Late Quaternary incision rates in the Vésubie catchment area (Southern French Alps) from in situ-produced 36 Cl cosmogenic nuclide dating: Tectonic and climatic implications

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Key Points:
- We obtained fifteen 36Cl exposure ages of a polished river cliff
- An incision rate of 2.2 mm/a is computed for the last 15 ka
- Incision rates are related to Holocene climatic changes

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Late Quaternary incision rates in the Vésubie catchment area (Southern French Alps) from in situ-produced ^{36}Cl cosmogenic nuclide dating: Tectonic and climatic implications

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Abstract We have estimated recent river incision rates using the in situ-produced ^{36}Cl cosmogenic nuclide concentrations. The target site consists of a ~25 m high vertical profile along a polished river cliff located in Jurassic limestones in the Vésubie catchment area, in the southern French Alps. The ^{36}Cl exposure ages of the sampled river polished surface range from 3 to 14 ka, i.e., after the Last Glacial Maximum. Our data suggest as a first approximation a linear age/height relationship and lead to a mean incision rate of 2.2 mm a^{-1} over the last 14 ka. More precisely, incision rates are characterized by two peaks reaching ~2 and 4–5 mm a^{-1} at 4–5 ka and 11–12 ka, respectively, separated by a period experiencing a lower incision rate (~1 mm a^{-1}). A chi-plot of the river longitudinal profile suggests that on the long term, the river is close to equilibrium conditions with a concavity index of 0.475. The evolution of the Vésubie River longitudinal profile over a time period of 2 Ma based on the stream power law of river incision was then modeled with varying erodibility coefficients and uplift rates ranging from 0.5 to 2 mm a^{-1}. The best fitting models yield erodibility coefficient values ranging from 2.5 to 9.0 × 10^{-6} $m^{-0.475}$ a^{-1} for the considered uplift rates. For long-term uplift rates lower than 2 mm a^{-1}, an increase of the erodibility coefficient during the last 16 ka, with two peaks at 11–12 and 4–5 ka, is necessary to precisely match the observed incision rates and is interpreted as resulting from recent climatic changes. These variations do not strongly affect the general shape of the river profile and suggest that the measured short-term incision rate is dominated by a climatic signal, which does not preclude the possible role of tectonic uplift.

1. Introduction

River incision is a complex process governed both by external factors such as climate, lithology, tectonic, or isostatic uplift, and by internal adjustments of the river dynamics [e.g., *Attal et al.*, 2008; *Daniels*, 2008; *Vandenberghe*, 2003]. At a given location along the river channel, incision rate may thus vary through time depending on the amount of water runoff (mainly controlled by climatic conditions), transient effects due to localized channel uplift or base-level fall (i.e., knickpoint retreat), or autogenic factors. Determination of river incision rates at different time scales has many applications, either for short-term soil denudation issues, nutrient fluxes variations, or climate changes estimates [e.g., *Ferrier et al.*, 2013, and references therein]. It is also widely used to understand the internal dynamics of a river system and its response to various external forcings [e.g., *Brocard et al.*, 2003]. Finally, from a tectonic point of view, river incision may help deciphering rock uplift patterns in actively uplifting mountain ranges [e.g., *Wobus et al.*, 2006; *Kirby and Whipple*, 2012; *Baotian et al.*, 2013]. Accurate measurements of river incision rates coupled with reliable climatic estimates can thus help decipher the role of external forcing like tectonics or isostatic movements, and understanding the internal behavior of the catchment system. However, short time scale (i.e., one or several years) measurements of river incision can be difficult to extrapolate to long time scales, due to the stochastic behavior of large erosive events such as floods [e.g., *Stock et al.*, 2004] and to the variability of denudation processes during glacial and interglacial cycles. Therefore, isolating a single parameter like tectonic uplift rates from measured river incision rates is not a straightforward issue. Classically, tectonic geomorphology aims at quantifying tectonic rates from offset recent markers such as terraces, and/or from the dynamic response of fluvial systems (i.e., incision rate variations) or hillslope processes to vertical motions. For instance, over the two last decades, cosmogenic

nuclides such as ^{10}Be have been widely used to date fluvial terrace abandonment ages and infer Quaternary slip rates on various active faults [e.g., *Brown et al.*, 1998; *Ritz et al.*, 1995; *Van der Woerd et al.*, 1998] or to date the onset of landslide activity [e.g., *Sanchez et al.*, 2010] or individual rock avalanches [*Akçar et al.*, 2012]. Besides, dating of strath terraces can also be used to determine river incision rates and infer denudation rates [e.g., *Burbank et al.*, 1996]. In any case, deriving uplift rates or incision rates from staircase terraces rely on the implicit assumption that the exposure age corresponds to the age of terrace abandonment and that incision started immediately after. Furthermore, one has to determine whether the terrace formation is due to dominant tectonic or climatic forcing [e.g., *Baotian et al.*, 2013].

Here we propose an original alternative method to quantify long-term river incision rates, in order to identify both climatic and tectonic controls on the river system evolution. We provide an accurate determination of the duration of exposure to cosmic rays of well-preserved characteristic markers of river incision such as river cliffs or gorges using their accumulated in situ-produced ^{36}Cl cosmogenic nuclide concentrations [*Schaller et al.*, 2005; *Righter et al.*, 2010].

A first attempt of dating bedrock gorge incision has been recently carried out using in situ-produced ^{10}Be on a limited number of samples (4–5 per site) due to difficult sampling conditions [*Valla et al.*, 2010]. Up to now, the ^{36}Cl method has been mainly applied to the dating of successive exposures of an exhumed normal fault escarpment during repeated earthquakes [*Benedetti et al.*, 2002, 2003; *Palumbo et al.*, 2004; *Carcaillet et al.*, 2008; *Schlagenhauf et al.*, 2010], revealing that high-resolution denudation rate estimates could be determined with this method. In all cases, an important issue regarding the dating of surface features using in situ-produced cosmogenic nuclides is the difficulty to accurately estimate the amount of nuclides that has been accumulated before either the surface deposition or the surface exposure of the collected samples. Accurate determination of bedrock surface exposure duration necessitates estimating these "inherited" ^{10}Be or ^{36}Cl concentrations, which affect the age of the following exposure event [*Sadier et al.*, 2012]. In addition, denudation processes (e.g., rock falls and dissolution) affecting the bedrock surface may impact the age estimate when integrated over long time period ($>$ 30 ka), but are generally negligible otherwise. However, both the effects of inherited cosmogenic nuclides and hillslope denudation may be considered as negligible for river cliffs for which the topographic shielding is large, and providing that the sampled polished surfaces are well preserved.

Following an approach similar to that of *Schaller et al.* [2005] and *Righter et al.* [2010], this paper provides quantitative data on medium-term (i.e., several ka) river incision rates using in situ-produced ^{36}Cl cosmogenic nuclide concentrations in a river gorge (Vésubie River, Southern French Alps). It relies on 15 samples from a ~25 m high river cliff, insuring a satisfying resolution on incision rate estimates. The results are then combined with a simple model of river incision to infer the relative importance of local uplift rates and recent climatic variations on the river incision rate over the last 15 ka. We then discuss these results in light of the geodynamic and climatic contexts of the Southern French Alps and make the connection between the active deformation of the Alps and the neighboring Ligurian margin.

