Accepted Manuscript published at Elements Vol. 17, pp. 41–46
(DOI: 10.2138/gselements.17.1.41)

How climate, uplift and erosion shape the Alpine topography

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ABSTRACT

Decades of scientific research across the European Alps quantify the vast array of processes shaping the Earth's surface. Developments in thermochronometry and terrestrial cosmogenic nuclides constrain spatial patterns of rock exhumation, surface erosion and topographic changes. These can be compared to sediments eroded from the Alps and preserved in surrounding sedimentary basins or collected from modern rivers. Erosion-driven isostatic uplift explains up to around 50% of the modern geodetic rock-uplift rates, revealing the importance of internal (tectonics, deep-seated geodynamics) and external (glacial rebound and topographic changes) processes. We highlight recent methodological and conceptual developments that have contributed to our present view of the European Alps, and suggest steps needed to fill gaps in our understanding.

KEYWORDS

Mountain geodynamics, erosion & sediment yield, topographic evolution, climate and glaciations, geodetic uplift, modeling, geochronology

INTRODUCTION

Mountain topography lies at the interface between the Lithosphere and the Hydrosphere/Biosphere, and its long-term evolution results from the interplay between internal and external driving mechanisms (Fig. 1A, e.g. Whipple, 2009). Internal forcing involves crustal thickening from tectonic shortening and deeper processes such as lithospheric delamination or sub-lithospheric mantle flow. External forcing is mainly characterized by climate, whose variability controls erosion and the building-melting of ice caps and glaciers, as well as the biota evolution and base-level changes, which all operate to redistribute material across the Earth's surface. Key components of this system are surface processes (Fig. 1A) which are central in regulating the interactions between internal and external drivers (Champagnac et al., 2014). Surface processes act in space and time directly on the Lithosphere (e.g. mass redistribution affecting the crustal stress field and thermal structure) and the Hydrosphere/Biosphere (e.g. erosion modulating rock weathering and carbon burial). They shape mountain topography and relief, with indirect feedbacks on tectonics (topographic effects on the lithospheric stress and thermal state) and climate (orographic precipitation and large-scale atmospheric circulation controlled by mountain topography). A quantitative characterization of the mechanisms that control mountain topographic evolution is challenging, since they are intrinsically linked but also operate at different spatial and temporal scales (10^1-10^6 meters or years), with thresholds and non-linear processes involved (Champagnac et al., 2014).

The European Alps are a classic example of a mid-latitude convergent mountain belt, extending over 1000 km (Fig. 1B) and forming an arc-shape which can be divided into three main sectors: Western, Central and Eastern Alps (Schmid et al., 2004). The Alpine orogeny is the result of continent-continent collision between the European and Adriatic plates since the Late Eocene. The main topographic construction and rock exhumation, i.e. unroofing history or a rock's path towards Earth's surface, began at ca. 35 Ma or earlier mostly driven by crustal thickening (Kuhlemann et al., 2002; Schmid et al., 2004). The main drainage organization and major drainage divide between Alpine sectors (Fig. 1B) were established relatively early in the orogeny, following the main tectonic structures (Figs. 1B), and are strongly influenced by the Early-Oligocene to Early-Miocene exhumation of crystalline massifs. The overall Alpine topography reached high elevations during the early collisional stages, with Early-Oligocene elevations similar to present-day in the Western Alps (as revealed by palynology; Fauquette et al., 2015), and the high topography of the Central Alps was acquired during mid-Miocene times (from stable-isotope paleoaltimetry; Campani et al., 2012). It has been suggested that the topography of the Eastern Alps developed during Late Oligocene (Kuhlemann et al., 2002), but this has not yet been confirmed quantitatively. As a mid-latitude mountain range, and given their spatial extent, the European Alps are characterized by a variety of climatic regimes, with high spatial variability in precipitation and temperature. This climatic setting leads to various geomorphic processes (fluvial, hillslope, glacial) which control erosion (i.e. surface mass removal by both mechanical and chemical processes), sediment export to forelands or intramountain deposition. During the Late Cenozoic, global climate evolved towards cooler conditions and increased variability (Zachos et al., 2001). The onset of glaciation since ca. 3 Ma for the Northern Hemisphere also impacted the European Alps, with extensive glacier coverage during glacial periods (Fig. 1B; Ehlers and Gibbard, 2004). Cyclic glacial/interglacial conditions and associated transient geomorphic responses have shaped the modern Alpine topography and relief. Today, tectonic horizontal shortening from plate convergence appears only active in the Eastern Alps, while the Western and Central Alps are subject to limited shortening and even extension in some areas (Serpelloni et al., 2016). However, geodetic measurements (GPS, leveling) show that modern rock-uplift rates (i.e. vertical surface rock velocity, relative to a reference base level) are faster in the Western and Central Alps than in the Eastern Alps (Sternai et al., 2019).

