separate this analysis from longitudinal profile analysis (and to what extent is this an improvement)?
A: We have removed the river bed hypsometry (see above) and used longitudinal stream profiles only. As such, the comparison between these variables becomes obsolete. We hope that this clarifies our intents and our paper.

R: - Figure 9. Raises the question of how good the topographic data are in this challenging terrain...
A: These photos really illustrate extreme conditions that we have encountered in the Rhône basin, and this appears to have confused reviewer Brocklehurst. We decided to remove it. Indeed, our analyses is based on a lidar 2 m-DEM, which offers an unbeatable database, at least for the scale of an entire basin.

R: - Figure 14. Is the mean HI the mean of the HI values from the individual basins, or the HI of all of the topography within a litho-tectonic unit? A: We consider the HI of each basin now (boxplots). Also the torrential catchments labelled are only considered very briefly in the text – how important are they? A: They are usually basins of comparatively small size. Sediment transport in these basins is accomplished in pulses that transport a lot of material in short time. One could argue that the basins are probably controlled rather by short-term events such as earthquakes or exceptional high rainfalls and not so much by the longer-term processes we are looking at. However, now we just treat them as a “normal” basin and included them into the analysis, without prior interpretation.

R: - Figure 16. More detail and justification on the locations of the cross sections, please.
A: We decided not to use Vfw anymore, since it could not convince both reviewers, and for the new approach it would not add much.

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. Many studies in orogens around the world have analysed how these controlling variables and their spatial and temporal variations might affect the landscape's topography. Here, we focus on the upper Rhône basin situated in the Central Swiss Alps to explore the relation between topography and possible controlling variables. The Rhône basin has been affected by some of the highest uplift rates, high orographically driven rainfalls, and traces of multiple glaciations. Furthermore, the availability of high-resolution geological, climatic and topographic data makes it a suitable laboratory to study the relationships of these variables.

Elevation, relief, slope and hypsometric data as well as river profile information are extracted from around 50 tributary basins using digital elevation models to characterize the landscape's topography. Additionally, uplift over different time scales, glacial inheritance, mean annual and intensity of precipitation, as well as erosional resistance of the underlying bedrock are quantified for each tributary basin. Results show that the chosen topographic and controlling variables vary substantially between the different tributary basins. We test whether the observed topographic differences in the Rhône basin can possibly be linked to any of the possible controlling variables through statistical analyses. Results indicate that the variation of elevation, slope and relief can be linked to differences in long-term uplift rate, whereas elevation distributions (hypsometry) and river profile shapes show correlations with the LGM mean ice thickness. This confirms that the landscape of the Rhône basin has been highly pre-conditioned by (past) uplift and glaciation. However, the results from linear discriminant analysis (LDA) suggest that the differences in bedrock erodibilities between the basins are more powerful to explain most of the topographic variations. We therefore conclude that, although effects related to glacial and uplift pre-conditioning have resulted in measurable impacts on the landscapes of the Rhône tributary basins, variations in lithology and therefore erodibility is at least as important a factor to be considered in geomorphological studies, at least in the European Alps.

1. Introduction

1.1 Motivation of this study

The topographies of the world's mountains have been formed by rock uplift, which ~~were~~is usually initiated by lithospheric processes such as plate convergence, collision and crustal thickening (England & Molnar, 1990). However, topographic growth on Earth is not indefinite, but limited by erosional feedback mechanisms. Once threshold topography has been reached, any further rock uplift (material input) will be balanced by denudation~~,~~ (material output), and this concept is known as topographic steady-state (e.g., Adams, 1980; Stüwe et al., 1994; Willett & Brandon, 2002, and many more). 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 and landscape form is highly variable in space and time, and that ~~it depends~~the related topographies depend on a large number of variables, such as climate, glaciation, tectonics, and lithology~~ and topography.~~. For example, climate and denudation are coupled in such way that ~~a general wetter climate with high orographic rainfall increases~~increased precipitation yields higher river discharges, which in turn tend to enhance rates of fluvial ~~erosion and the related sediment flux~~channel incision (e.g. ~~Willet~~Willett, 1999; ~~Willet~~Willett et al., 2006~~; Chittenden~~). Rainfall intensity, paired with the total amount of precipitation, plays an important role in erosion processes by driving hillslope erosion (e.g. Wischmeier, 1959) and by contributing to the triggering of mass wasting events that are responsible for mobilizing large amounts of sediment (e.g. Bennett et al., ~~2013~~2012). Glacial ~~erosion~~carving was found to be even more efficient than fluvial erosion~~ through~~, particularly where glaciers have relatively high ~~slip~~sliding rates and high basal shear stresses, and ~~also through~~where subglacial water pressure gradients are large (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~~).~~; Jansen et al., 2014). This seems to be especially valid for the Quaternary period, when multiple glacial advances and retreats have formed the mountainous landscapes in many orogens (e.g. Kelly et al., 2004). ~~In contrast~~On an orogen-wide scale, other authors have reported that the tectonic control on denudation and landscape form has been more pronounced than a climatic one. For example, periods of accelerated uplift in the Alps around 5 million years ago, recorded by ~~mineral cooling~~apatite fission track ages (Michalski & 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~~). Besides a possible climatic driver, deep-crustal processes such as unbending and unloading of the subducting slab have been taken into account to explain this large-scale phenomenon (Sue et al. 2007; Baran et al. ~~(~~2014~~) who compiled data about large-scale patterns of erosion in the Alps.~~; Fox et al., 2015). Wittmann et al. (2007) measured Holocene erosion rates in Alpine river sediments, which correlate very well with ~~measured~~ geodetic-based rock uplift rates~~,~~ ~~suggesting~~. These relationships have been used to suggest that vertical ~~rock~~ movement ~~is~~of rock has mainly been 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 local as well as basin-scale relief that can be extracted from digital elevation models (Granger et al., 1996; Schaller et al., 2001; Montgomery & Brandon, 2002). ~~Furthermore~~Finally, lithology ~~is another~~and related rock-mass strengths have been considered as additional factors controlling ~~factor~~denudation and particularly landscape forms, since soft lithologies like marls are eroded ~~much easier~~faster than hard lithologies such as granites or gneisses, and mechanically stronger rocks can sustain steeper slopes (e.g. Molnar et al., 2007; Korup and Schlunegger, ~~2006; Kühni & Pfiffner, 2001~~2009; Korup & Weidinger, 2011; Korup, 2008; 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.~~; Scharf et al., 2013).