2. Geological and Tectonic Setting

The Vésubie River is a large tributary of the Var River, which is the largest catchment in the southern French Alps (about 2200 km^2). The Vésubie River flows in an approximately NS direction, from the external crystalline Argentera-Mercantour massif down to its confluence with the Var River, about 40 km away from its source, and then to the Mediterranean Sea (Figure 1). The Vésubie River source is located in crystalline rocks in the Argentera-Mercantour massif, but the river cuts through the Mesozoic and Cenozoic cover of the southernmost subalpine belts along most of its course. These belts have been deformed mostly during the Miocene during the opening of the Ligurian basin and the alpine collision [e.g., *Clauzon*, 1975; *Campredon et al.*, 1977; *Sage et al.*, 2011]. This area is still undergoing active deformation as evidenced by the abundant, although moderate seismicity [e.g., *Courboulex et al.*, 2007; *Bauve et al.*, 2012, 2014; *Petersen et al.*, 2014]. Several pieces of evidence advocate for ongoing uplift of the margin: submarine canyons located east of the Var river mouth display a convex-up longitudinal profile characteristic of recent or active uplift on a fault system located offshore, at the foot of the thinned continental margin [*Migeon et al.*, 2011], and the Messinian erosion surface visible on seismic profiles appears deformed and tilted [*Bigot-Cormier et al.*, 2004]. However, indices of recent uplift are much more difficult to detect onshore. *Corsini et al.* [2004] and *Sanchez et al.* [2011] propose an onset of the exhumation of the Argentera-Mercantour massif in early Miocene times (~22 Ma)

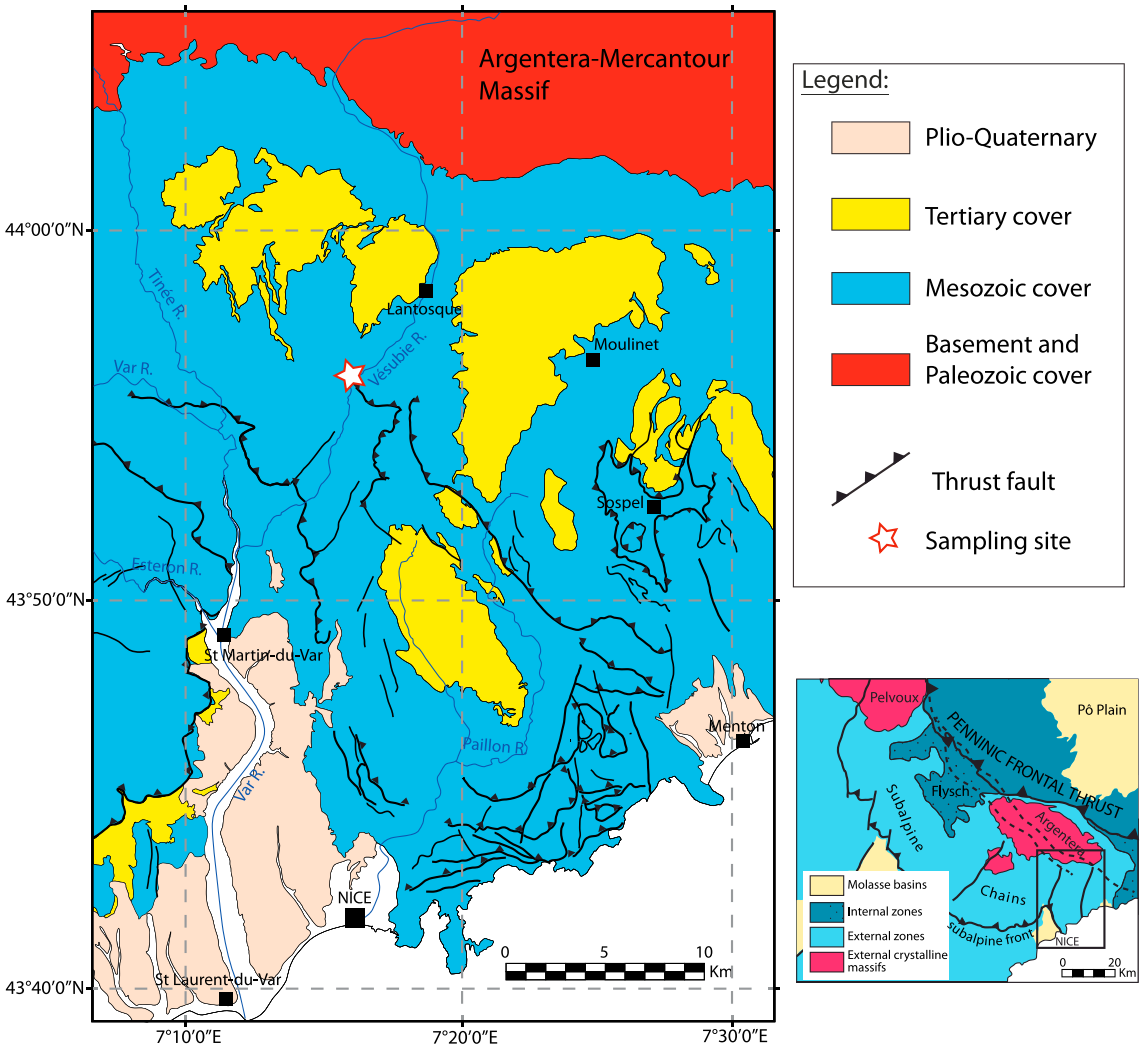

Figure 1. Geologic setting of the Vésubie and Var catchment areas. Southern French Alps [after *Sanchez et al.*, 2011]. Open red star shows the sample location. Inset shows the tectonic setting of the study area in the framework of the western Alps. Internal units consist of alpine metamorphic domains thrusted over the external, nonmetamorphic basement and cover units.

from $^{39}Ar/^{40}Ar$ dating on phengites. Besides these results, there was until now no available data on the rate of river incision in the sediment cover, i.e., between the crystalline basement outcropping to the north and the submarine part of the margin to the south.

To quantify river incision, a nicely preserved polished river cliff located in Upper Jurassic (Tithonian) limestones in the Vésubie catchment area (Southern French Alps) was targeted. This cliff has been cut almost vertically by the Vésubie stream and is located about 10 km upstream from its confluence with the Var River (Figure 2). This site has several advantages: the polished gorge is overhanging, and it is particularly well preserved and devoid of any trace of erosion, dissolution, or collapse. Some calcite stalactites appear on the cliff surface, due to the resurgence at the top of the cliff of highly concentrated karstic waters, which suggests that water runoff on the cliff surface cannot cause additional dissolution and is localized on these concretions. Because of the sedimentary strata dip, only the right bank of the river exhibits such a cliff, the gentler slope of the left bank insuring thus a sufficient exposure to cosmic rays. The lithology is homogeneous, which guarantees that possible incision rate variations are actually due to climatic or tectonic changes, and not to lithological contrasts. Finally, the site is located in the lower part of the Vésubie stream at an altitude of about 300 m, far away from any imprint of glacial erosion, which are limited to elevations of more than 1500 m [*Julian*, 1980]. At this place, the valley has the shape of a typical wineglass canyon with an

