# Basin and river profile morphometry: a new index with a high potential for (at least) relative dating of tectonic uplift

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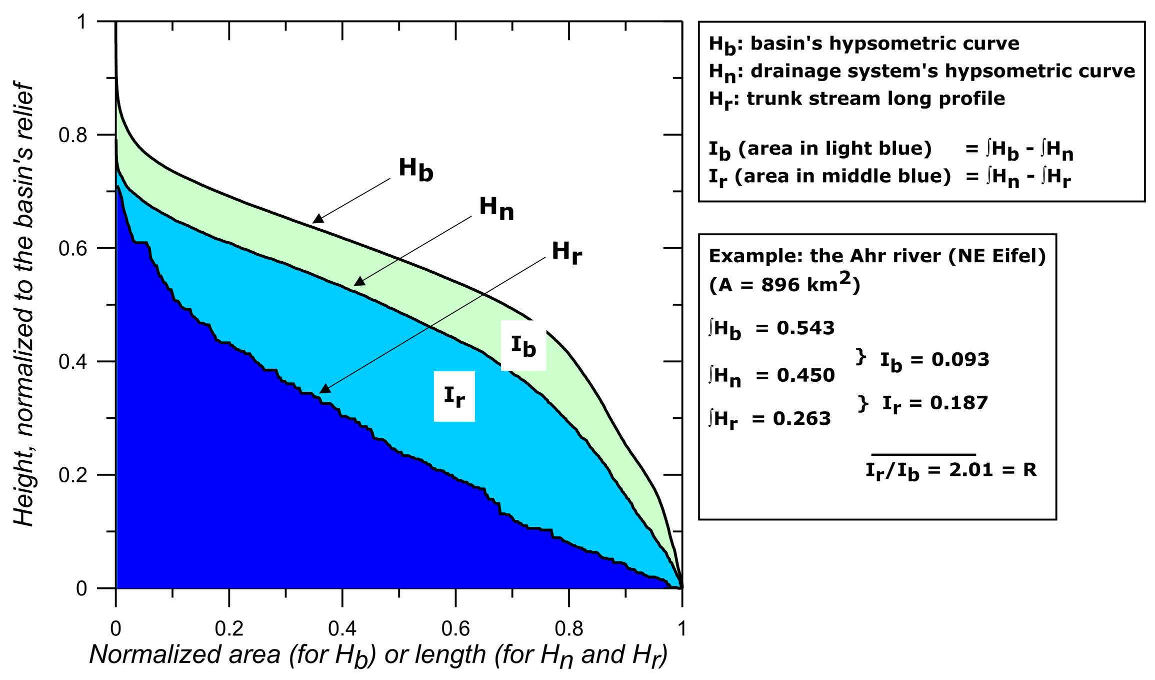
### 1. Introduction