The Central European Alps have been intensively studied ~~intensely regarding the coupling of~~about how surface and crustal-scale processes ~~paired with~~have been coupled through time, and how effects related to these mechanisms have been modulated by glacial ~~conditioning on~~ erosion and deposition (e.g. Persaud & Pfiffner, 2004; Gudmundsson, 1994; Champagnac et al., 2007; Schlunegger & Hinderer, 2001; Cederbom et al., ~~2004~~2011; Norton et al., 2010b; Schlunegger & Norton, 2013). However, much less attention has been paid to exploring how the tectonic architecture, and the nature of the bedrock lithology in particular, has driven surface erosion and has conditioned the shape of the Alpine landscape (Kühni & Pfiffner, 2001; Norton et al., 2010b), mainly because the spatial and temporal variability of uplift, climate, glacial cover~~, lithology and topography throughout the orogen~~ and lithology (Schmid et al., 1996; Kühni & Pfiffner, 2001; Bini et al., 2009) complicates an integrated understanding of the erosional patterns and the ~~Alpine sediment budget.~~resulting landscape form in this orogen. Nevertheless, because of the ~~large variations~~obvious spatial variation in bedrock lithology~~ in~~, the Alps~~, it is possible~~ offer an ideal laboratory 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~~at the basin scale (mean elevation, hypsometry, relief, hillslope gradients and stream profile shapes) are mainly grouped around identical lithologies, ~~which will be documented in this~~ or other conditions and driving forces (long- and short-term uplift, climate, etc.). It is the scope of this paper~~.~~ to explore these possibilities.

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~~around 5500 km^2. The Rhône basin was covered by some of the thickest Alpine glaciers during multiple glaciations throughout the Quaternary (Kelly et al., 2004; Bini et al., 2009) and has recently ~~experiences~~experienced some of the highest uplift rates in the Alps (Kahle et al., 1997; Schlatter et al., 2005). ~~We explore~~In particular, we test whether the ~~geomorphological response of~~ major spatially variable attributes that have been used to characterize a topography at the ~~landscape towards this strong glacial~~basin scale including: mean elevation, relief, slope, hypsometry, and ~~tectonic~~longitudinal profiles of streams bear information that can be related to any of the variables conditioning ~~by analysing the geomorphology of about~~or controlling erosion including: uplift across timescales, climate, LGM glaciation and lithology. To this extent, we compile topographic data from around 50 tributary ~~rivers~~basins 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 (figure 1). We complement our ~~geomorphic~~topographic data with published large-scale geological, climatic, glacial (LGM thickness) and exhumation data in order to attain a large-scale understanding of the predominant processes controlling the ~~Rhône River sediment budget~~landscape's form of this basin over multiple ~~time~~ scales. We find distinct ~~special~~spatial differences in the ~~response of fluvial erosion to glacial and tectonic forcings~~landscape's properties, which ~~are mainly~~can be related to ~~lithotectonic architecture~~the erodibility of the bedrock. This suggests that underlying lithology has exerted a fundamental control on erosion and the resulting landscape form.

1.2 Organization of the paper

We base our analyses on previous studies where uplift (long- and short-term), glacial inheritance, precipitation and erosional resistance of the underlying bedrock have been invoked to explain the landscape's characteristics, expressed through variables such as: mean elevation, hypsometry, relief, hillslope gradients and longstream profiles (Kühni and Pfiffner, 2001;

Wittmann et al., 2007; Norton et al., 2010; Schlunegger and Norton, 2013). We test these relationships through correlation and statistical analyses, and we conclude that variations in erodibility explain most of the morphometric variations that we can observe within the Rhône basin.

2. Geological setting

2.1 Geology

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

Figure 1: Location map of the study area showing the main Rhône River and 55 main tributary streams (>10km^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~~.

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 c. 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 c. 370 m a.s.l., c. 50 major tributary streams with sources in either Penninic units, 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 (figure ~~2~~2a). Variscan crystalline rocks of the European basement (granites, gneisses and 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 c. 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~~Sub-Penninic” basement nappes of the Gotthard massif (3%).

Kühni & Pfiffner (2001) reconstructed a large-scale erodibility map for the Swiss Alps, which is mainly based on the geological and the geotechnical map of Switzerland (Niggli & de Quervain, 1936). These authors used detailed field observations, frequency of landslides, as well as structural and topographic parameters from the Rhine basin (Jäckli, 1957) situated in the eastern Swiss Alps for calibration purposes, based on which erodibility classes were assigned to distinct lithologies (figure 2b). Lithologies with a very high erodibility are mainly encountered in Molasse and Flysch deposits. A medium erodibility has been assigned to Mesozoic carbonates that are exposed in e.g., the Helvetic nappes and Penninic Klippen belt. Paragneisses are considered to have a low erodibility, while the lowest erodibility has been assigned to orthogneisses, amphibolites and granitoid rocks that are currently exposed e.g. in the Aar massif.