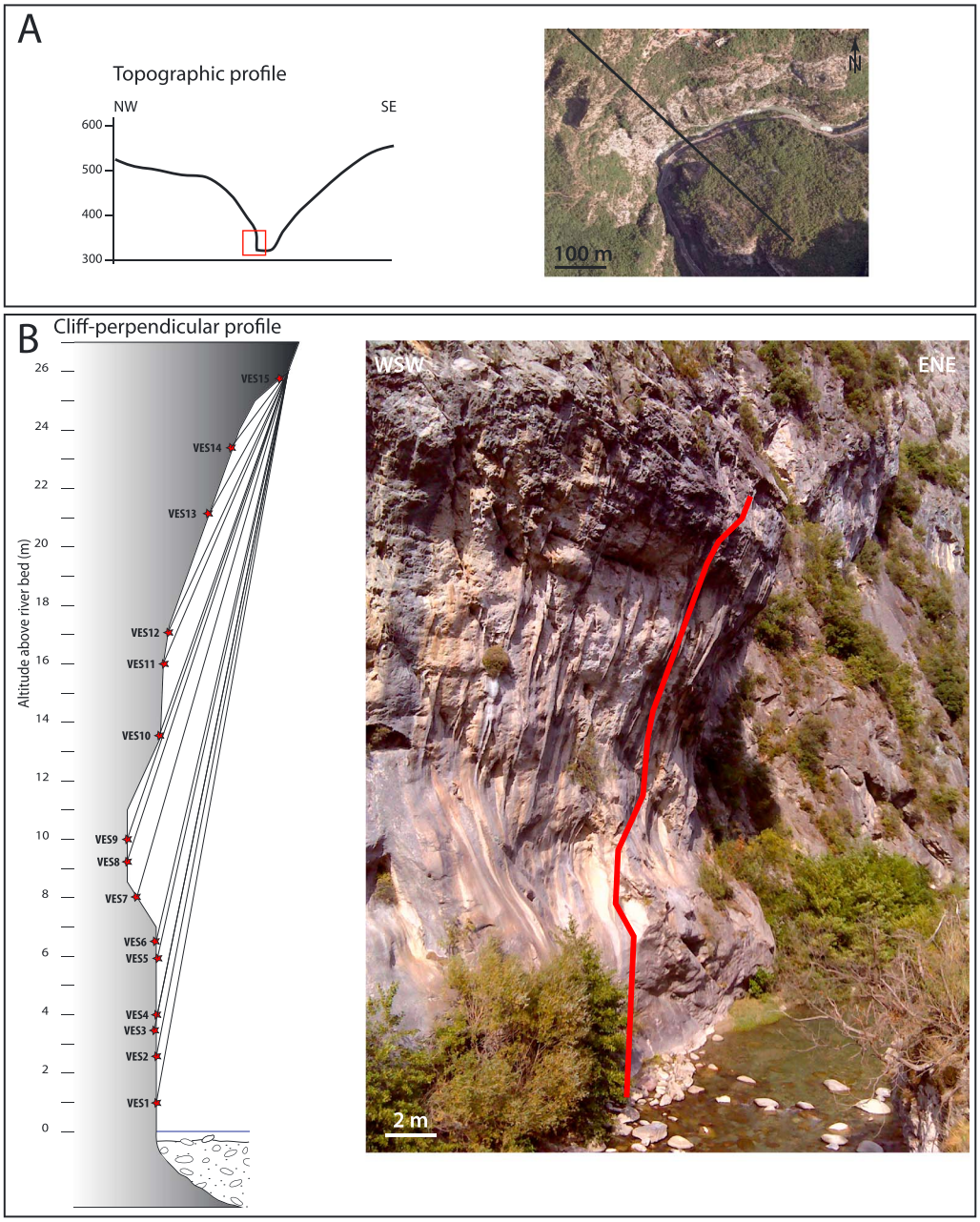

Figure 2. (a) Valley-perpendicular topographic profile and aerial view of the sampling site. Open red rectangle corresponds to the close-up view shown below. (b, left) Cliff-perpendicular topographic profile with altitudes relative to the present river bed. Red stars show the samples location. Thin lines are used to calculate the shielding effect of the overhanging cliff. Sample names are indicated in bold. (b, right) Picture of the polished river cliff. Red line indicates the approximate position of the sampled vertical profile.

ancient V-shaped alluvial valley located ~30 m above the river bed, and underlain by an almost vertical gorge (Figure 2a). Therefore, the effect of subglacial erosion can be ruled out.

3. Sampling and Methods

3.1. Chlorine-36 Sampling and Dating

Fifteen samples were collected along the cliff using a hammer and chisel. Their latitude, altitude, and position along the profile were precisely determined in the field (Table 1 and Figure 2b). The samples were crushed,

Table 1. Field Information and Scaling Factors Used for Calculation of the Production Rates[a]

Sample	Altitude Above Sea Level (m)	Height Above River Bed (m)	Cliff Slope (°)	Shielding Factor S_f	Scaling Factor Spallation S_n	Scaling Factor Muons S_μ
VES1	327	1	99	0.392	1.315	1.126
VES2	328.6	2.6	99	0.392	1.317	1.127
VES3	329.4	3.4	100	0.388	1.318	1.127
VES4	329.7	3.7	101	0.381	1.318	1.127
VES5	331.7	5.7	101.5	0.381	1.320	1.128
VES6	332.4	6.4	102	0.379	1.321	1.129
VES7	333.9	7.9	105.5	0.362	1.329	1.129
VES8	335.2	9.2	107	0.349	1.324	1.130
VES9	336	10	107	0.349	1.325	1.131
VES10	339.6	13.6	109	0.335	1.330	1.133
VES11	342	16	111	0.320	1.332	1.134
VES12	342.9	16.9	113	0.304	1.333	1.134
VES13	347.2	21.2	118	0.260	1.339	1.137
VES14	349.4	23.4	124	0.205	1.341	1.138
VES15	351.5	25.5	110	0.327	1.344	1.139

[a]Sample coordinates are 43°56′06.7″N and 7°15′54.8″E. No erosion or cover correction is applied. Sample thickness is 5 cm.

sieved, and chemically prepared at the French Cosmogenic Nuclides National Laboratory (LN2C; Centre Européen de Recherche et d'Enseignement de Géosciences de l'Environnement (CEREGE), Aix-en-Provence) to precipitate AgCl following the procedure fully described in *Schimmelpfennig et al.* [2009]. Their ^{36}Cl and Cl concentrations were determined by isotope dilution accelerator mass spectrometry at the French accelerator mass spectrometry (AMS) national facility Atmosphere-Surface Turbulent Exchange Research ASTER (CEREGE, Aix-en-Provence) and were both normalized to a ^{36}Cl standard prepared by K. Nishiizumi: KNSTD1600 with a given ^{36}Cl/^{35}Cl value of $(2.11 \pm 0.06) \times 10^{-12}$ [*Sharma et al.*, 1990; *Fifield et al.*, 1990]. The decay constant of $2.303 \pm 0.016 \times 10^{-6}$ a^{-1} used corresponds to a ^{36}Cl half-life ($T_{1/2}$) of 3.014×10^5 years. All the analytical and chemical data are presented with respect to the recommendations of *Dunai and Stuart* [2009]. Analytical uncertainties include the counting statistics, machine stability, and blanks correction (^{36}Cl/^{35}Cl blank ratios are 0.75 and 3.87×10^{-15}). Blank corrections represent between 0.6 and 6.7% of the sample concentrations. Cl concentrations of the samples are ranging from 15 to 32 ppm.