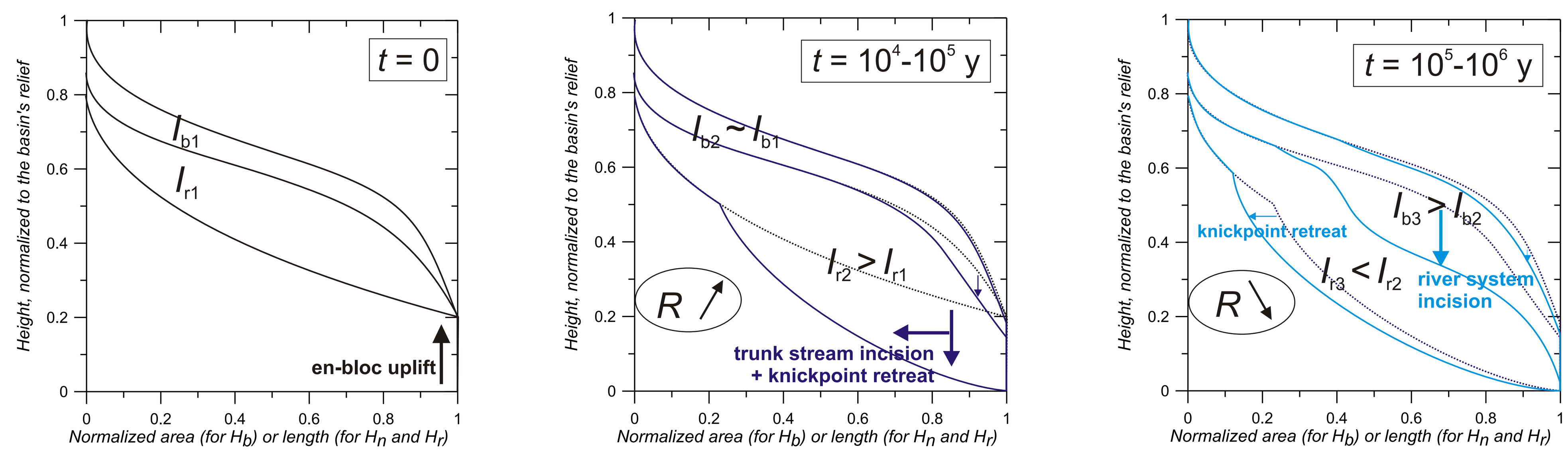
Geomorphometry may be a powerful tool to describe the characteristics of the landscape's response to tectonic signals, but the meaning of morphometric indices is often obscured by the interplay between the many variables controlling the geomorphological evolution. Moreover, although the so-called hypsometric integral refers to the basin scale, most indices are generally derived from the river long profiles and thus focus mainly on the short-term response of a drainage network to base level change, providing limited information in regions of older and/or moderate uplift. Here, an index $R$ has been created to yield a comprehensive view of the stage attained by the landscape's response. It is a ratio of differences between the three integrals linked respectively to the classical basin's hypsometric curve, to the main river's long profile, and at the intermediate level, to a 'drainage network's hypsometric curve'.




### 2. Theoretical meaning of the R index

The effectiveness of $R$ to capture time information within the transient response to a base level change is based on the assumption that river incision (also to some extent determining catchment denudation) occurs primarily through the propagation of an erosion wave.

Assume a region at steady state suddenly affected by a base level lowering, corresponding either to en-bloc uplift of a main catchment or, at a nested scale, to the arrival of a retreating knickpoint at the outlet of a tributary catchment. Obviously, this base level change, which causes an 'instantaneous' similar increase of all $\int H$ but no immediate variation of $R$, induces firstly incision of the trunk stream, where the erosion propagates fastest, in power law relation with basin size (knickpoint celerity $c_{KP} \propto A^{m/n}$, with $m/n > 0$). Therefore, the initial response of the system 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 $I_r$ increasing much more than $I_b$, and consequently $R$ getting rapidly higher. In the middle term (> $10^5$ years), however, erosion proceeds at progressively slower speed 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, lasting a few million years in areas of moderate uplift and relief, thus opposes a gradually decreasing $I_r$ to an increasing $I_b$, resulting in a decrease of $R$ with time. In the long term (> $10^6$ years), the drainage network finally reaches a new state of dynamic equilibrium and the signal is fully transmitted to the interfluves: $\int H_b$ turns decreasingly significant whereas $\int H_n$ and $\int H_r$ are now stable: $I_b$ diminishes for $I_r$ constant and $R$ starts therefore to re-increase slowly.




### 3. Undesired influences on R

- The lithological effect on R is efficiently removed by its form as a ratio of differences between integrals that are equally affected by this variable.

- The catchment's shape influences the R index especially in the case of elongated catchments where tributaries are very short with respect to the trunk stream. It is therefore recommended to use the weighted index

$$R_w = R/\sqrt{E}$$

where the catchment's elongation E is calculated as

$$E = 4A/(\pi * L_{bass}{}^2)$$

with A = drainage area in km² and $L_{bass}$ = catchment's maximum length, in km, measured from the outlet.