Figure 2:

a) 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 1:500000~~, Swiss Earthquake Catalogue, Kahle et al., 1997 and Schlatter et al., 2005)~~)

b) Erodibility map after Kühni & Pfiffner (2001), based on Niggli & de Quervain (1936) and Jäckli (1957) showing the general erodibility of bedrock

2.2 Tectonics

~~Structurally,~~The tectonic setting of the Rhône basin is dominated by the Rhône-Simplon fault system, ~~which accommodated orogenic extension mainly through~~where dextral strike-slip movements since early Miocene times have accommodated most of the orogenic extension (Schlunegger & Willett, 1999; Egli & Mancktelow, 2013). Seward & 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~~exhumation histories (Michalski & Soom, 1990; Schlunegger & Willett, 1999; Vernon et al., 2008; and references within, figure 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 .~~ In contrast, north of the fault in the Aar massif and the overlying Helvetic nappes~~.~~, related exhumation ages are considerably younger (1.5-12 million years). 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~~1997) and therefore show the youngest exhumation ages of c. 1.5-5 Ma (Michalski & Soom, 1990).

~~Recent uplift rates derived from GPS bedrock measurements~~Levelling and geodetic surveys ~~(Kahle et al., ~~revealed that~~1997; Schlatter et al., 2005) in~~ the Rhône basin ~~are~~has experienced some of the highest ~~recorded~~uplift rates throughout the entire Alpine orogen during the past years (Kahle et al., 1997; Schlatter et al., ~~, possibly caused by~~2005). These high uplift rates were related to a combination of ongoing collisional processes (Persaud & 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 mm/a) and decrease to <0.3 mm/a 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).~~ (figure 3a).

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 ~~(~~c. 18-24 ky ago~~,~~ (Kelly et al., 2004; Bini et al., 2009). At the eastern border of the Rhône valley, two separate ice domes formed the ice divide of the Rhône and the Rhine headwaters (Florineth & Schlüchter, 1998). From there, the ice ~~flew~~drained within the valleys (including the Rhône valley) down to the foreland in the north, ~~and~~from where 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, c. 9% of the ~~whole~~entire upper Rhône watershed is still glaciated, and most of the glaciers are situated in the East and Southeast of the basin (figure 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~~Aar massifs, 12.5% in the Penninic units and only 1.5% in the Helvetic nappes. Individual tributary basins like the Massa basin (figure 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 including oversteepened inner gorges reflect the landscape's strong glacial inheritance (Norton et al., 2010a;b; Valla et al., 2011).

2.4 Climate

The spatial distribution of precipitation in the current climate is shown in the form of total annual precipitation and high intensity rainfall represented by annual 90th percentiles of total daily precipitation. Computations are based on the RhiresD product of the Swiss Federal Office of Meteorology and Climatology MeteoSwiss (Schwarb, 2000). Within the upper Rhône basin, annual precipitation is characterized by a rather high variability in space, ranging from less than 500 mm per year along the Rhône Valley to more than 2500 mm per year at very high elevations (figure 3c). This spatial pattern is mostly driven by orography where inner, low elevations, sheltered valleys show relatively dry conditions, while the annual amount of precipitation is much larger at higher altitudes (e.g., Frei and Schär, 1998).

Figure ~~3a:~~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.~~ and a decrease towards the basin outlet at Lake Geneva. Contour lines indicating recent uplift (for the time span 1903-2003) are interpolated from Schlatter et al. (2005) and Kahle et al. (1997).

~~Figure 3b:~~b) Map showing the ~~maximum glacial extent~~ice thickness during the Last Glacial Maximum (from ~~Kelly~~Bini et al., ~~2004~~2009) and the recent distribution of moraine deposits (glacial till) and glaciers. ~~Today, glaciers are mainly located in~~

c) Spatial distribution of total annual precipitation averaged over 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.~~period 1961-2012 based on Schwarb (2000).

3. Methodology and Database

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~~. The landscape's response and related morphologic measures can then be suggestive for extents at which re-equilibrations to those perturbations have proceeded (e.g., Robl et al., ~~-~~2015, for the case of the European Alps). In this context, ~~precipitation patterns and geomorphological~~

~~parameters~~we extract morphometric data such as elevation, relief, slope, hypsometry and river ~~longitudinal~~long profiles~~, river cross sections and their height-width-ratios, as well as catchment-wide hypsometric and slope~~ from a digital elevation model (DEM) distributions ~~are frequently used~~ to ~~determine the landscape's condition~~characterize the landscape at the basin scale (e.g., Wobus et al., 2006; Brocklehurst & Whipple, 2004; Champagnac et al. 2012; Robl et al., 2015). We then test the possible relation of these topographic variables to external forcing mechanisms such as uplift, precipitation, glacial inheritance and erodibility through distribution and linear discriminant analyses~~Robl et al., 2015), which we adapt in this study~~.

~~3.1 Precipitation pattern~~

3.1 Topographic variables

All topographic variables including measures for elevation, slope gradients and river profile shapes (at the tributary basin scale) were extracted with standard geomorphological and hydrological tools in ArcGIS© version 10.1. The base dataset for all analyses was the 2-m-resolution digital elevation model (DEM) swissALTI^{3D} generated by the Swiss Federal Office of Topography (swisstopo) in 2014.

3.1.1 Mean elevation, Relief and Slopes

We calculated mean elevation within each basin from the 2m-resolution DEM.

The local relief corresponds to the difference between the highest and the lowest point of elevation in a defined area (Ahnert, 1984). Because the studied tributary basins have significantly different catchment sizes (ca. 10-700 km^2), it is not meaningful to calculate the local relief over the entire catchment. For a better comparability, we instead chose a 1-km-diameter circular sampling window, in which the mean elevation difference is calculated using focal statistics (Montgomery & Brandon, 2002; Korup et al., 2005). Finally, slope values were calculated in ArcGIS© with the imbedded slope algorithm from the 2-m-DEM. We excluded currently glaciated areas from the calculation, because they would bias the results towards higher frequencies of lower slopes. Mean slope values were then calculated from this database for each tributary basin.