The full chemical composition of three samples was analyzed by inductively coupled plasma–atomic emission spectroscopy (ICP-AES) and inductively coupled plasma–mass spectrometry (ICP-MS) at the Centre de Recherches Pétrographiques et Géochimiques - Service d'Analyse des Roches et des Minéraux (CRPG-SARM) facility (Nancy, France) in order to insure that the chemical composition of the limestone was homogeneous, which appears to be the case (Table 2). All the contributions from the various ^{36}Cl production mechanisms using these relevant parameters were then taken into account to determine each sample specific production rate [*Schimmelpfennig et al.*, 2009]. The in situ-produced ^{36}Cl production rate also depends on the incoming cosmic ray flux that varies with the Earth magnetic field, with the latitude of the study area and with the amount of topographic obstruction around the sample, the latter being generally the most important factor to take into account to obtain an accurate age estimate [*Gosse and Phillips*, 2001]. Because temporal geomagnetic field variations are negligible at these latitudes and over the period considered, the latitudinal and altitudinal scaling were determined at a constant geomagnetic field [*Stone*, 2000]. The elementary ^{36}Cl production rate from spallation of calcium at sea level and high latitude used is 42 ± 2.0 atoms of ^{36}Cl g^{-1} of Ca a^{-1} as established at a site less than a few hundreds of kilometer away from the sampling site [*Braucher et al.*, 2011]. Calibrated at a site for which latitude, elevation, and exposure duration are similar to those of the sampling site, this "local" production rate significantly reduces the uncertainties linked to the scaling processes. Finally, in our case, considering the topographic shielding was particularly important because the samples were collected on an almost vertical, even sometimes overhanging surface, which means that at least 50% of the incoming ray flux was blocked by the topography in the immediate vicinity of the samples. In order to insure a correct estimate of the topographic shielding, we have measured both the local (i.e., near the sample location) and the average cliff slope above the sample (Figure 2b and Table 1). Measurements were performed directly at the sampling sites using a compass, inclinometer, and a tape measure. The largest number (angles larger than 90° indicate an overhanging

Table 2. Major and Trace Element Composition of Three Samples VES4, VES12, and VES15 Measured by ICP-AES and ICP-MS, Respectively, at the SARM-CRPG Facility (Nancy, France)[a]

Sample	SiO_2 (wt %)	Al_2O_3 (wt %)	Fe_2O_3 (wt %)	MnO (wt %)	MgO (wt %)	CaO (wt %)	Na_2O (wt %)	K_2O (wt %)	TiO_2 (wt %)	P_2O_5 (wt %)	H_2O (%)	CO_2 (%)	Li (ppm)	B (ppm)	Cl (ppm)	Cr (ppm)	Gd (ppm)	Sm (ppm)	Th (ppm)	U (ppm)
Uncertainties	< 15%	< 15%	< 15%	< 10%	< 10%	< 2%	< 15%	< 15%		< 10%	< 10%	< 5%	< 15%	< 15%	< 15%				< 15%	< 15%
VES4	0.34	0.13	0.09	0.0068	0.57	54.04	0.02	0.03	<d.t.	0.04	0.29	43.83	1.4	2	33	<d.t.	0.645	0.513	0.29	0.56
VES12	0.38	0.14	0.06	0.0077	0.48	54.27	0.02	0.03	<d.t.	0.04	0.38	43.68	1.0	2	< 20	<d.t.	0.564	0.440	0.25	0.53
VES15	0.81	0.2	0.08	0.0081	0.48	54.2	0.04	0.05	<d.t.	0.03	0.31	43.43	1.2	2	23	<d.t.	0.623	0.510	0.58	0.94

[a]d.t. means detection threshold.

surface) was then used for the shielding estimate due to the cliff obstruction. Besides the cliff itself, the shielding effect of the surrounding topography was measured with a compass as the height (in degrees) of the horizon with respect to the horizontal. The topographic shielding factor S_f is then as follows:

$$S_f = \int_{\phi=0}^{2\pi}\int_{\theta=\theta_h}^{\pi/2} \sin^{2.3}\theta\cos\theta \mathrm{d}\theta\mathrm{d}\phi - \int_{\phi=0}^{\phi_c}\int_{\theta=\theta'_h}^{\pi/2} \sin^{2.3}\theta\cos\theta \mathrm{d}\theta\mathrm{d}\phi \quad (1)$$

where θ is the angle of incidence of cosmic rays measured from the horizontal, θ_h is the angle of topographic obstruction for a "normal" (i.e., not overhanging) surface, ϕ is the azimuth, ϕ_c is the azimuthal extent of the overhanging cliff (about 180°) and θ'_h is the supplementary angle of topographic obstruction for an overhanging surface ($\theta'_h = \pi - \theta$). Shielding factors range from 0.20 for the most shielded samples to 0.40 for the most exposed ones (Table 1). Measurement error of the topographic obstruction of about 5° will induce shielding factor estimate uncertainties ranging from less than 0.4% (for a low dipping topography) to at most 5% (for large topographic angles). Moreover, the shielding between sampled points varies only with the local dip of the cliff (i.e., on an azimuth aperture of less than 180°). Consequently, such shielding factor estimate errors will introduce a systematic bias, which will affect absolute age values but will have a very limited effect on age differences, hence on the incision rate estimates.

The exposure ages were finally calculated according to *Schimmelpfennig et al.* [2009]. Because the sampled bedrock is highly shielded and deep beneath from the overlying surface topography, the inherited component has been neglected. The presented exposure ages are thus maximum, yielding to potentially underestimated incision rates. Given the reasons presented above, the age bias due to possible inherited ^{36}Cl is most likely negligible and anyway systematic; hence, it does not affect the incision rate estimates.

3.2. Numerical Model of River Incision

Inferring uplift rates from incision rates would require the Vésubie River to be globally in an equilibrium state, i.e., that river incision everywhere balances a possible tectonic uplift or base-level fall. Incision is often modeled using the stream power law [e.g., *Stock and Montgomery*, 1999; *Whipple and Tucker*, 1999, and references therein]:

$$E = KA^m S^n \quad (2)$$

where E is the incision rate, K is an erodibility coefficient, A is the drainage area, S is the along-channel slope, and m and n are area and slope coefficients, respectively. For an equilibrium river profile, the incision rate E balances the relative uplift rate U such as $E = U$ and

$$S = \left(\frac{U}{K}\right)^{1/n} A^{-m/n} \quad (3)$$

where the ratio m/n is the concavity index.

Slope-area relationships can therefore be used to infer an equilibrium or transient state of river incision. However, as pointed out by *Perron and Royden* [2013], slope-area plots are often scattered because of the topographic noise. Therefore, we chose to use the chi-plot method of *Perron and Royden* [2013] to assess equilibrium conditions along the Vésubie River. The chi-plot method is based on the transformation of the linear x coordinate system (i.e., the river longitudinal distance) into a nonlinear dimensionless coordinate system which accounts for the power law growth of the drainage area with the

Table 3. Natural Chlorine, Calcium, and Cosmogenic ^{36}Cl Content in the Limestone Samples and Resulting ^{36}Cl Exposure Ages[a]

Sample	Cl (ppm)	Ca (wt %)	^{36}Cl/^{35}Cl (10^{-14})	Atoms ^{36}Cl/g	Atoms ^{36}Cl/g Uncertainty	^{36}Cl Age (yr)	Internal Uncertainty (year)
VES1	25.93	38.6	4.0723	32.939E^3	2872.8	3100	265
VES2	25.43	39.7	3.5559	40.786E^3	2636.5	3961	255
VES3	24.04	39.5	5.6413	42.605E^3	2738.6	4105	256
VES4	27.87	39.9	4.2001	50.003E^3	3082.3	4929	304
VES5	22.59	39.9	6.4384	72.085E^3	3894.9	7329	396
VES6	23.61	38.5	7.5541	56.008E^3	5699.0	5564	560
VES7	24.53	39.8	5.9445	69.699E^3	4151.0	7417	442
VES8	23.89	39.9	7.8241	91.989E^3	4367.8	10219	485
VES9	21.96	39.8	11.1803	83.041E^3	8704.2	9056	942
VES10	20.06	39.3	12.4060	87.755E^3	4163.6	10017	458
VES11	32.11	39.1	8.9020	75.790E^3	4562.0	8688	502
VES12	15.05	39.7	6.0929	62.310E^3	3365.7	8098	437
VES13	21.88	39.8	6.5153	83.226E^3	4669.6	12387	695
VES14	20.88	39.7	7.5460	83.430E^3	3928.0	15876	747
VES15	19.99	40.0	10.1884	113.482E^3	4586.9	13435	543