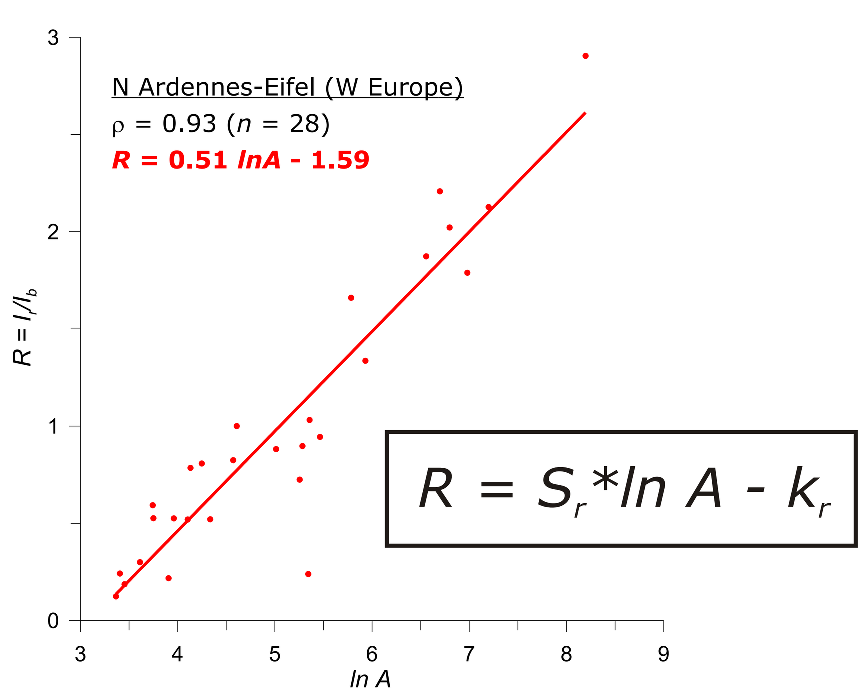
- R is strongly correlated with catchment's size (see figure), reflecting the way an erosion wave propagates from the outlet of a catchment toward its headwaters. The relation is expressed as

$$R_{(w)} = S_{r(w)} * \ln A - k_{r(w)}$$

R is therefore not directly usable as a proxy for relative uplift age but $S_{r(w)}$, the derivative of $R_{(w)} = f(\ln A)$, may be considered as another time indicator, this time free of catchment 's size effect (see below).

- Uplift rate (or amount) also potentially affects R. From the currently collected data, it seems that the uplift rate effect is mainly incorporated in the intercept $k_{r(w)}$ of the relation between $R_{(w)}$ and ln A, i.e., it changes R independently of drainage area.

- Catchment's heterogeneity, e.g. with respect to lithology, drainage density, general shape, is the most disturbing influence on R because it is difficult to remove.




