Morphometric dating of the fluvial landscape response to a tectonic perturbation

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Abstract. Despite constant progress in numerical and field studies of landscape evolution, time evolution is still poorly constrained in many uplifted areas where low denudation rates prevent the use of low temperature thermochronology, especially outside high relief mountainous areas. Here, I show that regional statistics of the landscape metric *R* involving hypsometric integrals at three nested levels of a catchment are able to isolate the time effect on landscape geometry during the latter's transient response to a tectonic perturbation. Analysis of 210 catchments from 9 regions of known uplift age worldwide shows that the regionally characteristic, *R*-derived S_R index is in inverse power law relation with the time elapsed since a base level lowering. Suggesting a response time of ~5 My, this finding has important implications for quantifying the rate of landform evolution and determining whether a landscape has reached steady-state form.

1. Introduction

For more than a century, geomorphologists have tried to model the response of fluvial landscapes to perturbations and to establish its governing laws on a quantitative basis. From the beginning, the cycle of erosion of *Davis* (1899) and concurrent conceptual models (e.g., *Penck*, 1919) were strongly controversial and of limited practical reach, especially because of limited links to field data and a total absence of quantitative outcomes. Therefore, while alternative landscape evolution models around the 1950s' remained vague about time constraints, the attention turned more and more to the analysis of individual processes, then to erosional systems, finally giving rise to the development of numerical modeling of landscape evolution, starting with the work of *Ahnert* (1970). However, these empirical, more or less firmly physically-based models still struggle with so many poorly constrained factors controlling the erosion and transport equations that their predictive power remains rather limited (*van der Beek and Bishop*, 2003). As a result, most parameter estimates have only a regional meaning and, while the various governing laws implemented in the fluvial incision models make different predictions in terms of the style of landscape's transient response to perturbation but predict similar steady-state topographies (concave-up profiles), we still lack a way of assessing quantitatively the temporal evolution of the response.

A quite different approach is envisaged here, focusing on the intrinsic geometric properties of the fluvial landscape as a whole. The working hypothesis is that the evolution of such overall morphological properties is most liable to obey a statistical law describing their response rate and thus opening a window toward quantitative age estimates of perturbations. Many studies have indeed shown that regressive erosion within a single stream depends on a variety of variables that may determine significant local changes in propagation rate, thus ruling out to provide a universal calibration of a simple fluvial erosion law (e.g., *Whipple and Tucker*, 1999, 2002; *Sklar and Dietrich*, 2001; *Attal et al.*, 2008). By contrast, the effects of many subsidiary variables, such as rock resistance, climate, or sediment load, stand a chance of averaging closer to zero and being damped when considering larger-scale features such as the overall degree of incision of the drainage network. The very existence of deep gorges cut in resistant rocks suggests for example that bedrock erodibility is a second-order control on incision at the landscape scale, with much more limited influence on the vertical component of river erosion than on its lateral counterpart. Therefore, this study applies to uplifted areas the *R* landscape metric (*Demoulin*, 2011), which combines in a single expression the measure of vertical erosion at different hierarchical levels of a catchment, in order to isolate time-dependent characteristic features of the landscape and to derive age data.

2. A time-dependent landscape metric and the associated index

The *R* metric was devised especially to yield an estimate of the progress of a landscape's response to tectonic uplift (*Demoulin*, 2011). It is able to capture and integrate the response at the various hierarchical levels of the landscape that react successively in time. Calculable for fluvial catchments of every size, this metric takes the form of a ratio of two-by-two differences between the normalized hypsometric integrals of the classical basin hypsometric curve H_b, the drainage network hypsometric curve H_n, and the trunk stream long profile H_r (**Fig. 1**), thus describing three nested morphological levels respectively indicative of the long-, medium-, and short-term components of the landscape response,

$$R = \frac{\int_0^1 (H_n - H_r) dl^*}{\int_0^1 (H_b - H_n) dl^*} \tag{1}$$

where l^* is the dimensionless expression of length (for H_r and H_n) or area (for H_b).