[a]To compare the ^{36}Cl exposure ages presented in this paper with ages issued from different dating methods. A 4.76% uncertainty related to the spallation production rate has to be added to the internal uncertainties. Spallation production rate is 42 ± 2.0 atoms of ^{36}Cl g^{-1} of Ca a^{-1}. The samples contain between 1.8 and 6.8 × 10^6 atoms of ^{36}Cl, and between 1.14 and 4.26 × 10^{19} atoms of Cl.

downstream distance. The chi-coordinate integrates drainage area variations (with respect to a reference area A_0) over the stream distance from its base-level position x_b up to the considered channel point x:

$$\chi = \int_{x_b}^{x} \left(\frac{A_0}{A'x}\right)^{m/n} \mathrm{d}x \tag{4}$$

Within this coordinate system, an equilibrium river profile in a landscape experiencing uniform uplift and with uniform rock resistance to erosion approaches a straight line, providing that m and n are correctly determined. However, a straight line profile on a chi-plot does not necessarily mean that the river is in steady state. If this is the case, the slope of the regression line C can then be used to either infer the uplift rate or the erodibility coefficient with the following:

$$C = \left(\frac{U}{K}\right)^{1/n} {A_0}^{-m/n} \tag{5}$$

To assess equilibrium and estimate the m/n ratio of the Vésubie River profile, we use the chi-analysis tools software developed by *Mudd et al.* [2014] with a reference drainage area of 1000 m^2. We then model the evolution of the incision in the Vésubie River over a time period of 2 Ma (i.e., long enough to get close to dynamic equilibrium conditions). The model is based on the stream power law of river incision (see above) and assumes that the drainage area does not change with time. The latter is measured along the river using a digital elevation model extracted from the SRTM (Shuttle Radar Topography Mission) 90 m resolution data set. The model computes iteratively the effect of river incision and uplift: at each time step, the slope is modified depending on the uplift rate, which in turn affects the local incision rate. We test the respective effects of uplift rate and erodibility coefficient K in order to fit the observed river longitudinal profile. The location of the channel point where uplift occurs is located close to the mouth of the Var River, i.e., about 80 km downstream from the Vésubie source, which means that all the landscape above sea level is uplifted. We assume that the uplift rate does not change with time during the whole model duration. Sea level variations are approximated by periodic high level stands every ~110 ka followed by progressive sea level drops until the Last Glacial Maximum (LGM) when the Mediterranean sea level reached about 120 m below sea level [*Lambeck and Bard*, 2000]. Initial conditions consist of a concave equilibrium profile located 100 to 300 m higher than the present-day one. Our tests show that the long-term equilibrium river longitudinal profile is not sensitive to initial conditions.

We then compute an age/height relationship at the channel location corresponding to the sample site (40 km downstream of the river head) such as the following:

$$h(t) = \int_{t=0}^{^{36}\mathrm{Cl}_{\mathrm{age}}} E\mathrm{d}t \tag{6}$$

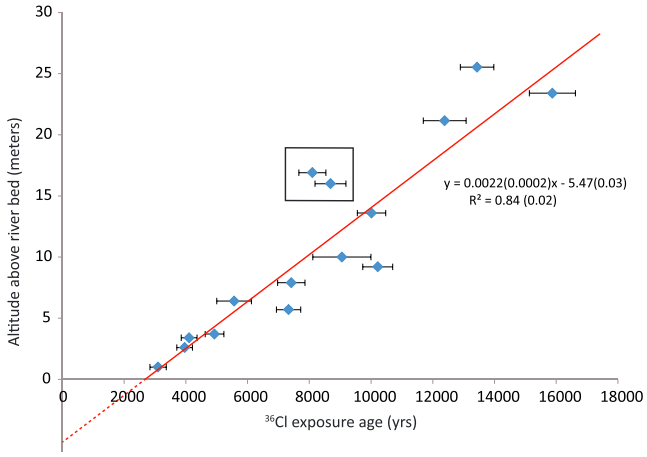

Figure 3. Altitude (relative to the river bed) and ^{36}Cl exposure ages of the 15 date samples with estimated uncertainties. Box indicates two inferred outliers (VES11 and VES12). Solid line is computed from a linear regression (excluding the two outliers) and gives a mean incision rate of 2.2 mm a^{-1}. Numbers in parenthesis correspond to estimated uncertainties on the linear regression fit.

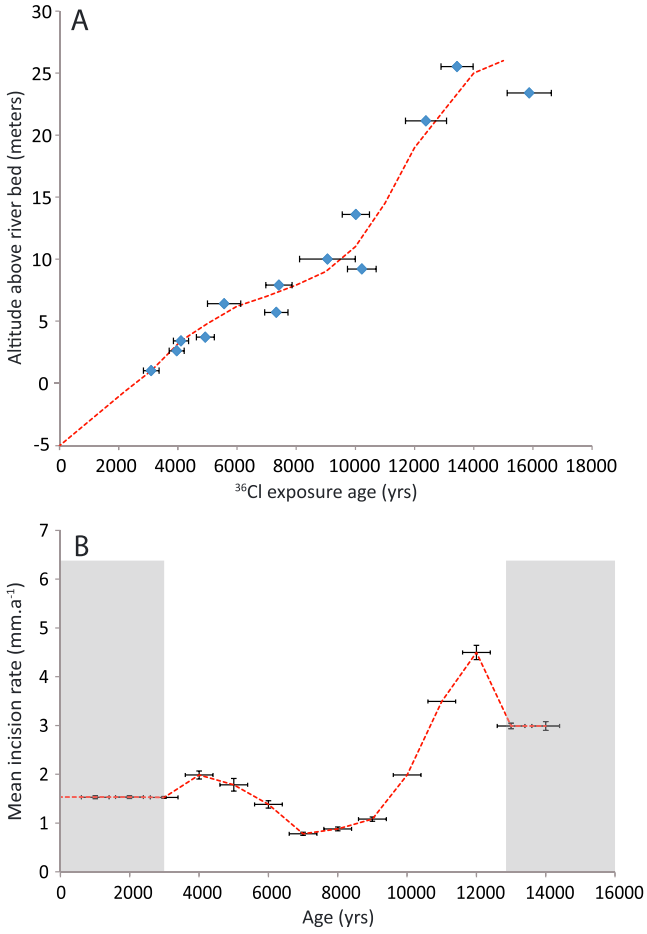

Figure 4. (a) Mean ^{36}Cl ages and (b) incision rates computed with a sliding average window of 1 ka (dashed red lines). Grey areas correspond to under-constrained incision rates due to too few data points.

where $h(t)$ is the height of a sample above the actual river bed (where $h = 0$), E is the incision rate, and t is the time since the beginning of the model. As h is only a relative altitude, we choose as a pinpoint the maximum altitude of the river cliff, i.e., 26 m for an age of circa 16 ka, extrapolated from the dated samples (section 4). We then modify the K value for the last 16 ka in order to fit the observed age/height distribution.