3.2 Hypsometry

~~spatial~~We used the hypsometric integral (Strahler, 1952) as measure for the distribution of elevations within the catchments. In particular, the hypsometry of a basin can be used to infer the stage at which the landscape has evolved, where progressive erosion will continuously lower the overall topography and elevations will be skewed towards lower values (Strahler, 1952; Brozović et al., 1997). The hypsometric integral (HI) can be expressed as the integral below the hypsometric curve, which in turn represents the proportion of a basin that lies below a given elevation (Hurtrez et al., 1999). The hypsometric curve displays normalized elevations on the ordinate and normalized cumulative area above the corresponding elevation on the abscissa. The convexity of the shape of this curve increases (and corresponding HI values are accordingly higher) as the distribution of elevations are skewed towards higher values. In contrast, s-shaped or concave hypsometric curves and lower HI values occur in more evolved landscapes, where erosional processes have preferably removed areas of high elevation (Brozović et al., 1997; Brocklehurst & Whipple, 2002; 2004; Montgomery et al., 2001). Accordingly, we calculated the HI for each watershed >10 km^2 using a bin size of 100 m suitable for hypsometric analyses through eq. (1):

$$HI = \frac{H_{mean} - H_{min}}{H_{max} - H_{min}} \qquad \text{(Eq. 1),}$$

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

3.2.1 River profiles

Several authors have quantified the concavity of longitudinal river profiles (e.g., Whipple & Tucker, 1999; Whipple, 2004; Wobus et al., 2006) through the application of Flint's law (Flint, 1974), where the local channel gradient S is related to the upstream drainage area A through (eq. 2):

$$S = k_s \cdot A^{-\theta} \qquad \text{(Eq. 2)}$$

Here, the coefficient k_s corresponds to the steepness index, while the exponent θ is referred to as the concavity index. In case of normally graded stream profiles, S and A show a linear relationship in log/log plots (figure 4). The slope of this linear regression line corresponds to the concavity index θ, while the intercept with the y-axis is the value of the steepness index k_s.

Longitudinal river profiles were extracted from the hydrologically filled 2-m-DEM provided by Swisstopo using ArcGIS© 10.1 and the Matlab© based TopoToolbox by Schwanghart & Kuhn (2010). The code calculates the hydrologic flow into each pixel, and based on this extracts the main channel of the river (i.e., the pixels in which the hydrologic flow is largest).

Along the main channel, elevation and distance, as well as slope and upstream area are extracted in order to plot the river profile and the slope/area relation, respectively. Θ and k_s are then calculated through linear regressions of the slope/area plot. We performed this regression over the entire stream length to allow better comparison between the different streams (e.g., Korup, 2008).

Figure 4: Exemplary plot showing the linear regression of the logarithmic slope/area plot, of which the two variables θ *and* k_s *can be derived.*

3.3 Possibly controlling and conditioning variables

Parameters are referred to as controlling or conditioning variables if they have been used to explain the topographic development of the Rhône drainage basin across scales including: uplift (Wittmann et al., 2007), precipitation ~~in the current climate is shown in the form of~~ and/or glacial inheritance (Schlunegger and Norton, 2013) and erodibility (Kühni and Pfiffner, 2001). As such, these variables potentially explain the patterns of first-order morphometric variables outlined above. We assign quantitative values for the four variables to each tributary basin, thereby using published maps as basis (see chapter 2).

3.3.1 Uplift

We explore the controls of rock uplift on the landscape from of the Rhône basin thereby considering two different time scales. First, patterns of long-term exhumation and related rock uplift can be extracted from apatite fission track cooling ages (chapter 1.2). Accordingly, for each tributary basin, we calculate mean cooling-ages based on the map by Vernon et al. (2008). The tributary basins are then categorized using a ternary division into relatively recent (1.5-5 My), intermediate (5-8 My) and old (>8 My ago) cooling ages, which basically follows the assignment to classes by Vernon et al. (2008).

To account also for recent surface uplift rates, we use the data provided by Schlatter et al. 2005, which we interpolated along the study area. This dataset is based on geodetic levelling surveys conducted for around 10.000 control points all over Switzerland by the Swiss Federal Office of Topography between ~1903 and 2003. We divide recent surface uplift into three intervals including low (0.5-0.9 mm/a), intermediate (0.9-1.4 mm/a) and high (1.4-1.6 mm/a) rates and assigned related classes to each tributary basin.

3.3.2 Precipitation

We use the distribution of respectively total annual precipitation (~~figure 3c) and high intensity rainfall represented by~~ amount) and annual 90th percentiles (intensity) of total daily precipitation~~.~~, respectively, to characterize modern precipitation rates and patterns. Computations ~~were~~are 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 ~2x2 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~~Computations are conducted directly on the native grid and consecutively distributed over a 250x250 m grid by proximal interpolation. Precipitation amount and 90th percentile of total daily precipitation ~~are~~were calculated on annual basis and averaged over the 52 year period 1961-2012 for each catchment. Quantiles are computed only for wet days, assuming a threshold of 1 mm/day for distinguishing wet and dry days.

~~*Figure 3c: Spatial*~~For the precipitation amount, we divide the basins into three evenly spaced classes: 975-1340, 1340-1840 and 1840-2278 mm/y. For the precipitation intensity indicated by the 90th percentile, we also divide the basins into three evenly spaced classes: 19-25, 25-31 and 31-37 mm/day.