This expression of R must be corrected for the effect of the drainage network's hierarchical structure. Indeed, the size contrast between trunk and tributaries controls, through the degree of drainage area change at junctions, the patterns of migration rate of the erosion front within the system, and thus affects the behaviour of the metric. As this contrast is tightly related to basin elongation E, the correction factor $1/\sqrt{E}$ relies on a measure of the latter, calculated as $4A/(\pi * L_b^2)$, with A = basin size and L_b = maximal length of the basin, measured from its outlet.

Demoulin (2011) also showed that the R value of a catchment is primarily controlled by the size of the contributing drainage area A, in fact so much that the metric is highly correlated with that variable within every region (**Fig. 2**). To remove this effect, which reflects the way an erosion wave propagates from a basin's outlet toward its headwaters, the slope of the logarithmic function $R = f(\ln A)$, typical of each particular region and called S_R hereafter, is used as the actual, R-derived, time indicator.

The effectiveness of R to extract time information from the landscape shape is based on the recognition that the transient response to a base level change occurs primarily through the propagation of a wave of erosion travelling from the catchment outlet upstream through the drainage network, and leading eventually to interfluve lowering. Suppose a region initially in geomorphic equilibrium affected by a base level lowering resulting either from an uplift pulse or an acceleration of uplift or still, at a nested scale, from the arrival of a retreating knickpoint (i.e., a local convexity in an otherwise concave-up river long profile) at the outlet of a tributary catchment. Obviously, this base level change, which causes a similar instantaneous increase of the three hypsometric integrals but no immediate variation of *R*, induces firstly incision of the trunk stream, where the erosion propagates fastest, in power law relation with the size of the contributing drainage area (*Whipple and Tucker*, 1999). Therefore, the initial stage of the system's response is characterized by a marked decrease of $\int H_r$, while $\int H_n$ diminishes only slightly and $\int H_b$ hardly changes, leading to a rapid increase in *R* (**Fig. 3**). Then, in the medium term, the low courses of the trunk stream and its major tributaries having reached a new equilibrium, erosion proceeds at a progressively slower pace in the upper course of the trunk while it propagates simultaneously in an increasing number of tributaries and sub-tributaries, so that the decrease of $\int H_r$ slows down and, concurrently, that of $\int H_n$ accelerates strongly. In the same time, $\int H_b$ is still more or less unaffected. This stage of the evolution, probably lasting a few million years in areas of moderate uplift, thus results in the slow decrease of the metric with time. In the long term, the drainage network as a whole tends towards steady-state and the signal is fully transmitted to the interfluves, unless a new perturbation has occurred in the mean time.

In this scheme, it is the progressive decrease of *R* with time in the middle stage of the landscape response that lends all its interest to the metric. From a compilation of knickpoint migration rates, *Loget and Van Den Driessche* (2009) calculated that trunk streams of regional importance (10^3<*A*<10^4 km^2) display average propagation rates of 3-10 m/yr at the 10^4 yr time scale. Based on these figures, incision in the drainage network ($\Delta\int H_n$) generally starts to exceed in quantity that in the regional trunk stream alone ($\Delta\int H_r$), and the *R* values of the largest streams begin to decrease, with a lag-time of a few 10 ky with respect to the tectonic signal. Defining the time origin at that moment thus comes to neglect this lag-time.

Finally, *Demoulin* (2011) showed that, during the transient response phase after a region has been uplifted, the S_R index is theoretically expected to evolve with time following a temporal pattern of slow and regular decrease after a rapid initial increase very similar to that of the R parameter. A high S_R value thus indicates a recent uplift, a lower one points to an older event, the relative uplift age being given by how much the index has decreased back toward its steady-state value.

3. Implementation of the R/S_R analysis

In order to explore whether the R/S_R morphometric analysis is able to provide a quantitative law of landscape evolution, I calculate here the S_R index of various areas worldwide where the age of the last perturbing uplift is more or less well constrained. The study is based on 210 basin data from 9 uplifted regions (**Table 1**).