**References**

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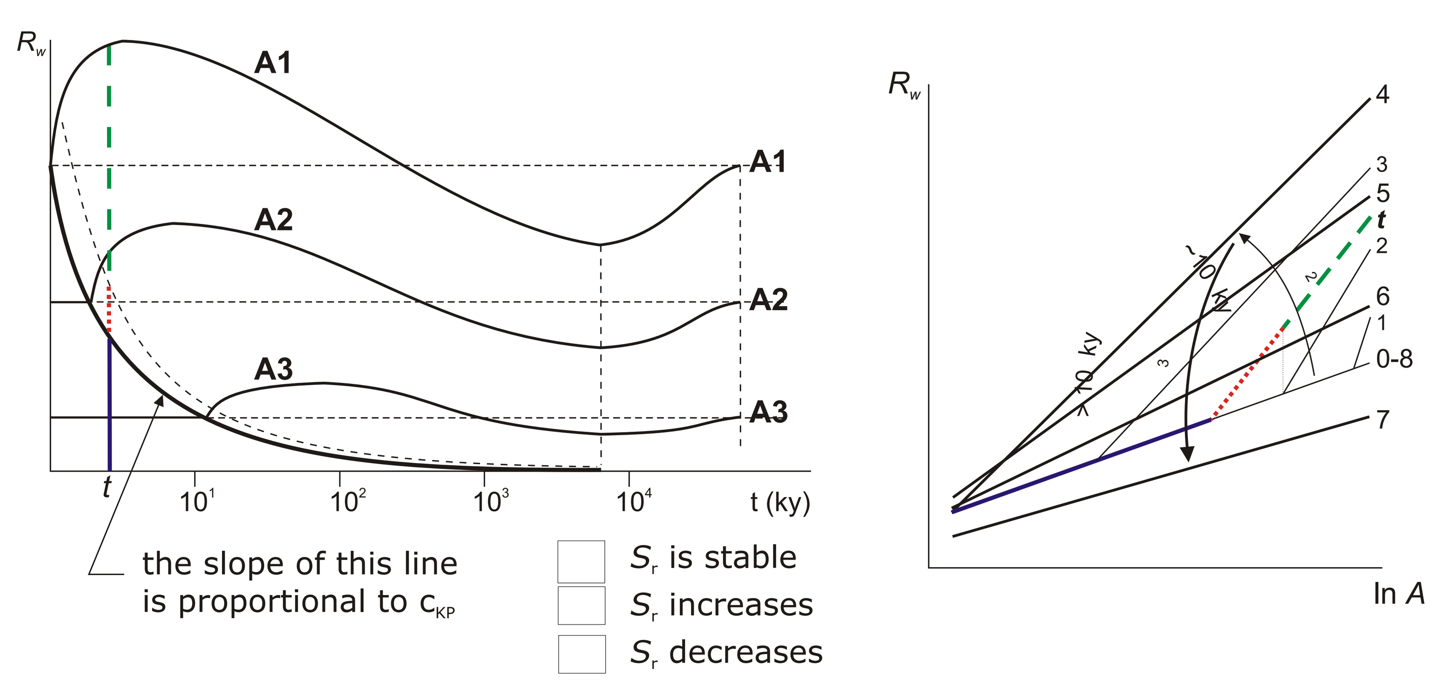
Demoulin A., E. Hallot, 2009. Shape and amount of the Quaternary uplift of the western Rhenish shield and the Ardennes (western Europe). *Tectonophys.* 474, 696-708.

Demoulin A., 2011. Basin and river profile morphometry: A new index with a high potential for relative dating of tectonic uplift. *Geomorphology* 126, 97-107.

### 4. Evolution of $R_w$ and $S_{rw}$ in function of time

The left figure illustrates the evolution of $R_w$ in function of time (see above box) for different catchment sizes (A1 > A2 > A3). The starting time of $R_w$ change is all the more delayed as one considers smaller tributary catchments, in inverse proportion with the decreasing celerity of the erosion wave migration. The right figure shows the resulting change with time of the curve $R_w = f(\ln A)$ and of its slope $S_{rw}$. After a comparatively brief ($10^0$-$10^2$ ky) initial increase of the slope $S_{rw}$ shifting gradually from the right to the left of the curve (stages 0 to 4), the latter flattens again over the longer term (>$10^3$ ky) when erosion is active within the whole drainage network (stages 4 to 7). Finally, a slight re-increase of $S_{rw}$ occurs when the drainage network is at equilibrium and interfluve denudation predominates (stage 8). The curve at time $t$ refers at a particular moment located in the left figure and shows the basin size domains concomitantly experiencing stability, increase, or decrease of $S_{rw}$ (with respect to the preceding stage 2).