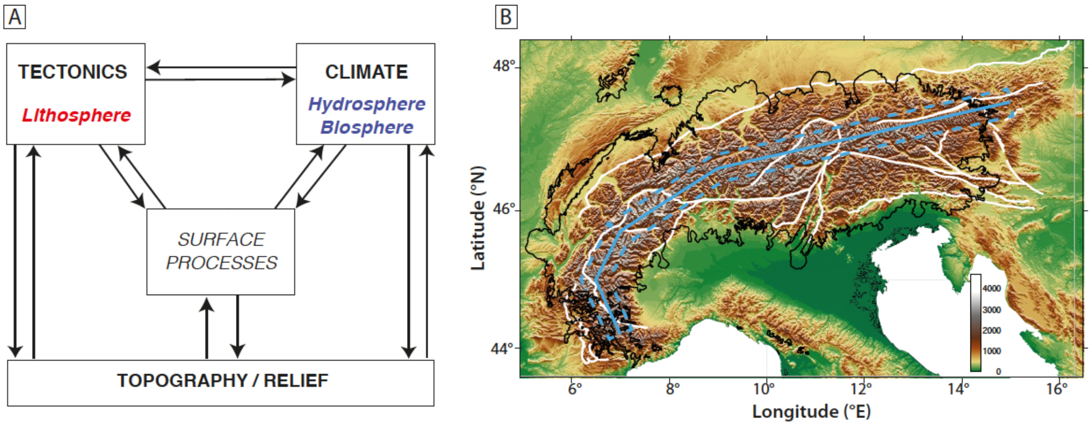

Figure 1. Alpine Topography & Relief. (A) Sketch of the interplays and feedbacks between tectonics, climate and topography/relief in mountain evolution. This complex system involves interactions between the Lithosphere and the Hydrosphere and Biosphere, with surface processes regulating the interactions (details on these are presented in the original figure of Champagnac et al., 2014). (B) Modern topography of the European Alps (90-m resolution DEM) with Last Glacial Maximum (LGM) ice extent (white lines; Ehlers and Gibbard, 2004), major Alpine tectonic lineaments (Schmid et al., 2004) and swath profile (thick and dashed blue lines).

Here, we review some key pieces of evidence constraining the topographic evolution of the European Alps. We present how methodological developments, especially regarding topographic, geochronologic and modeling methods, have quantified long-term erosion and relief development. Such a quantitative framework is needed to assess the relative contributions of internal and external forcing in the evolution of the European Alps, and to diagnose the potential drivers for modern rock-uplift patterns observed along the Alpine arc.

OLIGOCENE-MIOCENE EVOLUTION OF THE ALPS

The main Alpine collisional phase started at ca. 35 Ma, with the rapid development of mountainous topography, major drainage reorganization (Lu et al., 2018), and onset of sediment production on both the pro- (northern) and retro- (southern) sides of the orogen (Kuhlemann et al., 2002; Fox et al., 2016). Sedimentary basins surrounding the European Alps offer a crucial archive to reconstruct the evolution of sediment yield during mountain building. The main challenges when using sediment records as proxies for long-term erosion history are (1) sediment preservation and possible re-mobilization after deposition or the recycling of sedimentary rocks during orogenesis, (2) changes in the river drainage patterns (i.e. inferred link between sediment deposits and original relief sources), and (3) chemical erosion and the importance of dissolved load in the total erosion budget. Figure 2A presents a compilation of erosion products for the European Alps (Kuhlemann et al., 2002), showing two main periods in the sediment yield history (35-15 Ma and 15-0 Ma, Fig. 2A). There is a significant increase in sediment yield between ca. 30 and 25 Ma, reflecting topographic building and relief development allowing the onset of active geomorphic processes and efficient sediment production. Between 25 and 15 Ma, sediment yields remained high and have been punctuated by short pulses which are proposed to reflect changes in tectonic forcing and movements of the drainage divide (Kuhlemann et al., 2002). The mobility of the drainage divide is also evidenced by antagonistic trends in sediment discharge between the Northern and Southern Alps. This 25-15 Ma period is considered the main tectonic constructional phase of the European Alps (especially for the Eastern Alps). The 15-5 Ma phase is characterized by a significant decrease in sediment yield just before 15 Ma for both the Western/Central and Eastern Alps, followed by steady sediment flux for the Western and Central Alps. For the Eastern

Alps, a minor increasing trend can be observed during the mid-Miocene. Finally, the most striking observation from Kuhlemann et al. (2002) is the significant increasing trend beginning at ca. 5 Ma (Miocene/Pliocene transition, Fig. 2A), observed for the entire European Alps but apparently more important for the Western and Central Alps.

