Fluvial inverse modelling for inferring the timing of Quaternary uplift in the Simbruini range (Central Apennines, Italy)

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Abstract— **The regional topography of the Central Apennines results from convergence between the African and Eurasian plates that led to the formation of a Neogene NE-verging imbricate fold and thrust belt. During the final stages of the orogenic deformations, the whole area was affected by strong uplift and by extensional faulting oriented along the main direction of the Apennine chain. In this framework, the landscape evolution in subaerial conditions started diachronically and is testified by the relicts of clastic deposit at different height from base levels of the present drainage network. In the Simbruini range, there are no absolute dating records neither of the most ancient clastic units deposited after the Messinian thrust-top facies nor of tectonic events. Trying to fill this gap, we used geomorphometric analyses to infer the timing of the recent phases of the tectonic history of the Simbruini range. Specifically, we identified the main non-lithological knickpoints along the river longitudinal profiles, clustered their altimetric distribution and correlated them with the levels of continental clastic deposits reserved at different elevations. Furthermore, we inferred the uplift history of the range by applying the inverse modelling of the river longitudinal profiles. Assuming a block uplift model, the drainage network cutting the Simbruini range recorded on average about 2.4 Myr of tectonic history, characterized by variable base level fall rates (corresponding to uplift rates). According the average tectonic history, the highest base level fall rate of 690 m My^{-1} was reached at 1.65 Ma, followed by the minimum of about 370 m My^{-1}, reached at 0.75 Ma, and by a second rise, up to a present-day value of 660 m My^{-1}.**

I. Introduction

The Central Apennine chain developed from the Late Oligocene to present, as a consequence of the convergence and the following collision between the African and Eurasian plates. The study area is located in the Simbruini-Ernici range, sited in the intermediate sector of the Central Apennines, a thrust-belt/foredeep system progressively migrating towards the NE [1-2] (Figure 1). It strikes NW-SE and is part of the Latium-Abruzzi paleogeographic domain made up of a carbonatic succession from Mesozoic to Miocene [3-4]. The range is bordered by the Latina Valley to the SW and the Roveto Valley to the NNE, filled with Tortonian to Messinian siliciclastic sediments, mainly deposited in feredeep basins [5]. The last recorded sedimentary cycle of the Central Apennine chain is given by the thrust-top clays and conglomerates (Messinian), that crop out scattered on the deformed bedrock units [6]. Specifically, the study area is located in the axial culmination of the antiformal central Simbruini range (Figure 1), where the strong uplift brought Triassic dolostones to be exposed, in correspondence of an important and complex tectonic lineament called the "Vallepietra - Filettino - Mt. Ortara Line" [6-7]

From the topography perspective the building of relief was slow during the phase of major crustal shortening occurred during Miocene-Pliocene, but strongly accelerated in the Quaternary, when the shortening slowed down and the whole area was affected by strong uplift and extensional faulting striking mainly NW-SE [8-10]. The landscape evolution in subaerial conditions started diachronically and is testified by the relicts of clastic deposit at different height from base levels of the present drainage network. Many Authors [8-10] reported on gently undulated low relief surfaces located in the mountain slopes and tops and interpreted as the remnants of old landscapes formed before the Quaternary uplift. Nevertheless, in the Simbruini range, there are no absolute

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dating records neither of the most ancient clastic units deposited after the Messinian thrust-top facies and the evolution of tectonic events is still not well understood.