4. Results

4.1. Chlorine-36 Exposure Ages and Incision Rates

The ^{36}Cl exposure ages of the sampled polished surface range from 3 to 14 ka (Table 3 and Figure 3), i.e., posterior to the LGM phase (~20 ka). Although the expected increase of the sample ages with the height above the river bed is globally observed, samples VES11 and VES12 appear to be much younger than expected considering their altitude and are therefore possible outliers. A linear trend fits well the data, giving a mean incision rate of 2.2 ± 0.2 mm a^{-1} for the last 14 ka (Figure 3). The best fitting regression line (computed without the two supposed outliers) implies a y intercept roughly 5 m below the actual river bed, which is possibly due to the transient natural infill by boulders and pebbles visible in the river bed (Figure 2). In order to evaluate more precisely incision rate variations and limit the biases inherent to data noise, mean incision rates were computed from a smoothed age/height curve obtained by sliding averaging windows of 1 ka (Figure 4a). Incision rates are characterized by two peaks reaching ~2 and 4–5 mm a^{-1} at 4–5 ka and 11–12 ka, respectively (Figure 4b), separated by a period of lower incision rate (~1 mm a^{-1}).

4.2. Chi-Plot and Forward Model of River Incision

The best fit regression line in the chi-plot is found for the Vésubie River with $m/n = 0.475$ (Figure 5 (top)). In the following, we will assume that $m = 0.475$

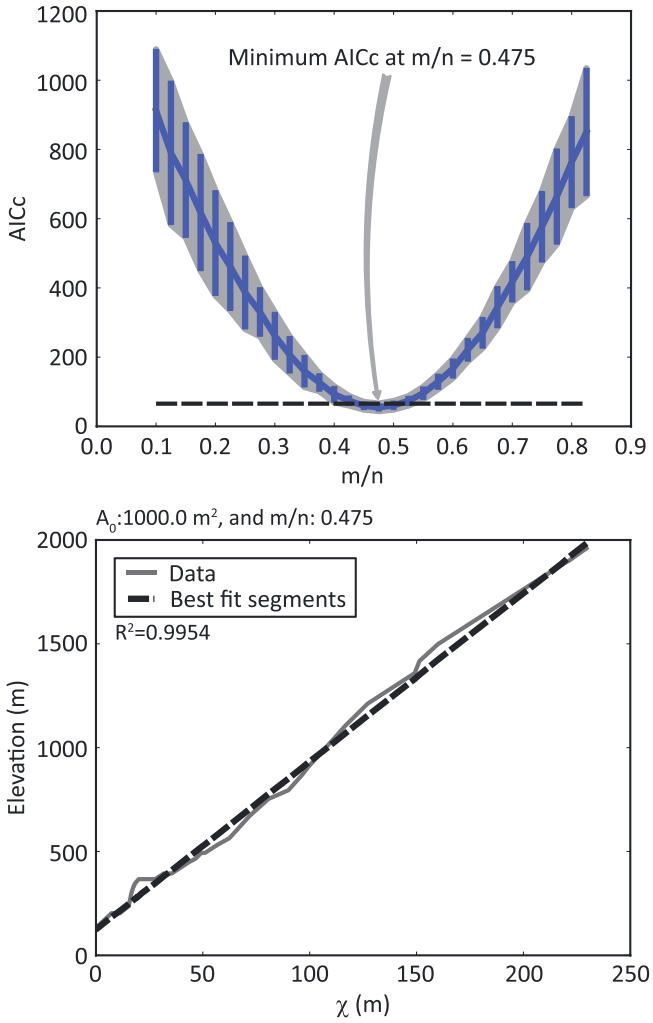

Figure 5. (top) Akaike Information Criterion [*Akaike*, 1974] calculated by the chi-analysis tool [*Mudd et al.*, 2014] to estimate the goodness of fit as a function of the concavity index (*m/n*) in the chi-plot representation of *Perron and Royden* [2013]. (bottom) Chi-plot of the Vésubie River longitudinal profile with the best fitting *m/n* value (0.475).

and $n = 1$, which is consistent with the stream power law in which the rate of incision is proportional to the rate of energy dissipation per unit bed area [e.g., *Whipple and Tucker*, 1999]. The computed R^2 value is very close to 1 ($R^2 = 0.9954$, Figure 5 (bottom)), which suggests that the river has a typical concave up longitudinal profile with a concavity index of 0.475. Although minor deviations from this profile occur, possibly due to local effects (e.g., changes in substrate) or short-term variations in boundary conditions (e.g., climate), the river longitudinal profile possibly represents a long-term equilibrium profile. A first set of models is then performed in order to test the effect of uplift rate *U* and erodibility coefficient *K* on the shape of the equilibrium river profile (Figure 6a). Based on short- and long-term uplift rate estimates published in the study area [*Serpelloni et al.*, 2013; *Sanchez et al.*, 2011; *Darnault et al.*, 2012], we test *U* values between 0.5 and 2 mm a^{-1}. We then define a best fitting *K* value that allows us to obtain a river equilibrium profile matching the observed one for these uplift rates (Figure 6a and Table 4). However, without any other constraints, it is impossible to determine *U* and *K* independently. This long-term model is then used to fix a pinpoint that corresponds to the maximum height of the river cliff slightly extrapolated from dated sample ages and heights, i.e., approximately 26 m above the river bed for an estimated age of ~16 ka. We then test if long-term *U/K* couples matching the river longitudinal profile also satisfyingly explain the observed age/height distribution of dated samples on the river cliff (Figure 6b). For all uplift rates lower than 2 mm a^{-1} (i.e., lower than the recent incision rate), the long-term *U/K* values predict incision rates that are too small for the recent period. Considering that the uplift rate should not significantly vary in the short-term, we then change the average *K* value for the last 16 ka in order to fit the observed age/height distribution. Results show that over the last 16 ka, the *K* value should be of $9 \pm 1 \times 10^{-6}$ $m^{-0.475}$ a^{-1} for every tested uplift rate, in order to fit the observations.

We then use this average *K* estimate with an arbitrary uplift rate of 1 mm a^{-1}, and take into account higher frequency variations of the *K* coefficient over the last 16 ka in order to fit more precisely the obtained ages, heights and incision rates. Short-term and high-amplitude variations of the erodibility coefficient *K* during the last 16 ka allow us to match precisely the observed ages and incision rates but do not strongly affect the general equilibrium profile of the river (Figure 7). The largest erodibility coefficient is modeled for the time period between 11 and 12 ka, where it becomes more than twice as high as the average 16 ka value (i.e., ~2×10^{-5} $m^{-0.475}$ a^{-1}).