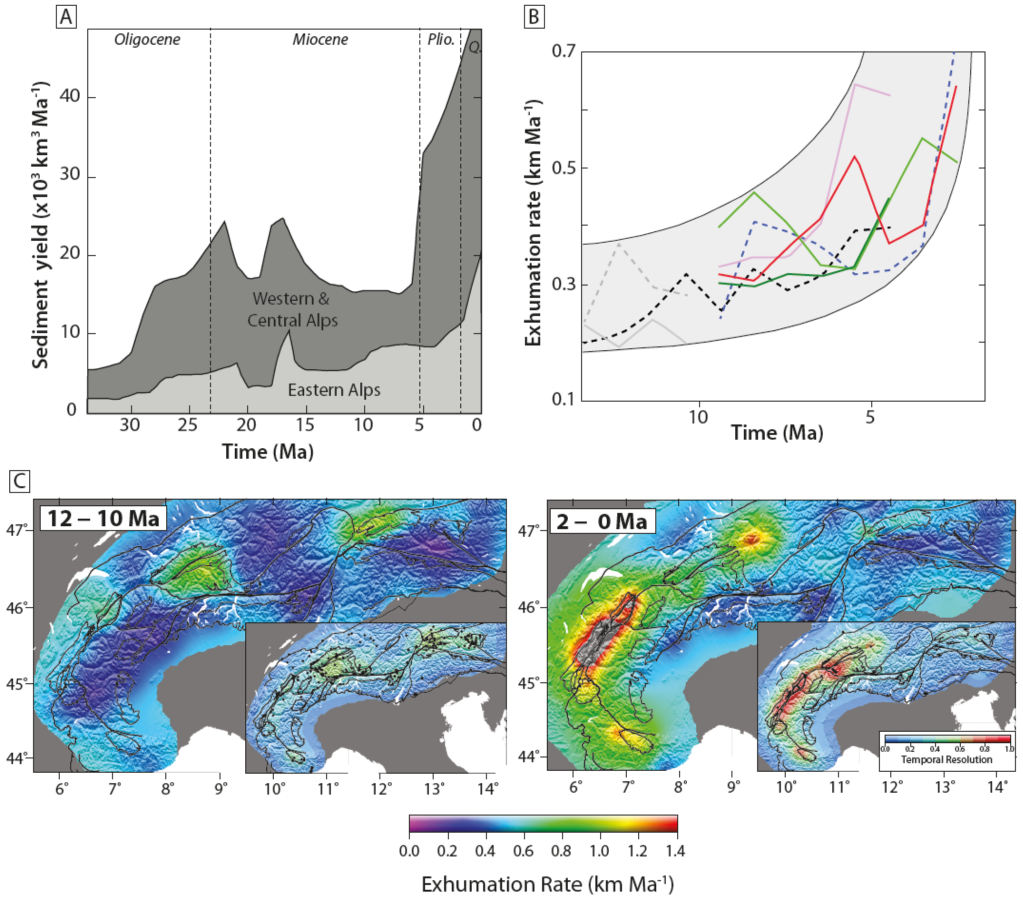

Figure 2. Erosion & Sediment Fluxes. (A) Late-Cenozoic sediment budgets for the Eastern and Western/Central (including Southern) Alps, after Kuhlemann et al. (2002). (B) Exhumation of Western (thick colored lines) and Central (dashed colored lines) Alps, extracted from geometric reconstruction of bedrock thermochronometric isoages (Vernon et al., 2008). Note the overall increase trend (grey envelope) in exhumation since ca. 5 Ma, similar to sediment yield trends shown in (A). (C) Spatial distribution of Alpine exhumation from linear inversion of thermochronomotric data. 12-10 Ma (left) and 2-0 Ma (right) time windows are presented for illustration of the temporal variability (insets show temporal resolution for each time window). Black lines indicate main Alpine massifs and tectonic lineaments (Schmid et al., 2004). Based on Fox et al. (2016).

Sediment yield records indicate that Alpine orogeny has experienced major changes in topographic and erosion histories. However, given the large-scale spatial integration of sediment records, assessing the spatio-temporal patterns in erosion at massif scale has remained challenging. Thermochronometry records the time since a rock passed through an effective closure temperature, and can provide a direct quantification of rock exhumation towards Earth's surface driven by erosion and tectonic unroofing. In addition, the thermal field of the upper crust is also sensitive to rock uplift and surface topography (i.e. amplitude and wavelength). Low-temperature thermochronometry (apatite and zircon thermochronometers, i.e. with closure temperatures <250 °C) can be used to quantify rock exhumation, at a timescale provided by the respective rock cooling ages. Detrital thermochronometry, from modern river sediments or past sediment records, provides an integrated overview of Alpine long-term erosion. Despite fragmentary records for the early construction stages, detrital thermochronometry confirms erosion pulses during the Oligocene but suggests an overall steady erosion over the European Alps since ca. 15 Ma at rates of 0.1-0.4 km Ma^{-1} (Bernet et al., 2001). Within this apparent steady setting, detrital thermochronometry has also revealed major changes in sediment provenance that reflect re-organization of river drainage patterns for the Eastern Alps (around 20 Ma) and Western/Central Alps (around 13-10 Ma), in agreement with sediment records (Kuhlemann et al., 2002).