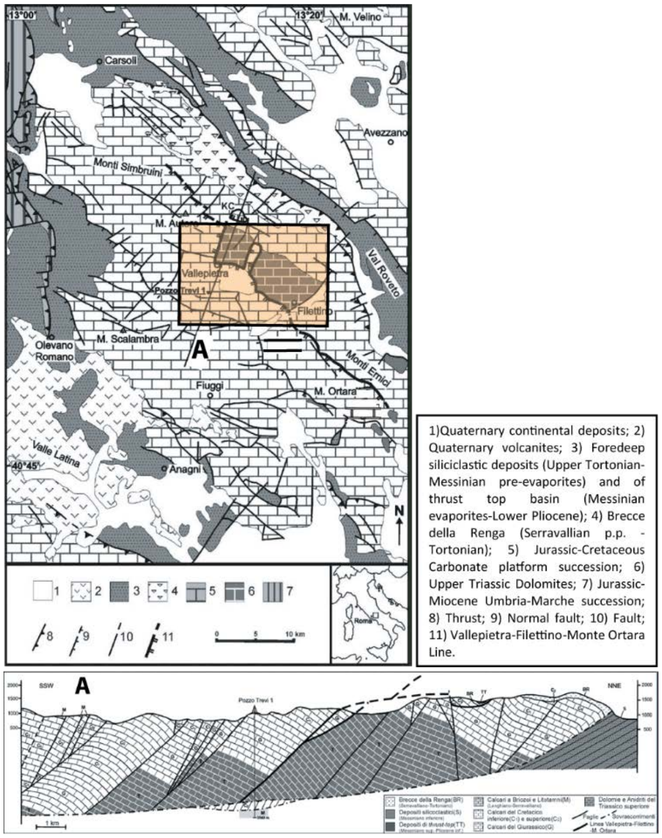

Figure 1. Structural map of the Central Apennines. In the rectangle it is locate the region of interest, the Simbruini range. It is also reported a geological cross-section (A) of the main structural units (modified from [9]).

In this framework, the general purpose is to shed light on final stages of the post-orogenic deformation in the central Simbruini range through geomorphometric analyses. Specifically, we identified the main non-lithological knickpoints along the river longitudinal profiles, constraining the final morpho-evolutionary stages of the valleys cutting the range. Furthermore, we attempted to reconstruct the uplift history of the range through the inverse modelling of the river longitudinal profiles.

II. METHODS

In tectonically active areas, the evolution of topography can provide key insights into the spatio-temporal variations of uplift. Fluvial landscapes record elements that reflect temporal and spatial variations in rock uplift rates which are experienced as base level changes. In rapidly evolving landscapes such as the valleys cutting the Simbruini range, the morphometric record of tectonic perturbation is limited to the most recent times. We investigated the plano-altimetric distribution of the main non-lithological knickpoints along the river longitudinal profiles of the valleys cutting the Simbruini range, included in the Aniene River drainage basin. Furthermore, after calibrating the river profiles with an erodibility value, we applied the inverse modelling of river longitudinal profiles, thus constraining the base level change histories that such knickpoints testify to.

The drainage network was extracted from the 10 m-resolution TINITALY Digital Elevation Model [11] using TopoToolbox, a set of Matlab functions for topographic analysis [12]. We performed the inverse modelling of the longitudinal profiles of the drainage network using a Matlab code gently provided by Sean Gallen.

A. *Linear Stream Power Law for Inverse modelling*

In detachment-limited conditions, typical of tectonically active regions, the evolution of the river profile is described by the stream power law (SPL) [13] as the change in elevation z of a channel point x through time t, which relates to the competition between erosion (E) and uplift (U):

$$\frac{dz(x,t)}{dt} = U(x,t) - E\,(x,t) \tag{1}$$

where fluvial erosion E is calculated as:

$$E\,(x,t) = \;K\,A\,(x)^{\,m}\,(\tfrac{dz\,(x,t)}{dx})^{n} \tag{2}$$

The powers m and n are positive constants controlling the erosion mechanism. Specifically, m depends on the climatic conditions and hydraulic properties of the discharge, and n is function of other erosional thresholds [14]. The erodibility, K, reflects the lithology, the climatic conditions and channel geometry. In the general case, K can vary in space and time, but in the treatment presented here, it is taken as a constant. A power-law relationship between the local channel slope (S) and the upstream drainage area (A) reveals the steady-state river profile:

$$S\,(x,t) = (\tfrac{E(x,t)}{K})^{\frac{1}{n}}\,A(x)^{-\frac{m}{n}} = k_s\,A(x)^{-\theta} \tag{3}$$