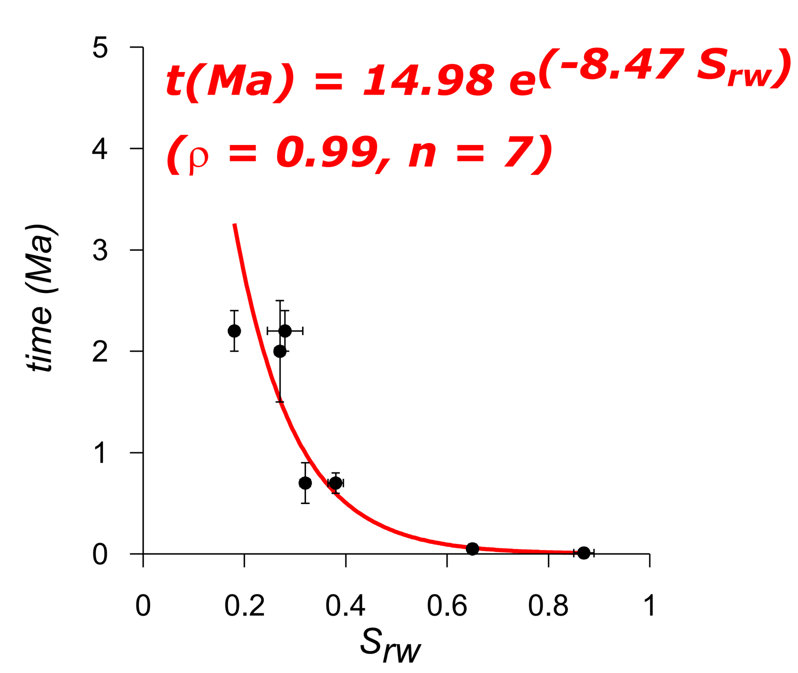

### 5. Validation of $S_{rw}$ as a time indicator

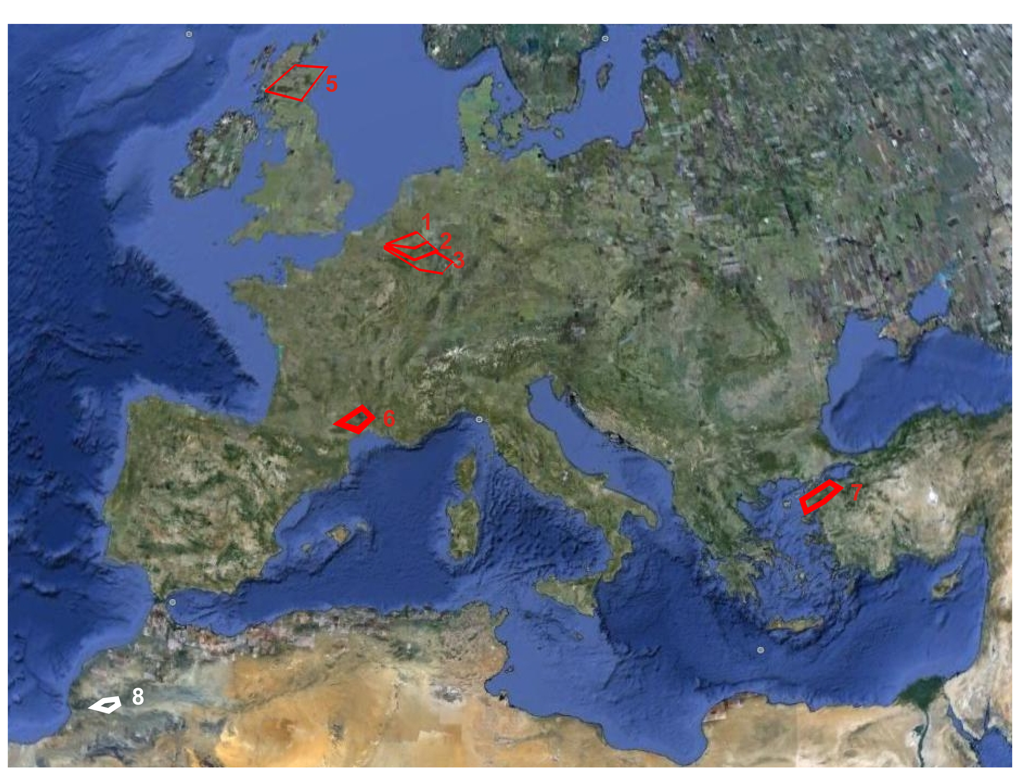
The efficiency of $S_{rw}$ as an indicator of uplift age has been tested in two stages. In a first analysis, I used the Rhenish shield (western Europe), an area of moderate Quaternary uplift in the northern foreland of the Alpine arc, as a test case. It has recently been shown that this massif underwent a wave of uplift that migrated from south to north during the Quaternary (Demoulin & Hallot, 2009). Estimates of $R_w$ for 85 rivers distributed in three subareas of the massif fully confirmed the dependence of $S_{rw}$ on time, showing the expected decrease of the index values from the northern subarea of recent uplift to the southern region of Early Pleistocene uplift. Once its initial increase is completed (assumedly in a few ten thousand years), $S_{rw}$ appears to be a reliable indicator of relative uplift (or any other cause of base level lowering) age.