Bedrock thermochronometry provides direct quantification of erosion and topographic history. Since the 1970's, over 3000 bedrock cooling ages (including multi-thermochronometers) have been acquired across the Alps, providing dense datasets for extracting exhumation patterns in space and time (Vernon et al., 2008; Fox et al., 2016). Bedrock thermochronometry suggests early onset of erosion in the Eastern Alps (Tauern window and Austroalpine units) and Southern Alps (Bergell and Adamello massifs), with Early- to mid-Miocene erosion pulses linked to tectonic shortening and crustal thickening, followed by overall moderate erosion magnitudes since the mid-Miocene. A Late-Miocene erosion increase has also been documented for the Southern Alps, while this has not been observed with bedrock thermochronometry in the Eastern Alps. In the Western and Central Alps, thermochronometric data highlight exhumation contrasts, with mid-Miocene erosion onset linked to the exhumation of the External Crystalline Massifs (Aar-Gotthard, Mont-Blanc, Belledonne-Pelvoux; Schmid et al., 2004) and within more internal parts of the orogen (Lepontine Dome), followed by an apparent major increase in erosion during the Late Miocene (Fig. 2B). This ca. 5-Ma erosion signal, similar to the sediment record (Fig. 2A), has raised long-lasting discussions about the potential contributions of tectonics *vs.* climate in late-stage erosion dynamics of the European Alps. For the Western and Central Alps, both hypotheses have been postulated with an orogen response to (1) a climate shift at the Miocene-Pliocene transition, with enhanced climatic variability and possibly increased precipitation favoring efficient geomorphic processes and sediment production/export (e.g. Vernon et al., 2008), (2) deep-seated geodynamic processes such as lithospheric slab detachment (e.g. Fox et al., 2015). For the Eastern Alps, limited post-Miocene rock uplift and erosion has been documented, although not recorded by thermochronometry, and related to changes in regional tectonics (i.e. inversion of Pannonian Basin; e.g. Ruszkiczay-Rüdiger et al., 2020 and references therein).

Recent numerical developments in thermal(-kinematic) models and inversion approaches (e.g. Fox et al., 2016; Fig. 2C) have allowed researchers to include multi-thermochronometers for assessing bedrock erosion histories. For the Western and Central Alps, these methods have revealed a more complex erosion framework. There is evidence for mid-Miocene onset of high erosion rates (Fig. 2C) with tectonic uplift from crustal thickening, but also for a subsequent decrease in erosion towards the Late Miocene-Early Pliocene. Temporal erosion trends from bedrock thermochronometry (Fig. 2C) and sediment yield records (Fig. 2A) slightly differ for the Late Miocene. The progressive exhumation and exposure of crystalline and highly-resistant rocks at this time could have caused an overall decrease in bedrock erosion (lower erodibility) while increasing the relative abundance of crystalline clasts (better preservation) in the sediment record. Finally, inversion of bedrock thermochronometry reveals a major increase in erosion since ca. 2 Ma (Fig. 2C) for the Western/Central Alps, although the resolution of both current thermochronometric data and imaging of the Earth's interior via inversion of seismic data cannot be used to distinguish between either tectonics *or* climate forcing, nor to recognize feedbacks triggering this erosion increase (Fox et al., 2015).

ALPINE TOPOGRAPHY & PLIOCENE-QUATERNARY GLACIATION

Alpine landscapes present typical glacial landforms with glacial cirques, U-shaped wide, steep and deep valleys (Fig. 1B), but also "hidden" landscape features such as overdeepnings which form major lakes and sediment infills in the present-day topography. Although the Quaternary geomorphic imprint of glacial erosion is obvious, key questions remain regarding its timing, magnitude and spatial variability. Is landscape transition from fluvial to glacial landforms a rapid process that occured during the early glaciations? How variable are spatial patterns and rates in glacial erosion between different glacial periods? Are fluvial features (such as inner gorges and hanging valleys) markers of post-glacial landscape re-adjustment or do they evolve through multiple glacial/interglacial cycles? Numerical outcomes suggest that glacial erosion in the Western/Central Alps has propagated from low to high elevations during the successive glacial periods, as the landscape evolved from fluvial to glacial conditions (Sternai et al., 2013). However, quantifying via observations the impact of Plio-Quaternary glaciation on Alpine erosion and topography has remained difficult due to (1) the relatively short timescales involved (1-2 Ma for the Quaternary and 10-100 ka for individual glacial/interglacial cycles) compared to the current resolution of thermochronometric methods, and (2) the preservation of, and/or access to, continuous sedimentary records or geomorphic markers for individual glaciations. For the European Alps, the onset of major glaciation follows the Northern Hemisphere glaciation (ca. 3 Ma), with a major environmental and stratigraphic change reported at ca. 0.9 Ma (e.g. Muttoni et al., 2003). Previous Plio-Quaternary glacial phases would have been of limited extent, leaving only scarce sediment records in the internal parts of the Alpine massifs. The mid-Pleistocene transition (MPT, ca. 1.2 Ma) promoted global climate change with the switch from low-amplitude short (symmetric 40-ka) to high-amplitude long (asymmetric 100-ka) glacial/interglacial cycles. For the European Alps, this MPT change would have resulted in the development of extensive and long-lasting glaciers that reached the Alpine forelands (Muttoni et al., 2003).