3.3.3 Glacial inheritance

We use the glacial extent during the LGM and related patterns of ice thickness (Florineth & Schlüchter, 1998; Kelly et al., 2004; Bini et al., 2009), mainly because this variable has been used to explain some of the landscape forms in the Central European Alps (Schlunegger & Norton, 2013). We calculate LGM-related ice volumes within each tributary basin by subtracting today's landscape elevation (derived from the DEM) from the LGM surface map by Bini et al. (2009). Areas that were above the ice during the LGM are excluded from the resulting map. We calculate mean values of the resulting ice thickness for each tributary basin and classify them into three evenly spaced intervals, 167-292, 292-471 and 471-651 m.

3.3.4 Erodibility

We use the erodibility classes defined by Kühni & Pfiffner (2001) (see chapter 2.1) as a measure for the erosional resistance of the underlying bedrock. Flysch and Molasse deposits are assigned a high erodibility (1). Mesozoic carbonates as they occur in the Helvetic nappes have a medium erodibility (2). Paragneisses and other poly-metamorphic rocks that are exposed mainly in the Penninic nappes and subordinately in the External massifs have a low erodibility (3). Lowest erodibility values (4) have been assigned to granitoid rocks and orthogneisses. These rock types are common in the External massifs and subordinate in the Penninic nappes. Since most of the basins comprise rocks of different erodibilities (figure 2b), we calculate mean values for each basin thereby considering the relative proportion of erodibility classes per basin, and group them in high (1-2), low (2-3) and very low (3-4).

This division would need to be more precise on a smaller scale to allow the consideration of small-scale lithological variation. However, for our basin-wide approach, we found this division sufficiently precise.

3.4 Correlation, distribution ~~of total~~ and statistical analysis

Possible relationships between the topographic and the controlling variables are explored through regression analyses, where correlation strengths for each pair of variables are expressed by the square of the correlation coefficient, r^2. r^2 values >0.5 are considered to indicate a strong correlation, while values between 0.3-0.5 indicate weak correlation. No causal relationships are assigned for pairs with correlation <0.3. Several authors found that in some of the topographic measures analysed here may depend on basin size rather than on external forcing mechanisms (e.g., Willgoose & Hancock, 1997; Korup et al., 2005; Cheng et al., 2012). Because the tributary basins in the study area show quite a large range between ca. 10 - >700km^2, we also test possible dependencies of all topographic variables on basin size.

We then analyze the relation between the topographic and the controlling variables. To achieve this, all topographic variables are plotted in sets of boxplots for each controlling variable. The boxplots display the general range of the data, including the maximum and minimum values, the median, the upper and lower quartile, and outliers. These statistical measures help describing the general data distribution and their scatter. Furthermore, they allow comparing the distribution of data between the defined classes, and help identifying whether there exist significant differences.

We finally test whether the topographic variables of the studied basins are sufficient to predict the affiliations of the basins through linear discriminant analyses (LDA). In contrast to principal component analysis, LDA takes into account the affiliation of a sample to a certain group (McLachlan, 2004), in our case for example the group of basins with high uplift rate or low erodibility. Therefore, LDA allows testing whether a basin has been assigned correctly to a group (e.g. high uplift rate) based on its topographic characteristics. In addition, because the LDA reduces the dimensions of the data to a linear space, related results can be displayed in a two-dimensional scatter plot, where each sample is defined by two eigenvectors (McLachlan, 2004). The distinct groups should then be visible as clusters in this plot if the topographic variables are significantly different between the groups of the chosen category. Furthermore, the LDA approach yields in prediction of the affiliation of a sample to a group based on the eigenvalues inferred from the variables, and it allows comparing these results with the actual group affiliation.

4. Results

4.1 Values and correlations

Generally, all topographic variables show a relatively large scatter between the analysed catchments (see table 1). In particular, the mean elevations span the heights between ca. 1420 and 2890 m a.s.l.. The mean values of relief calculated for 1 km- radii range between 470-990 m, while slopes are between 19.5° and 40.7° steep on the average. The hypsometric integral has a mean value of 0.45, but scatters widely between 0.28 and 0.70 for the individual tributary basins. The river long profiles also show a wide variety in shape (figure 5). They display almost undisturbed concave, over s-shaped (concave-convex) with knickpoints to almost completely convex profiles. Accordingly, the θ and k_s values yield large scatters. Most important, nearly all river profiles have features indicative for topographic transient states such as multiple knickzones and convexities (figure 5).

Most of the topographic variables show no or only weak correlation (($r^2 < 0.3$, see figure 6) between each other. Only the pairs of slope/relief and HI/θ are characterized by a strong positive correlation with values of $r^2 > 0.5$. We did not observe statistically significant correlations between any of the topographic variables and basin size (all $r^2 < 0.3$).

For the controlling variables, table 2 shows the extracted values for each basin based on the categorization described in chapter 3.2. There exists a strong correlation between the two measures for precipitation ($r^2 = 0.710$, figure 7). Since all other variable pairs have r^2 values below 0.3, they can be considered as not strongly correlated. Note that also for basin size there is no statistically significant correlation between any of the analysed variables (figure 7).

Table 1: Topographic variables (section 2.1) extracted for the studied catchments

Table 2: Possibly controlling variables (2.2) extracted for the studied catchments.

Figure 5: Longitudinal river profiles with normalized distance and elevation.

Figure 6: Correlation matrix of the topographic variables extracted from the DEM (mean elevation, relief, slope, HI, concavity, ks) and basin size. The strength of correlation for each pair is given by the square of the correlation coefficient, r^2.

Figure 7: Correlation matrix of the possibly controlling variables uplift (short- and long-term), precipitation (annual mean and 90th percentile), LGM ice thickness and erodibility. The strength of correlation for each pair is given by the square of the correlation coefficient, r^2.