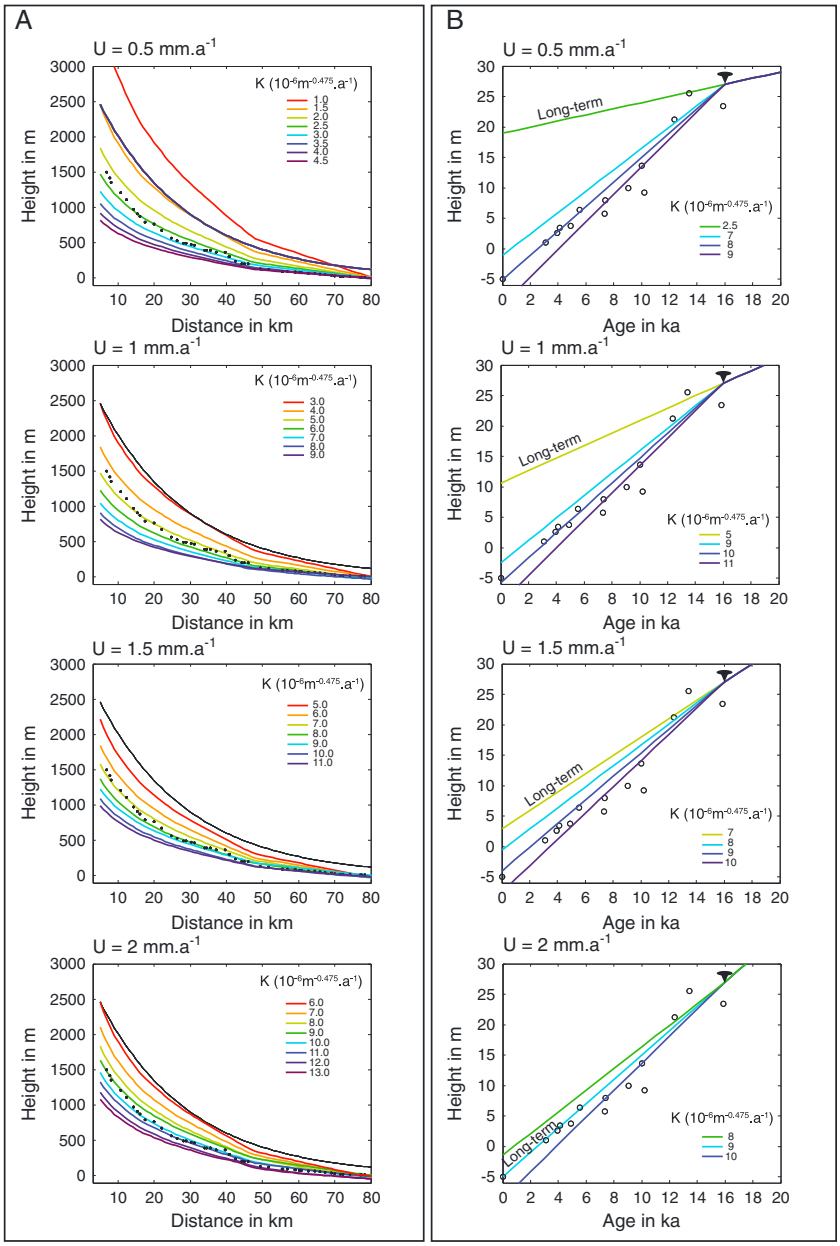

Figure 6. (a) Models of the equilibrium river profile (colored lines) with different *K* values for four different long-term uplift rates of 0.5 to 2 mm a^{-1}. Solid dots are measured altitudes along the river channel based on the SRTM digital elevation model. (b) Age/height relationships predicted at the sampling site for different long-term uplift rates and average short-term (16 ka) *K* values, including the long-term ones (best fitting curve on the corresponding Figure 6a). Open dots correspond to measured sample ages. Pinpoint at 16 ka, 26 m is indicated. Note that for every uplift rate lower than 2 mm a^{-1}, the average short-term (16 ka) *K* value is larger than the long-term one.

Table 4. Best Fitting *K* Values for Different Long-Term Uplift Rates Based on the Modeling of the River Longitudinal Profile

Uplift Rate (mm a^{-1})	*K* ($m^{-0.475}$ a^{-1})
0.5	$2.5 \times 10^{-6} \pm 0.5 \times 10^{-6}$
1.0	$5 \times 10^{-6} \pm 0.5 \times 10^{-6}$
1.5	$7 \times 10^{-6} \pm 0.5 \times 10^{-6}$
2.0	$9 \times 10^{-6} \pm 1.0 \times 10^{-6}$

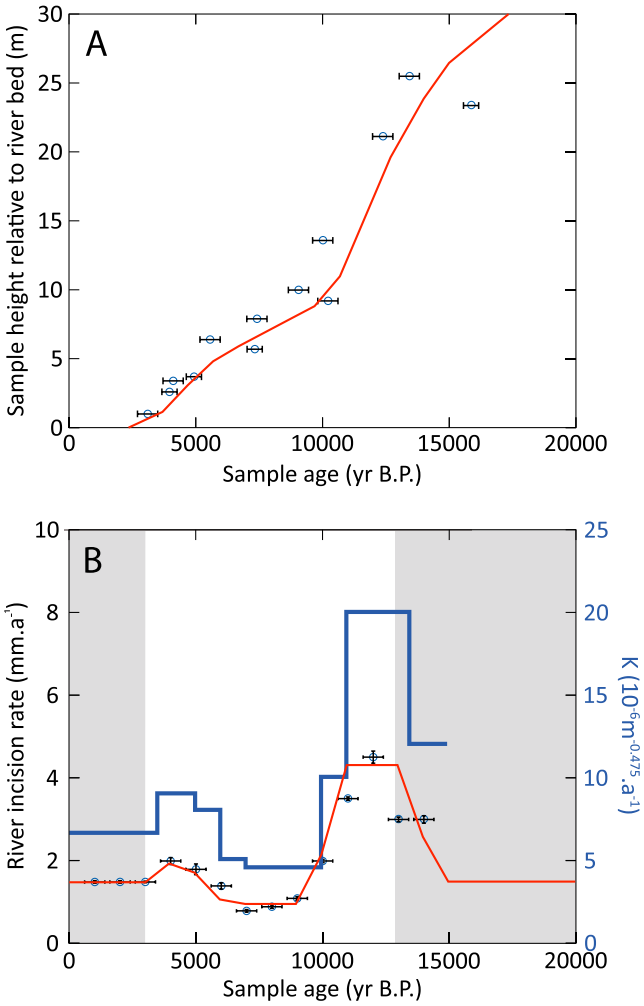

Figure 7. (a) Measured (open blue dots) and modeled (red line) height and age of the samples with short-term variations of the *K* coefficient. (b) Computed and modeled river incision rate through the last 16 ka. Thick blue line indicates the value of the *K* coefficient (scale on the right side of the plot).

5. Discussion

As a first approximation, the obtained ^{36}Cl exposure ages can be interpreted as resulting from a mean incision rate of ~2.2 mm a^{-1} over the sampled time period (14 ka), but a more precise analysis of the age/height distribution suggest that important variations can occur at shorter time scales. In any case, incision rate is due to the contribution of both climatic and tectonic (or isostatic) factors. Therefore, estimating the part of tectonic and/or isostatic uplift requires subtracting the shorter-term signals related to changes in climatic-hydrologic conditions. In the following sections, we investigate the effects of climate and of tectonic uplift in the estimated incision rates.

5.1. Impact of Glacier Retreat Climatic Fluctuations

Modeled increases in incision rates are dated at 4–5 and 11–12 ka. The oldest incision rate enhancement corresponds to the Preboreal warm period, which followed the Younger Dryas (YD) cold period. The YD corresponds to the last glacier advances in the Alps related to the major cooling event, which led to the deposition of Egesen stadial moraines [e.g., *Ivy-Ochs et al.*, 2008; *Böhlert et al.*, 2011]. Evidences of late Quaternary glaciations (i.e., stadials) are confined to altitudes higher than 1500 m in the Tinée, Vésubie, and Roya valleys. *Dubar and Poizat* [1976] recognize two different glacial stages, which they attributed to the Marine Isotopic Stages MIS-6 and MIS-2. Unfortunately, the chronology of glacier retreat and related climatic and environmental changes over the last 20,000 years, and particularly before 14 ka, is poorly constrained in alpine lakes on the French side of the massif [*De Beaulieu*, 1977; *Jorda and de Beaulieu*, 1977; *Jorda and Rosique*, 1994; *Jorda et al.*, 2000]. However, in upper valley slopes, polished surfaces have been dated by the ^{10}Be cosmogenic nuclide at 14.9 ± 0.8 ka [*Darnault et al.*, 2012], constraining the chronology of the deglaciation at these altitudes during the oldest Dryas, that is, well after the LGM period constrained by *Federici et al.* [2012] at 20 ± 1 ka. Furthermore, cosmogenic ^{10}Be dating of most glacier-polished surfaces at 11–12 ka indicates that deglaciation occurred in two stages at circa 15 and 11 ka in the Argentera-Mercantour Massif [*Darnault et al.*, 2012] and was locally correlated with an important release of glacial sediments and an increased river flow. The enhancement of the river gorge incision rate at 11–12 ka (Figure 4b) is thus correlated with the last stage of deglaciation of the Argentera-Mercantour Massif, which also coincides with the important downwasting of Egesen glaciers and a large change in hydrologic conditions [*Ivy-Ochs et al.*, 2008]. The preboreal global-scale warming event resulted in a nearly complete melting of the high-mountain ice cap in the Southern French Alps. Glacier melting and change in hydrologic conditions due to this cold-warm transition period can thus be invoked for this phase of increased incision. Moreover, a switch in sedimentation style from blue clays to organic-rich