In the Western/Central Alps, there is quantitative evidence for the impact of glaciation on Alpine topography (Fig. 3A). In the Swiss Central Alps, Haeuselmann et al. (2007) have used cosmogenic ^{26}Al/^{10}Be dating of buried cave sediments to quantify the Aare valley deepening with respect to the cave system. Dating results show two valley deepening periods over the Plio-Quaternary, with limited deepening (at ~0.1 km Ma^{-1}) until ca. 0.9 Ma followed by abrupt valley deepening (at >1 km Ma^{-1}). In the upper Rhône valley (Swiss Western Alps), Valla et al. (2011) used apatite ^{4}He/^{3}He thermochronometry to quantify the late-stage bedrock cooling along the valley flank.

Using geothermal constraints and thermal-kinematic modeling, their results highlight a quiescent erosion phase during Plio-Quaternary followed by subsequent valley incision (i.e. topographic change by spatially-focused erosion) at 1 km Ma^{-1} since ca. 1 Ma (Fig. 3A). These outcomes not only point towards a major erosional shift since around 1 Ma for the Western/Central Alps, but also reveal a topographic change with significant relief increase that is interpreted as glacial valley deepening. Such a topographic response to glaciation has not been observed or with limited magnitude for the Eastern and Southern Alps, despite similar glacial landforms with deep and wide U-shaped valleys (Sternai et al., 2012). Pre-glacial topographic reconstructions have been attempted using different methods, such as the geophysical relief approach (Champagnac et al., 2014) or by computing a steady-state fluvial topography (Sternai et al., 2012) with subsequent modifications by glacial processes. Although these models rely on a number of untestable (but plausible) assumptions (e.g. constant drainage network throughout the Quaternary), they provide useful first-order estimates for evaluating glacial topographic changes in the European Alps (Fig. 3B) and the associated isostatic response to non-steady erosional unloading (Fig. 5). Moreover, these results raise new contradictory observations and questions: topographic changes appear similar to slightly more pronounced for the Eastern Alps (Fig. 3B) than in the Western and Central Alps, whereas bedrock thermochronometry suggests significantly different trends for long-term erosion (Figs. 2C and 3B). Such observations cannot be explained by horizontal shortening, which has been limited in the Western/Central Alps and is ongoing in the Eastern Alps. One alternative mechanism could be the occurrence of deep geodynamic forcing (e.g. sub-lithospheric mantle flow) sustaining relatively high steady erosion in the Western and Central Alps compared to the Eastern Alps (Fox et al., 2015; Sternai et al., 2019). The observed differences (Fig. 3B) between Plio-Quaternary erosion estimates and Quaternary topographic changes would call for further research to quantify the respective contributions from “steady” (i.e. driven by rock uplift) erosion and “non-steady” topographic evolution of the European Alps.