To compute R and S_R, I used the SRTM 3'' digital elevation model in its 'filled' version 2, available from the CGIAR-CSI (http://srtm.csi.cgiar.org/). The SRTM data cover all land area between latitudes 60°N and 60°S and, despite their rather poor resolution of ~90 m, the induced uncertainty on R is empirically shown not to exceed a few percents (*Demoulin*, 2011). Its effect on S_R is small and remains within the standard error on the index as calculated from the regression of R on ln A. Data extraction was carried out with ArcMap 9.3.1, first-order streams of the drainage network being defined to start for catchment area > 0.5 km^2. The method used to obtain the hypsometric curves and integrals of basin, drainage network and trunk stream was described in detail by *Demoulin* (2011).

The reference event is either the last uplift pulse or increase in uplift rate that has induced a wave of regressive incision within the drainage network. In the Coast Ranges of northern

California for instance, the migration of the Mendocino triple junction caused the Big River basin to start rising 4 My ago (*Lock et al.*, 2006). However, according to the Mendocino Crustal Conveyor model (*Furlong and Schwartz*, 2004), the predicted two-hump temporal pattern of uplift in the trail of the migrating junction should imply renewed uplift of the basin after a time of dynamic relaxation. As the basin topography and drainage network show no sign of a recent uplift signal (because either it is still to come or the intervening dynamic downward flexure did not last enough to fully express itself in the topography and modify the ongoing landscape evolution), I nevertheless retain an age of 4 Ma for the Big River basin uplift. By contrast, in the Sila massif of Calabria (southern Italy), which is known to undergo uplift since ~0.7 Ma (*Westaway*, 1993), the current phase of fluvial regressive erosion is seemingly related to a marked increase of the uplift rate around 0.33 Ma (*Santoro et al.*, 2009), which is thus retained as the time of the last tectonic perturbation of the area. Additional age information about the study cases may be found as auxiliary material.

In the assessment of the relation $t = \mathrm{f}(S_R)$, the standard errors on the regression coefficients of the regional $R = \mathrm{f}(\ln A)$ regressions are taken as the measure of uncertainty on the S_R values, and the age errors are conservatively estimated from the published data (**Table 1**).

4. Results and discussion

A very good statistical fit ($r^2 = 0.96$) is obtained for a power law dependence of time on the S_R index

$$\boldsymbol{t = 0.009\ S_R^{-4}} \tag{2}$$

where t is expressed in Ma (**Fig. 4**). The alternative form of this equation

$$\Delta R/\Delta(\ln A) = 0.31\ t^{-0.25} \tag{3}$$

conversely highlights the time dependence of changes in landscape geometry determined by fluvial incision in response to uplift. With respect to an equally good exponential fit to the data, the power law fit offers the advantage of being physically more meaningful because it tends towards a lower limit of S_R that decreases only imperceptibly after a few million years and is assumed to characterize a landscape in geometric equilibrium. This S_R value is of about 0.20, in agreement with the figures obtained for two regions near equilibrium under very different uplift rates, namely the quasi-stable southern part of the Paris basin in France (S_R = 0.23±0.04, **Table 1**) and the uplifting Coast Ranges in California (S_R = 0.18±0.02) with mostly graded river profiles under an uplift rate of 1-2 mm/yr (Lock et al., 2006). In other words, the variation of R as 0.2*ln A would express an intrinsic property of fluvial landscapes in geometric (quasi-)equilibrium, and the time estimate associated with the corresponding value of S_R would define a landscape's response time in the order of 5 My.

As far as one sticks to the actual content of the R metric, i.e., a ratio between the degree to which the regressive erosion has invaded the whole drainage network and that to which the fluvial system has carved its valleys in the catchment, this response time apparently shows no dependence on external factors such as, in particular, climate and rock resistance, and on uplift rate. This is at least true between the areas composing the data set, where no clear link can be found between S_R and climatic setting or dominant rock type (**Table 1**). The absence of such controls on the index value at equilibrium primarily results from the formulation of the R metric as a ratio of differences between hypsometric integrals that they similarly affect. However, this cannot apply for the response rate. There, a first reason might be that, because of intra-regional spatial variability and/or interregional similarity of bedrock erodibility, and temporal oscillations of the Quaternary climates, the regional means of rock resistance and climate effects in the studied regions actually fall within a narrow range and consequently do not significantly affect the observed trend. Secondly, the excellent fit obtained may hide considerable uncertainty on the time estimates. Not only does the shape of the fitted curve make time very sensitive to the error on S_R estimates, especially for S_R<~0.4 (**Fig. 4**) but, taking into account the standard error on the estimate of the power law parameters, one also gets a {0.006-0.013} range, i.e., a variability by a factor 2, for the coefficient of equation (2). The simple relation linking time to S_R thus does not deny the impact of external controls on erosion rates but rather suggests that a multi-level statistical approach partly removes their effect.