4.2 Distribution analysis in boxplots

Each set of boxplots (figures 8-13) displays the topographic variables grouped into the three sub-classes defined for each of the controlling variables.

The mean apatite fission-track ages for each catchment can be used as a proxy for the long-term uplift history (Vernon et al., 2008). Figure 8 shows that the topographic variables generally group into these three classes (<5 My, 5 – 8 My, and >8 My; see above and Vernon et al., 2008), albeit with a large scatter. Catchments characterized by relatively old apatite ages show generally lower elevation, relief and slope values. Contrariwise, catchments yielding young apatite ages show the highest values of elevations, relief and slopes. In contrast, hypsometric integrals and river profile shapes do now show any variation between the three sets of fission track ages.

Values of short-term uplift rates, which have been quantified using geodetic data collected over the past century (Schlatter et al., 2005), yield a similar pattern concerning the relationships with topographic metrics. Elevation, relief and slope values tend to increase with increasing surface uplift rate (figure 9a,b,c), although the trend is less clear than in case of the long-term uplift variable. Hypsometric integrals and the river profile shapes show no clear trend with geodetic uplift rates (figure 9 d,e).

The mean ice thickness in each catchment during the LGM can be considered as a measure for the glacial imprint onto the landscape (Schlunegger & Norton, 2013). However, no clear variations can be observed between the three defined LGM thickness classes and elevation, relief and slope (figure 10a,b,c). In basins with thicker ice, the HI is clearly lower, and the river profile concavity higher than in basins with thinner ice (figure 10d,e).

Precipitation is quantified by the amount and the intensity of precipitation averaged over the ~~*period*~~ time span from 1961-2012~~. *Rainfall amounts increases with elevation due to orographic effects*.~~, for which data record is available. Regarding the amount of precipitation, the topographic variables do not show any clear variation in-between the three defined precipitation classes (figure 11). The only noticeable relation exists in the wet basins (>1836 mm/y), which are characterized by high elevations. For the intensity of precipitation, which we express here by the 90th percentile of daily precipitation, the results are also non-distinct (figure 12). However, the basins characterized by very high rainfall intensity show much steeper slopes than for the basins with less intense precipitation.

~~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 & Tucker; 1999, Snyder et al., 2000; 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.~~

~~3.2.11.1.1 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 & Whipple, 2002; 2004; Montgomery et al., 2004). 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 (figure 4). Furthermore, Strahler (1952) introduced the hypsometric 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 (figure 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 km~~^{2} ~~using a bin size of 100 m suitable for hypsometric analyses through eq. (1):~~

$$HI = \frac{H_{mean} - H_{min}}{H_{max} - H_{min}}$$ ~~(Eq. 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.~~

~~3.3 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 & Montgomery, 1995; Whipple & Tucker, 1999; Kühni & 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 & 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.~~

~~3.4 Valley height-width ratio~~

~~2~~

~~The *valley height-width ratio* (V_f) is a relatively straightforward measure for valley shapes derived from the valley cross section (Bull & 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):~~

~~$V_f = \frac{2\, V_{FW}}{(E_L - E_V)+(E_R - E_V)}$ (Eq. 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 (figure 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 & Kuhn (2010). The base map for all analyses was the 2-m-resolution digital elevation model swissALTI^{3D} provided by swisstopo©.~~

~~*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).*~~

~~*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.*~~

~~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 per year along the Rhône Valley to more than 2500 mm per year at very high elevations (figure 3e). 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 (figure 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 (figure 6). Indeed, the annual 90th percentiles of total daily precipitation do not show relevant differences in frequency between the three domains and the entire basin (figure 6). Median values of these heavy daily rainfalls range from 22 mm/day in the Penninic nappes, to 27 and 28 mm/day 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 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.~~

~~*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).*~~

~~**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 (figure 7), indicating that all tributary channels in the Rhône 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 (figure 7).~~

~~*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 (^) if >10%.*~~

~~This categorization is furthermore supported by distinct river bed hypsometric distributions (figure 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 (figure 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 (figure 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 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 (figure 9).~~

~~Channels situated in the Penninic units usually show hypsometric maxima at elevations of c. 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 (figure 11). These flat reaches usually show U-shaped valley cross sections and occur upstream of terminal moraines (figure 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, figure 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 (figure 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.~~

~~*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 (^) if >10%.*~~

~~*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).*~~

~~*Figure 10: Detail map of watersheds located in the Helvetic nappes north of the Rhône River (for location within Rhône basin, see figure 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 1:500000 and the Swiss Earthquake Catalogue)*~~

~~*Figure 11: Detail map of watersheds located within the Penninic units south of the Rhône River (for location within Rhône basin, see figure 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 1:25000 of Switzerland and the swisstopo© geological map 1:500000*~~

~~4.3 Catchment hypsometry~~

~~The hypsometric curves of basins within both the Penninic units and the External massifs show convex-up shapes (figure 12). The histograms show more or less normal distributions with a maximum at intermediate elevations and decreasing altitude frequencies towards higher and lower elevations (figure 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. 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 (figure 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 (figure 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 (figure 14), the two largest catchments (Massa and Lonza Rivers) have very high HI, suggesting a non-linear relationship.~~

~~*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.*~~

~~*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.*~~

~~*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.*~~

~~**4.4 Hillslope gradients**~~

~~The hillslope gradients extracted for the Externals massifs show an overall normal distribution with a modal value of 28° (figure 15). A minor peak in slope gradients <10° is probably related to the high glacial coverage in this litho-tectonic domain (see section 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° (figure 15).~~