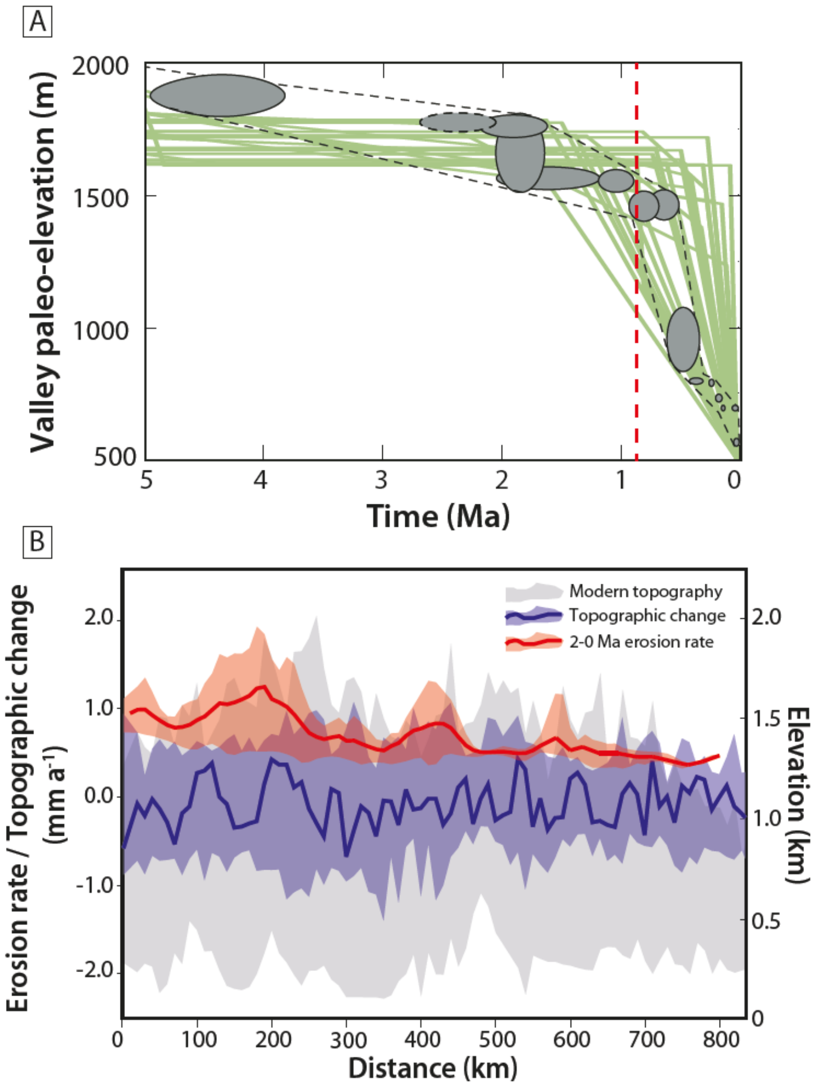

Figure 3. Plio-Quaternary Erosion & Relief Development. (A) Paleo-elevation (proxy for valley incision) of the Aare (dating of cave sediments, grey ellipses and black dashed lines; Haeuselmann et al., 2007) and Rhône (bedrock low-temperature thermochronometry, converted into valley floor paleo-elevations using thermal-kinematic modeling, green lines; Valla et al., 2011) valleys. Red dashed line indicates onset of major Alpine glaciation from stratigraphic evidence (Po River Basin; Muttoni et al., 2003). (B) Swath (see Fig. 1B for location) profiles of modern topography (Fig. 1B, grey envelope), 2-0 Ma erosion rate (Fig. 2C, red line and envelope) and topographic change over the last 1 Ma (Sternai et al., 2012; blue line and envelope).

MODERN ROCK UPLIFT AND EROSION: CAUSES AND IMPLICATIONS

The modern European Alps are characterized by limited shortening in the Western and Central Alps, and by ongoing active shortening in the Eastern Alps. In contrast, geodetic (leveling, GPS/GNSS) rock-uplift rates, averaged over the last 10 to 100 years, are highest in the Western and Central Alps (up to around 2 mm a^{-1}, Fig. 5; Nocquet et al., 2016; Sternai et al., 2019). What is driving the observed spatial patterns of rock uplift in the European Alps? Erosion rates have been invoked to explain these rock-uplift patterns, but their spatial and temporal quantification is required to recognize whether the European Alps are actually experiencing or not surface uplift.

Modern erosion for the European Alps has been estimated using sediment yield (river and reservoir gauges; Hinderer et al., 2013) and cosmogenic ^{10}Be (riverine sediments, Delunel et al., 2020) for the main drainage basins across the Alps. Modern sediment yield data cover the last decades and combine physical and chemical erosion. The spatial distribution of modern Alpine erosion shows a ~3 fold difference in erosion between the Western/Central Alps and the Eastern Alps, which is interpreted as reflecting enhanced chemical erosion of carbonate sedimentary rocks that are abundant in the external mountainous parts of the Western/Central Alps (Hinderer et al., 2013). Cosmogenic ^{10}Be-derived erosion yields millennial integration timescales and presents similar patterns, with higher erosion in the Western/Central Alps (~2-3 fold difference, Fig. 4) compared to the Eastern Alps. Moreover, both erosion datasets show no evidence for a modern climatic control (i.e. present-day precipitation patterns) on the spatial erosion distribution, but they rather reveal a significant slope/relief control on erosion which reflects intense glacial pre-conditioning of the Alpine topography as well as ongoing glacier retreat (Hinderer et al., 2013; Delunel et al., 2020). Millennial to modern erosion patterns indeed follow an expected geomorphic response since the last glacial maximum (ca. 20 ka ago), characterized by high post-glacial erosion rates and transient hillslope and fluvial topographic re-adjustment. It remains debated how long landscapes take to switch from glacial to fluvial conditions, and this response may take multiple interglacial periods (e.g. Montgomery and Korup, 2010; Leith et al., 2018).