The absence of uplift rate control on R may be explained partly in the same way. However, the uplift-dependent vertical amplitude of the erosion wave with respect to the basin relief should theoretically determine a highly variable initial amount of change in H_r and thus also a variable initial increase of R. Fortunately, the observed linear relationship between altitude and uplift rate and amount (*Tippett and Kamp*, 1995) leads to a first-order constancy of the proportion between uplift-dependent erosion amplitude and altitude-dependent basin relief, so that uplift rate leaves the metric unaffected in most cases.

5. Conclusions

The R/S_R morphometric analysis applied to uplifted regions worldwide has revealed that the S_R index describes an intrinsic geometric property of fluvial landscapes. Moreover, it brought to light a hidden geomorphic law linking the landscape shape to the time elapsed since a perturbation lowered its base level. Following an S_R increase in the initial stage of the landscape response to a tectonic perturbation, the return of the index to its steady state value occurs at a characteristic pace, independently of the rates and conditions of the individual erosion processes working toward recovery of the landscape equilibrium. In other words, the catchment-wide spatio-temporal distribution of river incision as expressed in the R metric is apparently more or less independent of the factors generally lumped in the K coefficient of most stream power-style incision models (*Whipple and Tucker*, 1999). The relation established between time and S_R suggests that the R/S_R measure might be a valuable morphometric alternative for dating uplift events up to a few million years, offering an independent validation of age estimates derived from cosmogenic nuclides or low temperature thermochronology. So far, the method is however limited to regions fashioned exclusively by fluvial processes, therefore excluding high mountain ranges, where glacial processes play a major role in the upper part of the catchments and require further morphometric research. It should thus be particularly helpful in areas of moderate elevation, where low to very low denudation rates limit the use of thermochronology.

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6. References

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Figure captions

Figure 1. Description of the *R* metric components for (a) the Abercrombie river (New South Wales, Australia) and (b) one subtributary of the same: $l^* = l/l_0$, with l_0 = length of the river, cumulative length of its drainage network, and basin area respectively for H_r, H_n, and H_b; $h^* = h/h_0$, with h_0 = basin relief. H_b, H_n and H_r are the hypsometric curves, i.e., cumulative distributions of altitudes, of the basin, the drainage network, and the trunk stream (H_r is therefore simply the trunk stream long profile). *E* describes the basin's elongation. Note the contrasted shape of the curves and *R* values for basins of very different sizes.

Figure 2. Correlation between the logarithm of basin size (*A*, counted in km^2) and the *R* metric (corrected for hierarchical structure of the drainage network) in the northern part of the Rhenish shield (western Europe).

Figure 3. After *Demoulin* (2011). Snapshots of basin's response to an uplift or, equivalently, to a base level lowering, and successive effects on the R metric. After all hypsometric integrals have been modified identically by the base level change (R unchanged), erosion propagates more rapidly in the trunk stream than in its tributary system, so that the decrease in $\int H_r$ precedes that in $\int H_n$ (and $\int H_b$) and R increases firstly rapidly. After some time, the trunk stream incision reaches the river upper course, where it slows down, while the erosion simultaneously propagates into an increasing number of tributaries and sub-tributaries, so that the decrease in $\int H_n$ becomes predominant and R decreases.