where $k_s = (E\,(t,x)\,/\,K)^{\,1/n}$ is known as the steepness index and m/n ratio or θ is defined as concavity index. According to the steady state conditions, the surface elevation, the erosion rate and the relative uplift rate do not vary over time, $U(x)= E(x)$, $n=1$ and the steepness index takes the form [15]:

$$k_s = \frac{E\,(x,t)}{K} = \frac{U(x,t)}{K} \tag{4}$$

If U and K are space-invariant, we can perform the integration of $(U/K)^{1/n}$ from a base level x_b to an arbitrary upstream point x of the channel to predict the elevation of a river profile [16]:

$$z(x) = z(x_b) + \left(\frac{U}{K {A_0}^m}\right)^{\frac{1}{n}} \chi \tag{5}$$

where A_0 is an arbitrary scaling area and χ is an integration of river horizontal coordinates defined by the equation:

$$\chi(x) = \int_{xb}^{x} \left(\frac{A_0}{A(x')}\right)^{\frac{m}{n}} dx' \tag{6}$$

The erosional wave celerity, $C(x) = K\, A(x)^m\, S(x)^{n-1}$, controls the speed at which perturbations travel along the channel [14]. The response time, τ(x), for perturbations to propagate from the river outlet, at $x = 0$, to a point x along the channel is expressed as [14]:

$$\tau(x) = \int_0^x \frac{dx'}{C(x')} = \int_0^x \frac{dx'}{K\, A(x')^m\, S(x')^{\,n-1}} = \frac{\chi(x)}{K {A_0}^m} \tag{7}$$

where x′ is an integration variable. The response time, τ(x), increases constantly with x, from the base level to the high channel reaches. τ-plot is the starting point for the linear inverse scheme to study the rock-uplift/base-level fall history recorded in the fluvial topography [14-15]. Concluding we assumed a spatially constant K and U as in a block uplift scenario employing the inverse approach stream power model solution proposed by Ref. [17-18].

III. Results and Conclusions

A plano-altimetric analysis of the major knickpoints distinguished based on their elevation drop, was conducted (Figure 2). Knickpoint histogram in Figure 2 shows quite well a cluster correlating to the highest clastic deposits (between 1550 and 1300 m a.s.l.) that are associated to the presence of a large anomalous patch of low relief/slope landscape. The low relief areas are especially visible in Vallepietra, Valgranara and Campocatino networks, are elevated by at least 700 m above the Aniene trunk channel and have low slope hanging reaches with increasing vertical drop towards downstream segments. The histogram shows also other two minor clusters of knickpoint at elevation of 1000-800 m a.s.l and 600-400 m a.s.l., respectively in the Valgranara, where another level of breccias crops out, and along the lower reach of the upper Aniene River valley. Major river systems were extracted that drain the upper valley of the Aniene River basin where drainage area exceeds 10^6 m^2. As described by Eq. 3, channel slope, S, and upstream drainage area, A, were plotted on a *SA log-log* plot (Figure 2) and used to calculate the channel concavity, θ. Moreover, the steepness index, *ks*, was computed to the entire drainage network using the obtained value of channel concavity.

