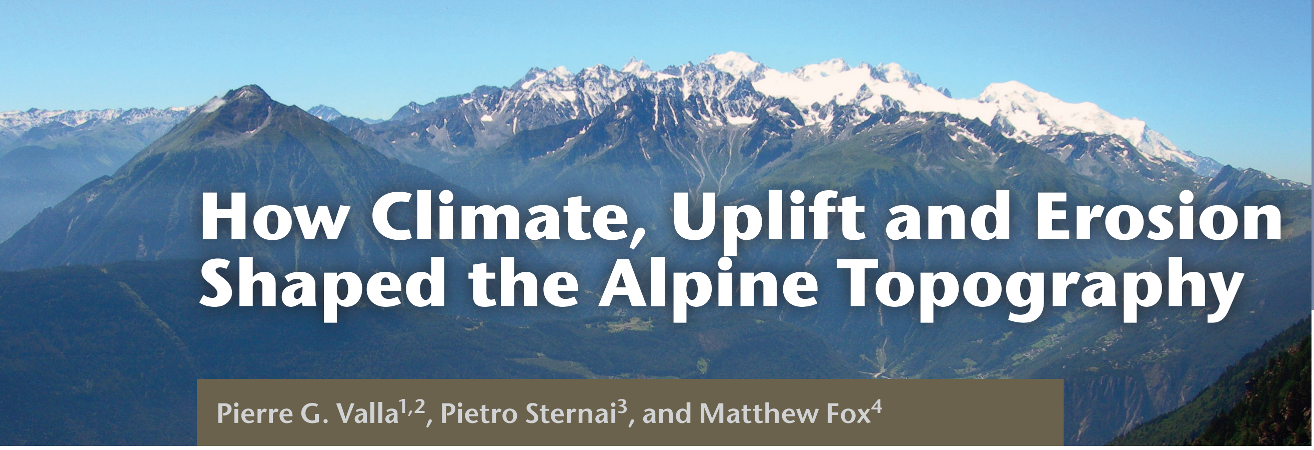

# How Climate, Uplift and Erosion Shaped the Alpine Topography

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**Decades of scientific research on the European Alps have helped quantify the vast array of processes that shape the Earth's surface. Patterns in rock exhumation, surface erosion and topographic changes can be compared to sediment yields preserved in sedimentary basins or collected from modern rivers. Erosion-driven isostatic uplift explains up to ~50% of the modern geodetic rock uplift rates; the remaining uplift reveals the importance of internal processes (tectonics, deep-seated geodynamics) and external processes (glacial rebound, topographic changes). We highlight recent methodological and conceptual developments that have contributed to our present view of the European Alps, and we provide suggestions on how to fill the gaps in our understanding.**

KEYWORDS: mountain geodynamics; erosion; topographic evolution; climate; glaciations; geodetic uplift

## INTRODUCTION

Mountain topography lies at the interface between the lithosphere below and the hydrosphere and biosphere above. The long-term evolution of a mountain range results from the interplay between internal and external driving mechanisms (FIG. 1A) (e.g., Whipple 2009). Internal forcings include crustal thickening from tectonic shortening and the deeper processes of, potentially, lithospheric delamination and sublithospheric mantle flow. External forcings involve components of the surface environment that we can generally describe as climate and whose variability controls erosion and the building or melting of ice caps and glaciers, as well as the evolution and activity of biota and sea-level changes (or, more generally, a regional "base-level" as reference for fluvial erosion and sediment deposition). Key components of this system are surface processes (FIG. 1A), which redistribute material across Earth's surface and 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., as mass redistribution that affects the crustal stress field and thermal structure) and the hydrosphere/biosphere (e.g., as erosion that modulates 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 driven by mountain topography). A quantitative characterization of the mechanisms that control mountain topographic evolution is challenging, because they are intrinsically linked to one another, but they operate at different spatial and temporal scales ($10^1$–$10^6$ metres and also years), and involve thresholds and non-linear processes (Champagnac et al. 2014).