Both modern geodetic rock-uplift rates and erosion-rate patterns (derived from sediment yield and cosmogenic ^{10}Be) present a similar increasing trend from the Western to Central Alps followed by a decrease towards the Eastern Alps, suggesting the existence of a functional relationship, with the proposed hypothesis of erosion-driven rock uplift for the European Alps (Champagnac et al., 2009). However, while patterns do correlate, modern erosion rates are generally lower than modern rock-uplift rates (Fig. 4), implying that the isostatic response to erosional mass removal cannot explain all the observed rock-uplift rates. This discrepancy may result from the different spatial and temporal scales covered by erosion and rock-uplift datasets, which can be problematic when extrapolating yearly to decadal sediment yield, climatic data and geodetic rock-uplift estimates to thousand-year timescales which are representative of cosmogenic ^{10}Be-derived erosion rates. An alternative explanation for the observed discrepancy between modern rock-uplift and erosion patterns, if any relationship between them should exist, could be that modern rock uplift integrates different external or internal contributions along the European Alps (Sternai et al., 2019). In Figure 5, we evaluate the spatial patterns of both the modern geodetic uplift and the respective contributions of external (i.e. deglaciation rebound and erosion-induced elastic adjustment) and internal (dynamic uplift from mantle flow) forcing mechanisms. These estimates are based on various assumptions, such as the sub-lithospheric mantle viscosity and lateral/depth variations, the timing and spatial variability in deglaciation or the importance of topographic change *vs.* steady background erosion for erosional unloading across the European Alps (see extended discussion in Sternai et al., 2019). For the Eastern Alps, the combination of erosional response and deglaciation rebound (external forcing) matches the geodetically-measured uplift, suggesting isostatic adjustment could be the only mechanism for uplift in this region. However, this scenario is unlikely since (1) the Eastern Alps are still experiencing shortening and associated tectonic uplift, as also suggested by local examples of inversion tectonics since ca. 3 Ma (e.g. Ruszkiczay-Rüdiger et al., 2020); in addition, (2) mantle upwelling below and sediment loading within the Pannonian Basin are likely to involve, respectively, dynamic uplift and subsidence in the Eastern Alps (Fig. 5). Modern limited rock uplift in the Eastern Alps thus appears to us as the result of a combination of opposing forcings. For the Western and Central Alps, the isostatic response to deglaciation and erosional unloading contributes up to around 50% of the observed geodetic rock uplift (Fig. 5). Given the limited tectonic shortening occurring in these regions, deeper mechanisms involving lithospheric and sub-lithospheric mantle flow (and related dynamic uplift) must be at play. Convective processes from lithospheric slab detachment below the Western Alps are particularly debated (Lippitsch et al., 2003; Zhao et al., 2016), since the occurrence, timing and spatial extent of such event(s) are still poorly constrained. For the Central Alps, the sub-lithospheric mantle flow contribution to rock uplift appears significant (Fig. 5), and can explain the high observed rock-uplift rates (up to 2 mm a^{-1}) when combined with the isostatic adjustments to external forcing.

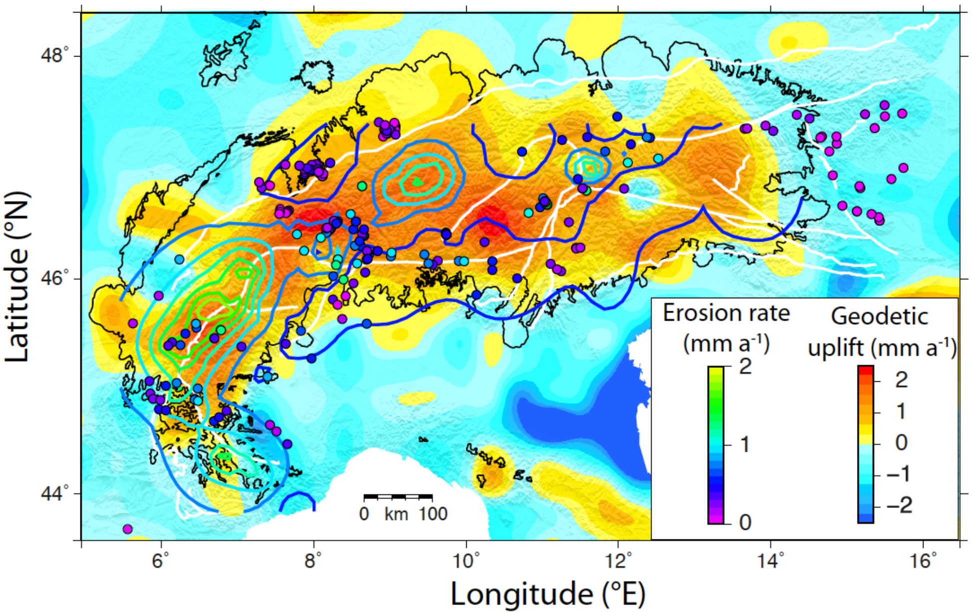

Figure 4. Modern Rock Uplift & Erosion. Spatial distribution (30-km resolution) of modern geodetic rock uplift (Sternai et al., 2019) over decadal timescales. Colored circles are catchment outlets for cosmogenic ^{10}Be-derived erosion estimates over millennial timescales (Delunel et al., 2020). Colored lines are 2-0 Ma erosion estimates from linear inversion of thermochronometric data (Fox et al., 2016). Black and white lines are LGM ice extent and major Alpine tectonic lineaments, respectively.