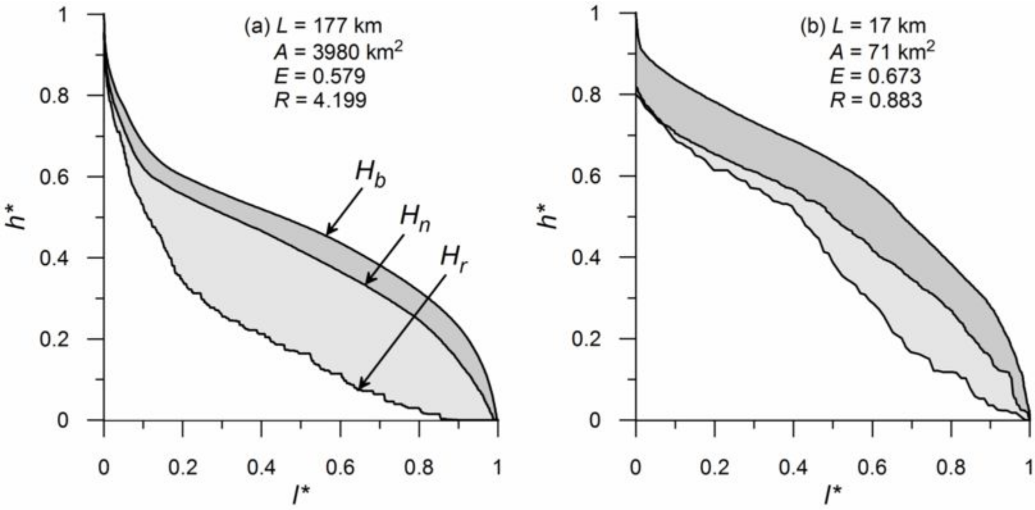
Figure 4. Time - S_R relationship (95% confidence area in light grey) as inferred from 8 regional study cases worldwide (**Table 1**; the Paris basin – Central Massif case is not included because of high uncertainty on age). The horizontal error bars correspond to the standard errors on the regression coefficients of the regional R = f(ln A) regressions, the vertical error bars are conservatively estimated from the published age data. The dashed line locates the approximate equilibrium value S_R tends to with completion of the landscape's response. *RS.* Rhenish shield.

Table 1. Age/S_R data of recently uplifted regions[a]

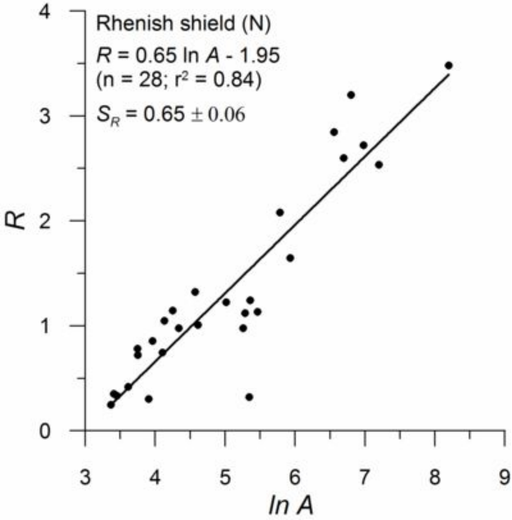
	rock type	relief (m)	n	age (Ma)	age error	S_R	S_R st. error
Rhenish shield (N)	(meta)sedimentary	643	28	0.05	0.05	0.65	0.06
Rhenish shield (center)	sedimentary	619	33	0.7	0.1	0.38	0.06
Rhenish shield (S)	sedimentary	728	22	2	0.5	0.27	0.05
Big River (N Coast Ranges, California)	metasedimentary	850	15	4	0.5	0.18	0.02
Scotland (E central)	metasedimentary + volcanic	1301	19	0.01	0.005	0.87	0.13
French Central Massif (S)	sedimentary + metasedimentary	1121	25	2.2	0.2	0.28	0.11
Sila (Calabria, Italy)	crystalline + sedimentary	1926	22	0.33	0.05	0.43	0.09
Voronezh massif (SW	crystalline	187	22	0.14	0.02	0.48	0.06

Russia)							
Paris basin – Central Massif	sedimentary + crystalline	945	24	>2.6?	?	0.23	0.04