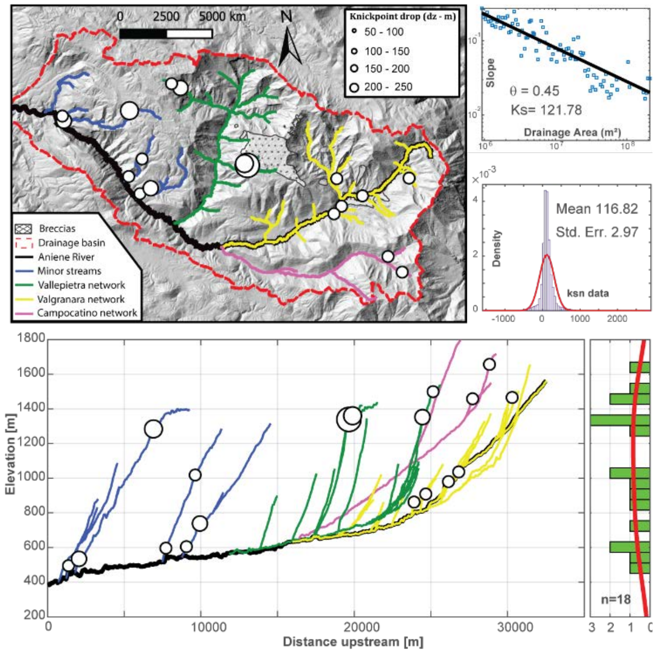

Figure 2. The planimetric view of the stream networks composing the upper Aniene River valley (including the Valgranara, Campocatino and Vallepietra sub-catchments) with the associated slope area plot and ksn density distribution. It is also reported the longitudinal profiles of the main streams of the drainage basin and knickpoint elevation histogram.

The average concavity, θ, relative to the entire drainage basin of the upper Aniene River valley is 0.45 while the steepness index, *ks*, 116.82 with a standard error of 2.97. In order to calibrate the erodibility K, we referred to literature data for the axial zone of the Central Apennines [9-10] by which provided an averaged uplift rate ranging from 0.5 to 0.7 mm yr $^{-1}$. In order to provide a sensitivity analysis on such a parameter, we find the max, mean and min K, applying Eq. 4 respectively between the max uplift rate and the min *ks*, the mean uplift rate and the mean *ks*, the min uplift rate and the max *ks*. We find that $K_{max} = 6.04 \times 10^{-6}\, m^{0.1}\, yr^{-1}$, $K_{mean} = 5.14 \times 10^{-6}\, m^{0.1}\, yr^{-1}$, $K_{min} = 4.24 \times 10^{-6}\, m^{0.1}\, yr^{-1}$. The inversion results were calibrated using the values of K_{est} and m (being $n = 1$ for the steady-state condition then θ = m = 0.45) with a time step size of 10 ka. In Figure 3, the stream network's elevation was reported in χ space and converted in τ space for the different values of K_{est} by applying Eq. 7. Regarding the linear river inversion curves under the block uplift assumption, the tectonic histories that we generically interpret as base level fall rate at the outlet point of the drainage system where the tectonic Simbruini range ends, are as longer as K_{est} is greater ranging from 2.1 Ma with K_{max} to 2.9 Ma with K_{min}. Moreover, the base level fall rates are greater increasing K_{est}.

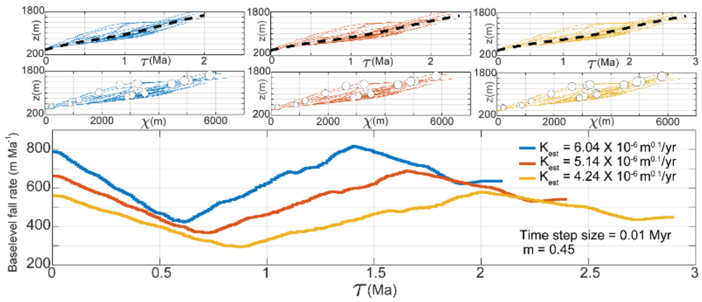

Figure 3. Empirical and best fit χ and τ plots of the stream networks of the upper Aniene River valley computed for K_{max}, K_{mean}, K_{min}. The linear river inversion curves obtained for the different values of K_{est} with the associated parameters chosen in the modelling.

The upper Aniene River valley records on average about 2.4 Myr of tectonic history. According to the average tectonic history in Figure 3, from 2.4 to 1.65 Ma, the base level fall rate constantly increases reaching the highest value of about 690 m My $^{-1}$. Then, from 1.65 Ma to 0.75 Ma it decreases except for a short period of time around 1.3 Ma where a slight increase is recorded. At 0.75 Ma the baselevel fall rate reaches its minimum of about 370 m My $^{-1}$ after which it rises again until to the present day with a value of about 660 m My $^{-1}$.

In conclusion, we tested the linear river inversion procedure in the Simbruini range in Central Italy, as an alternative tool for inferring the recent tectonic history from Pleistocene to the present day where it is still difficult to provide an accepted chronological evolution.

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