~~*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.*~~

~~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 in the past, often show a pronounced U-shaped valley cross section, whereas the outlets of the rivers often form narrow, deeply incised canyons (figure 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 (figure 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.~~

~~*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).*~~

~~*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.*~~

~~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 litho-tectonic 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 & 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 & 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 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 1:25000 geological maps of the area, these flat reaches are usually covered by gravel deposits (figure 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 (figure 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 (figure 8). Similar morphologies have been described by Korup & 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 & 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, but their river profiles are highly convex. Evidence for deep incision in these basins is mostly absent, except for the Massa River (figure 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 (figure 3a), the resulting surface uplift pulse could possibly explain the frequency of high elevations in these areas (Kühni & 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 (figures 7, 8, 14, 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 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 90th percentiles 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 c. 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 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 & Tucker, 1999; Snyder et al., 2000), and rivers located in lithologies with low mechanical strengths (such as the Helvetic thrust nappes, Kühni & 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.~~

Topographic variables show a relatively low scatter within the three erodibility groups, which is expressed by rather small boxes (figure 13). In particular, elevation, relief and slope values are significantly different between basins with high, medium and low erodibility. The relationships are less clear for hypsometric integral and river profile shapes.

Figure 8: Boxplots of the topographic variables grouped after the apatite fission-track ages (Vernon et al., 2008), which give long-term uplift information. The boxes represent the areas, in which 50% of the data plot (first and third quartile). The line in the middle is the median of the data. The whiskers mark the maximal and minimal value, and outliers are represented by white dots.

Figure 9: Boxplots of the topographic variables grouped after the recent uplift rates (Schlatter et al., 2005), which give short-term uplift information.

Figure 10: Boxplots of the topographic variables grouped after the LGM ice thickness (Bini et al. 2009), which are indicative for glacial inheritance.

Figure 11: Boxplots of the topographic variables grouped after the amount of precipitation, expressed by the annual mean precipitation.

Figure 12: Boxplots of the topographic variables grouped after the intensity of precipitation, expressed by the 90th percentile of total daily precipitation.

Figure 13: Boxplots of the topographic variables grouped after erodibility.

4.3 Linear discriminant analysis (LDA)

The LDA classification shows that the best results are generated when erodibility is considered as a classification basis (table 3). In particular, 80% of all basins are classified correctly on this basis, and the individual correct classification of the three groups ranges between c. 75% and 85%. In the scatterplots, a clear clustering of the three classes is visible (figure 14). The basins with low and high erodibilities form distinct point clouds, while basins with a medium erodibility occur in-between these coulds.

In the same sense, geodetic short-term uplift appears to be a good basis for clustering the basins upon their landscape metrics, since a total of 76% of basins are correctly classified. However, basins of group 3 (1.4-1.6 mm/y) are classified correctly only to 44%, which lowers the overall LDA performance. The clustering is well visible in the scatterplots (figure 14). Note, however, that the cluster of basins of class 3 lays between the ones of class 1 and 2.

Regarding the variables long-term uplift, LGM ice thickness and intensity of precipitation (90th percentile), the values of correct classifications range between 62 and 70%. However, in all three cases, there is always one class that yields a very low percentage of correct classification. A clustering is hardly visible in the scatterplot for the variable long-term uplift, and mostly absent for the variables LGM ice thickness and intensity of precipitation. Finally, with respect to the amount of precipitation, all three classes of this variable yield percentages around 70% if they are used as categorization basis. However, in the scatterplots, the clustering is rather bad as only class 3 forms a distinguishable point cloud, whereas the other two classes are indistinct from each other.

Figure 14: Scatter plots of the LDA results for long-term uplift (a), recent surface uplift (b), LGM ice thickness (c), amount (d) and intensity (e) of precipitation, and erodibility (f).

Table 3: Results of the LDA classification based on the topographic variables for each of the controlling variables.

5. Discussion

We found that topographic metrics of tributary basins in the Rhône valley show relationships with all four controlling mechanisms including uplift, glacial inheritance, precipitation and erodibility. For example, we found that river basins with a history of relatively fast inferred exhumation rate (apatite FT cooling age <5 My) have comparably higher elevation, relief and slope values, albeit with some poor correlations particularly regarding mean elevation and local relief (Fig. 8). This trend is consistent with studies analysing the relationship between long-term surface uplift and the development of topography (e.g., Ahnert, 1984; Small & Anderson, 1998; Brocklehurst & Whipple, 2002). However, we could not find any significant relation between uplift (neither long-term nor short-term), hypsometry and river profile concavity. This suggests that the distribution of elevations within the basin and the shape of the river profile have not been influenced by uplift.

In contrast, we found a relation between hypsometry, river profile convexity and the LGM ice thickness, where basins with a thinner ice cover have higher hypsometric integrals and lower θ values. Extensively glaciated basins characterized by thicker LGM ice can have lower equilibrium line altitudes (ELA) than only moderately glaciated basins, therefore allowing a stronger glacial modification especially in lower regions and thus a lowering of both the hypsometric curve and integral (Brocklehurst & Whipple, 2004). Also, ice thickness might influence the efficiency of glacial erosion in the valley through larger shear stresses driven by thick ice (Brocklehurst & Whipple, 2002; Dürst Stucki & Schlunegger, 2013). Potentially, thicker ice cover will promote the formation of flat and partially overdeepened lower reaches and steep head scarps, thereby forming valleys with concave thalwegs. Alternatively, large glacial erosion driven by thick ice could promote fluvial incision during subsequent interglacial times through a positive feedback response (Norton et al., 2010b), where the landscape's disequilibrium, conditioned by glacial erosion, promotes fluvial erosion through head ward retreat, thereby increasing the stream's concavity. This is particularly expected along valley reaches where glacial processes resulted in the formation of topographic steps. In either case, glacial perturbations paired with fluvial responses are expected to return thalwegs with larger concavities, which we invoke here to explain the positive correlations between these variables in the tributary basins of the Rhône River (Figure 10e). Although variations in LGM ice cover seem to be a valid explanation for the shape of some of the observed river profiles and the elevation distributions within the basin (see also Schlunegger and Norton, 2013), we could not detect a relation between ice thickness and elevation, relief or slope. This suggests that in our study area the degree of glacial inheritance is not responsible for relief production or ridgeline lowering in the basins, nor can it be invoked to explain patterns of slope angles, a note that has already been made by Norton et al. (2010b).