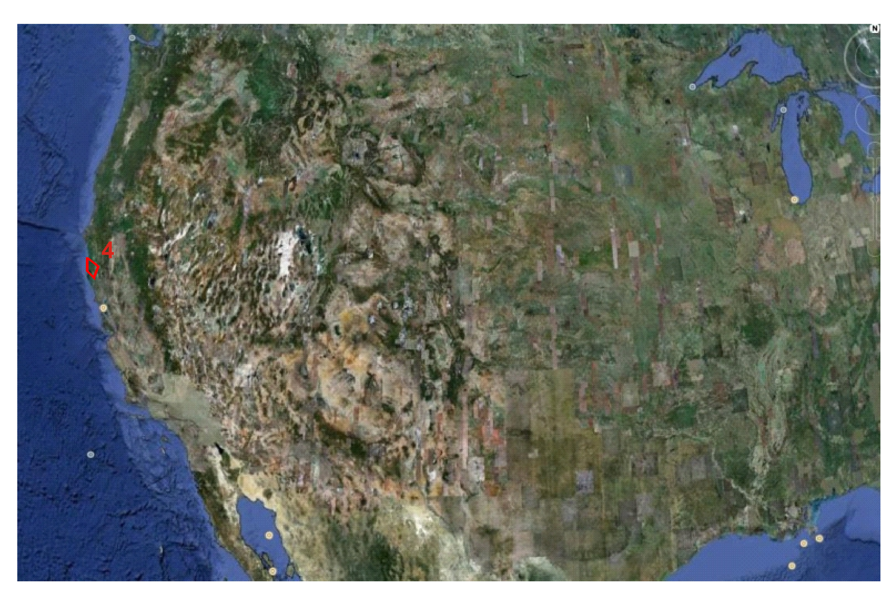
As this preliminary test was successfully passed, the next natural step was to estimate $R_w$ and $S_{rw}$ in areas worldwide where the age of a recent base level change is more or less well constrained (as this is also to some extent the case of the Rhenish shield), in order to assess whether a quantitative relation might be derived, that would allow one to infer absolute ages of uplift from $S_{rw}$ values. At present, the drainage networks of eastern central Scotland, of the Montagne Noire (southern Central Massif,France), and of the Kazdag massif (western Turkey), and the Big River catchment of northern California have been investigated. The current data set of regional $S_{rw}$ values tends to indicate that uplift age has indeed an exponential dependence on $S_{rw}$.

Finally, as a prospect to the potential of the $S_{rw}$ index, its value was evaluated from a set of 21 rivers draining the south-central High Atlas across the Southern Atlas fault (Morocco). The poster A163 (Hall A) presented today by Boulton et al.(2011) reaches the conclusion that '*the slip-rate of the Southern Atlas fault has probably increased within the last 1-2 Myr*'. According to the estimated $S_{rw}$ of 0.52 and the currently available relation between time and $S_{rw}$, this slip acceleration would have occurred around 0.18 Ma.

| region | age (Ma) | age error | $S_{rw}$ | ($S_{rw}$ *error*) |
|---|---|---|---|---|
| 1.Rhenish shield (N) | 0,05 | 0,05 | 0,65 | 0 |
| 2. Rhenish shield (centre) | 0,7 | 0,1 | 0,38 | 0,015 |
| 3. Rhenish shield (S) | 2 | 0,5 | 0,27 | 0,01 |
| 4. Big River (N California) | 2,2 | 0,2 | 0,18 | 0,005 |
| 5. Scotland (E central) | 0,01 | 0,005 | 0,87 | 0,02 |
| 6. Central Massif (S) | 2,2 | 0,2 | 0,28 | 0,035 |
| 7. Kazdag (W Turkey) | 0,7 | 0,2 | 0,32 | 0,01 |
| **8. High Atlas (S central)** | **0,18** | ← | **0,52** | () |



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