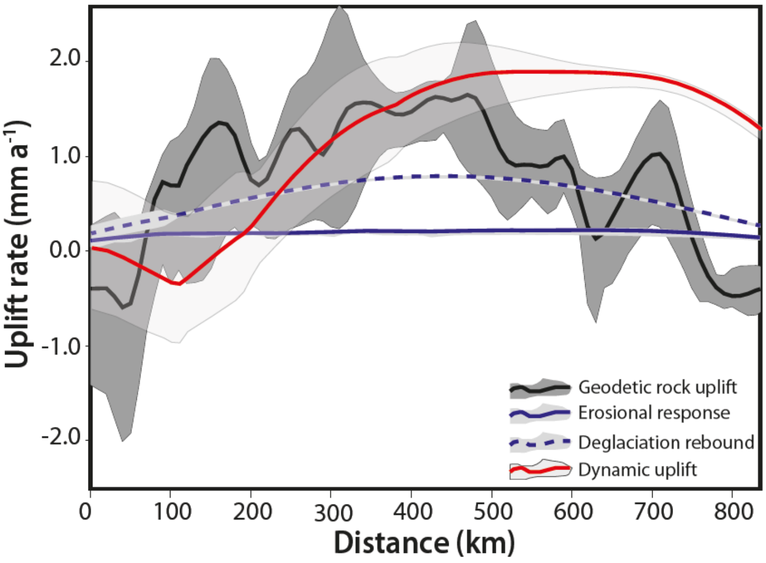

Figure 5. Modern Geodetic Uplift & Potential Uplift Contributions. Swath (see Fig. 1B for location) profiles of modern geodetic rock uplift (Fig. 4, black line and dark-grey envelope),

external (erosional adjustment from topographic changes and deglaciation rebound, blue plain and dashed lines respectively with grey envelopes; Sternai et al., 2012; Spada et al., 2009) and internal (dynamic uplift, red line and light-grey envelope; Zhao et al., 2016) forcing mechanisms. The different contributions are sourced from Sternai et al. (2019).

SUMMARY & OUTLOOK

Our review of Late-Cenozoic evolution of the European Alps is based on different methodologies, ranging from sediment yield analyses (modern and past records), geochronology (mainly low-temperature thermochronometry and terrestrial cosmogenic nuclides) and geodesy or geophysics combined with numerical modeling. This method diversity allows us to assess the different spatial and temporal scales involved with Alpine erosion and topographic evolution. The existing data show a complex spatio-temporal evolution of the European Alps, with onset of topographic construction in the Early Oligocene, and significant tectonic controls on erosion and topographic building via crustal thickening and drainage pattern changes until the mid-Miocene. Plio-Quaternary erosion and topographic evolution appear to be controlled by climatically-driven geomorphic processes, with major glaciation impact on topography since ca. 1 Ma in the Western and Central Alps, but apparently not in the Eastern Alps. In addition, there is a spatial contrast in both modern erosion and geodetic rock uplift between the Western/Central and Eastern Alps. This strongly suggests that the late-stage evolution of the European Alps is reflecting the interplay between external (climate) and internal (solid Earth) mechanisms. Future studies need to provide higher resolution in thermochronometric data for late-stage erosion of slowly-eroding regions, where current data only provide average erosion histories over long periods. This will be possible with the recent development of very low-temperature thermochronometers. In addition, further geomorphic markers and sediment archives need to be investigated and dated to improve the existing chronology for the progressive (or not) Alpine topographic evolution and for glacier fluctuations (timing and extent) during previous glacial/interglacial cycles of the Plio-Quaternary. Such improvements would provide a quantitative framework for the recent erosion history of the Alps, which is required to estimate the isostatic response to erosional unloading, considering both steady background erosion and topographic changes, in addition to deglaciation. Finally, sub-lithospheric mantle flow and potential slab detachment are likely to contribute to the modern geodetic rock uplift.

Higher-resolution tomographic models would provide important information for further constraining these contributions across the European Alps.

ACKNOWLEDGMENTS

P.G.V. acknowledges funding from the French ANR-PIA program (ANR-18- MPGA-0006) and the Swiss SNSF (PP00P2_170559). P.S. was supported by the Italian Ministry of Education MIUR (Rita Levi Montalcini, DM 694–26/2017, and Dipartimenti di Eccellenza 2018–2022 grants). M.F. is supported by NERC (NE/N015479/1). The authors warmly thank B. Salcher, K. Whipple and an anonymous reviewer for their constructive and insightful reviews, as well as the editors A. McCarthy and O. Müntener for their invitation and suggestions.

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