Erodibility offers a possible explanation for reconciling some of the lack of correlations between landscape metrics, long-term uplift and LGM ice thickness outlined above. The main difference between the domains north and south of the Rhône River is their lithology, and therefore their erodibility. Basins north of the Rhône are mainly underlain by lithologies of the Helvetic thrust nappes (erodibility classes 1-2) and the Aar massif (erodibility classes 3-4), while basins south of it comprise bedrock that are predominantly situated in Penninic thrust nappes (erodibility classes 2-3). Indeed, topographic variables show quite strong variation in-between the three erodibility classes. Basins with low bedrock erodibility have higher elevation, relief and slope values than basins with a high erodibility. One factor influencing the erodibility of a rock is clearly the mechanical strength of the rocks, which has been inferred to be lower in carbonates than in granites or gneisses (Hoek & Brown, 1997; Kühni & Pfiffner, 2001). Rocks with a lower mechanical strength are eroded more easily in response to rainfall, runoff and mass movements (Norton et al., 2011; Cruz Nunes et al., 2015), which over a long time span can result in a lowering of elevation. Furthermore, slopes underlain by a mechanically weak material are more prone for failure than lithologies with greater strengths, particularly in transient landscapes as is the case here. As consequence, it is possible that mechanically weaker lithotypes are not able to sustain high hillslope gradients over long periods of time (Kühni & Pfiffner, 2001)

Besides the mechanical rock strength itself, the susceptibility of the landscape towards erosion is also controlled by other factors including the structural fabric (faults, schistosity, bedding orientation) and seismicity (e.g. Persaud & Pfiffner, 2004; Molnar et al., 2007; Chittenden et al., 2014), as well as soil cover and potentials for mass movements like landslides (Norton et al., 2010a; Korup & Schlunegger, 2009; Cruz Nunes et al., 2015). Indeed, we could observe a spatial clustering of earthquakes in the study area (figure 15), where earthquakes occur most frequent to the northwest of the Rhône-Simplon-lineament in the area of the Helvetic nappes. Here, most earthquakes show a strike-slip focal mechanism and occur along steep-dipping ENE-WSW to WNW-ESE trending faults (Maurer et al. 1997). In the Penninic nappes south of the Rhône-Simplon-lineament, earthquakes show a wider spatial scatter and predominantly normal fault focal mechanisms. In contrast, earthquakes in the East of the study area occur more rarely, which coincides with the lack of large-scale tectonic faults (figure 15). Tonini et al. (2014) demonstrated that landslides are spatially clustered on the hillslopes bordering the Rhône valley and not in the tributary basins, and that gravitational slope deformations are likely coupled to earthquakes. Furthermore, they observed that landslides occur predominantly in unconsolidated Quaternary material (mainly glacial till), and that former landslide material is promoting new instabilities, thereby creating a positive feedback mechanism. Accordingly, their map of landslides in the Rhône valley shows a pattern similar to the distribution of faults, earthquakes and quaternary deposits (figure 15), all of which being focused in the Helvetic nappes and near the lower elevations and valleys of the Penninic nappes.

Finally, the precipitation parameter is poorly correlated with any of the topographic characteristics. The only correlation between precipitation and landscape metrics has been found for basins with very high precipitation rates, which appear to have generally high elevations, and also higher slope values. However, this is probably connected to the strong orographic effect in the Rhône basin (Frei and Schär, 1998). Basins that are characterized by higher elevations experience on average more (and also more intense) rainfall than the basins located in lower and therefore more shielded locations. In this context, the precipitation is rather the effect of than the cause for the high elevations. Therefore, the topographic variables can be assumed to be largely independent from climatic conditions such as precipitation (Schlunegger & Norton, 2013).

Figure 15: Compiled map of faults (geological map of Switzerland 1:25000), earthquake epicentres (Swiss Earthquake catalogue) and landslides (Tonini et al., 2014). For reasons of clarity, we display only the earthquake epicentres of a short time period. For the full dataset and more detail about the data, see Fäh et al., 2011.

5. 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 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.~~

We used standard topographic variables including mean elevation, relief, slope, hypsometry and river profile concavity to characterize the topography of the Rhône basin. A strong variation of these factors was observed between several sub-catchments. We thus tested whether these differences can be explained by differences in uplift, glacial inheritance, precipitation conditions, or erodibility. From boxplots and linear discriminant function analysis we found that the variation of variables can best be explained using the affiliation of the basins with the general erodibility of the underlying bedrock. However, we also found correlations of some topographic variables with glacial inheritance and uplift. In particular, we showed that uplift could be responsible for the development of elevation and relief in the study area, whereas the ice thickness during the LGM influenced the elevation distribution (hypsometry) of the basins, as well as the shape of some of the river profiles. We conclude, therefore, that although the landscape shows evidence for pre-conditioning effects related to uplift and glaciation, the high spatial variation of bedrock erodibility offers the best explanation for the observed patterns of landscape form in the Rhône basin. In addition, the erodibility variable depends not only on the mechanical strength of the underlying bedrock, but also on the fault and earthquake densities, as well as the potential for landslides.

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