sediment is ^{14}C dated at 11.5 ka from several lakes sequences located in the South Alps [*Jorda and de Beaulieu*, 1977; *Brisset et al.*, 2013]. The change in lake sediment lithology corresponds to the Holocene climatic optimum, which is recognized in records of alpine lake catchments by soil formation [*Ortu et al.*, 2008; *Mourier et al.*, 2010]. Thus, the development of vegetation could explain the following decrease in incision rate recorded after 11 ka in the studied Vésubie River section.

The increase in incision rates at 4 to 5 ka may also be explained by a climatic factor, corresponding to the middle-late Holocene boundary at 4.2 ka B.P. [*Walker et al.*, 2012]. This boundary corresponds to a period of increased runoff [*Walker et al.*, 2012]. However, several authors have also proposed that changes in sediment content of alpine lakes may reflect anthropic causes [e.g., *Brisset et al.*, 2013]. Agriculture and pastoralism might also have been more important, and the destruction of forests in the water catchment due to this increased land use might have contributed to a larger soil and bedrock erodibility around 4–5 ka [*Dubar and Anthony*, 1995; *Magny et al.*, 2009; *Brisset et al.*, 2013]. Holocene fluvial sequences in the French Riviera have shown that between 5 and 8 ka B.P., the hydrological regime of rivers was continuously low, whereas the 4–5 ka B.P. period is characterized by more abundant and coarser sediment discharge consistent with a larger incision rate upstream [*Dubar and Anthony*, 1995]. Finally, *Sanchez et al.* [2010] and *Zerathe et al.* [2013, 2014] have shown that several large-scale landslides were triggered in the southeastern Alps during the 3.3–5.1 ka time period. This coincidence can be regarded as a new evidence of possible intense hydrological pulses in this region during the middle-late Holocene climatic transition.

5.2. Long-Term Uplift Rate and Incision Coefficient

The age versus height distribution of sampled points can be satisfactorily reproduced with a power law model of stream incision in which the mean erodibility coefficient K for the last 16 ka is of $9 \pm 1 \times 10^{-6}$ $m^{-0.475}$ a^{-1}, whatever the uplift rate. K variations over shorter time scales are also constrained independently of the uplift rate. This suggests that measured incision rates are dominated by a climatic signal rather than by the effect of tectonic uplift, at least for the recent period (14–15 ka). By comparing long-term (2 Ma) U/K couples that fit the river longitudinal profiles and the short-term (16 ka) K values that reproduce the measured age/height distribution of samples, two interpretations arise: if the long-term uplift rate was significantly lower than the short-term incision rate (i.e., lower than 2.2 mm a^{-1}), then the K coefficient should have increased during the recent period, due to enhanced water runoff for instance. On the other hand, if one considers that the long-term K coefficient has not changed during the last 2 Ma, then the long-term uplift rate should be equal to the short-term incision rate (i.e., 2.2 mm a^{-1}).

Long-term uplift estimates derived from thermochronology [*Sanchez et al.*, 2011] are of about 0.8–1 mm a^{-1} since 22 Ma in the Argentera-Mercantour massif. Uplift rates of 1–2 mm a^{-1} have also been obtained by GPS measurements in the higher parts of Alps, although no data point exists close to our study area [*Serpelloni et al.*, 2013]. *Vernant et al.* [2013] proposed that these rapid uplift rates are due to an isostatic readjustment in response to a recent increase in denudation rates. A similar interpretation from Apatite Fission Tracks / Helium ages is proposed by *Valla et al.* [2011] and *Cederbom et al.* [2011], who documented increased denudation rates since 1 Ma in the Central Alps and 5 Ma at the alpine scale, respectively. In the External Crystalline Massifs, the long-term exhumation rate is of the same order (1 mm a^{-1}) over a period between 15 and 22 Ma [e.g., *Rolland et al.*, 2008; *Sanchez et al.*, 2011]. Hence, independent data suggest that the long-term uplift rate should be about twice as low as the mean 14 ka incision rate obtained by ^{36}Cl dating. This in turn suggests that the average K coefficient has increased during this recent period compared to the longer term (2 Ma) rate. The valley-perpendicular topographic profile has a typical wineglass shape (Figure 2) with a steep inner gorge underlying more gentle hillslopes, which is in agreement with this hypothesis.

In any cases, our models consistently predict satisfying river longitudinal profiles for a constant rock uplift rate, which thus represents the net uplift rate of the onshore continental margin with respect to its offshore oceanic (or thinned continental) counterpart, since sea level variations are taken into account. This result is in agreement with previously published evidences for active uplifting of the North Ligurian margin east of the Var River valley as evidenced by anomalously convex submarine canyons longitudinal profiles [*Migeon et al.*, 2011] and by the tilting and offset of the Messinian erosion surface on the offshore thinned margin [*Bigot-Cormier et al.*, 2004]. Both studies propose that an active reverse fault system located at the foot of the thinned continental margin is responsible for the observed deformations. Comparison with GPS data suggest

that this uplift is at least partly related to the ongoing Africa-Eurasia plate convergence responsible for moderate compressional strain in this area [*Calais et al.*, 2000]. Whatever the long-term rock uplift rate, our study provides evidences of rapid incision of the Mesozoic sedimentary cover of the Vésubie catchment area at a rate of 2.2 mm a^{-1} during the late Pleistocene to Holocene period.

6. Conclusion

Quantification of river incision rate using in the situ-produced ^{36}Cl cosmogenic nuclide was successfully performed in a carbonate river gorge dug by the Vésubie River, in the Southern French Alps. The processed samples allows us to decipher incision rate variations with a resolution of about 1 ka during the last 14 ka, and give a mean incision rate for the considered time period of 2.2 mm a^{-1}. Modeling of the evolution of the incision in the Vésubie River over 2 Ma based on the stream power law shows that an equilibrium profile compatible with observations can be reached with any long-term uplift rates of 0.5 to 2 mm a^{-1}, and K coefficients of 2.5 to 9×10^{-6} $m^{-0.475}$ a^{-1}. However, matching the average age/height distribution of the samples for the last 14 ka requires a significant increase in the K coefficient (up to $9 \pm 1 \times 10^{-6}$ $m^{-0.475}$ a^{-1}) if the considered long-term uplift rate is significantly lower than the average incision rate of 2.2 mm a^{-1}. This is in agreement with the wineglass shape of the valley at this place, suggesting slower incision and perhaps more active hillslope processes prior to 14 ka, followed by enhanced vertical incision. Moreover, the age/height distribution of samples highlights two periods of rapid incision: (i) one at ~11–12 ka and (ii) one at ~4–5 ka. These periods coincide with changes in climatic conditions characterized by more abundant rainfall and increased runoff.

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