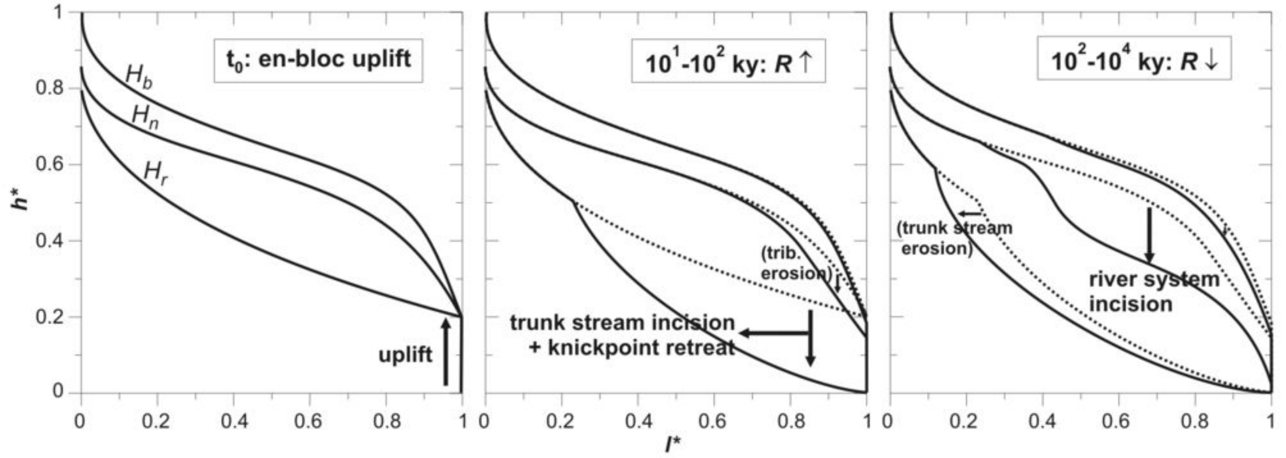
[a]Age data are from *Demoulin and Hallot* (2009) for the Rhenish shield, *Lock et al.* (2006) for the Coast Ranges of northern California, *Bishop et al.* (2005) for Scotland, *Larue* (2008) for the southern French Central Massif, *Santoro et al.* (2009) for southern Calabria, *Matoshko et al.* (2004) for the Voronezh massif, belonging to the upper Don basin, and *Larue* (2003) for the middle Loire area at the transition between Paris basin and Central Massif; n denotes the numbers of basins analyzed per area.

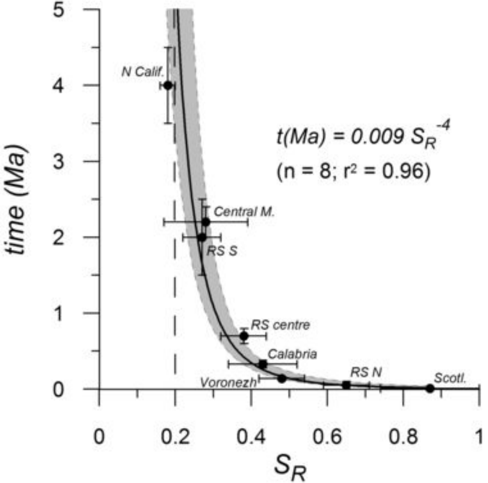


(a) L = 177 km
A = 3980 km2
E = 0.579
R = 4.199
Hb
Hn
Hr
h*
l*
1
0.8
0.6
0.4
0.2
0
0
0.2
0.4
0.6
0.8
1
(b) L = 17 km
A = 71 km2
E = 0.673
R = 0.883
h*
l*



Rhenish shield (N)
R = 0.65 ln A - 1.95
(n = 28; r² = 0.84)
S_R = 0.65 ± 0.06
R
ln A
0
1
2
3
4
3
4
5
6
7
8
9


t0: en-bloc uplift
H_b
H_n
H_r
uplift
10^1-10^2 ky: $R\uparrow$
(trib. erosion)
trunk stream incision
+ knickpoint retreat
10^2-10^4 ky: $R\downarrow$
(trunk stream erosion)
river system incision
h*
l*



5
4
3
2
1
0
time (Ma)
N Calif.
$t(Ma) = 0.009\ S_R^{-4}$
(n = 8; r² = 0.96)
Central M.
RS S
RS centre
Calabria
Voronezh
RS N
Scotl.
0
0.2
0.4
0.6
0.8
1
S_R