The European Alps are a classic example of a mid-latitude convergent mountain belt, extending over 1,000 km (FIG. 1B) and forming an arcuate shape which can be divided into three main sectors: the 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 that started during the late Eocene and is ongoing. The main topographic construction and rock exhumation – i.e., the unroofing history, or a rock's path towards the Earth's surface – began at ~35 Ma or earlier, mostly driven by erosion in response to the rock uplift associated with crustal thickening (Kuhlemann et al. 2002; Schmid et al. 2004). The main drainage organization and divide were established early in the orogeny, following the main tectonic structures (FIG. 1B) and were strongly influenced by the early Oligocene to Miocene exhumation of crystalline massifs. Western Alpine topography reached high elevations during the early collisional stages, palynology revealing early Oligocene elevations similar to present-day (Fauquette et al. 2015). The high topography of the Central Alps was acquired during the middle Miocene, deduced from stable-isotope palaeoaltimetry (Campani et al. 2012). It has been suggested that the topography of the Eastern Alps developed during the late Oligocene (Kuhlemann et al. 2002), but this has not yet been confirmed quantitatively.

As a mid-latitude mountain range with large 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 the forelands, and intramountain deposition. During the late Cenozoic, global climate evolved towards cooler conditions and increased variability. The onset of glaciations starting at ~3 Ma in the Northern Hemisphere also impacted the European

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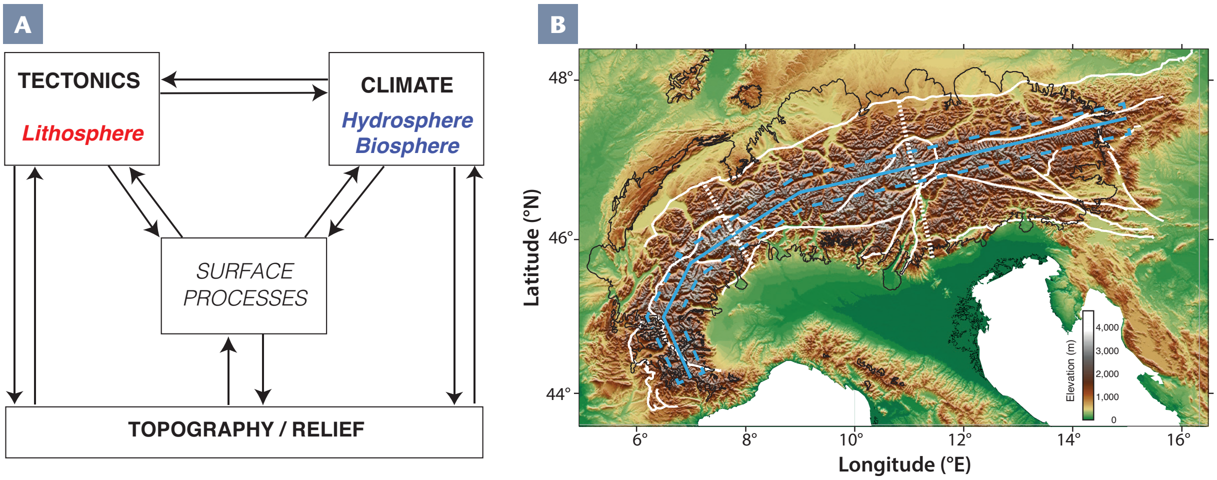

**FIGURE 1** Alpine topography and relief. (**A**) General flow chart of the interplay and feedback between tectonics, climate and topography/relief in mountain evolution. This complex system involves interactions between the lithosphere and the hydrosphere and biosphere, with surface processes regulating the interactions. BASED ON CHAMPAGNAC ET AL. (2014). (**B**) Modern topography of the European Alps at 90 m resolution digital elevation model. Black lines = ice extent at last glacial maximum (~20 ka, Ehlers and Gibbard 2004); white lines = major Alpine tectonic lineaments (Schmid et al. 2004); dotted white lines = spatial limits for Western, Central and Eastern Alps (Delunel et al. 2020); continuous and dashed blue lines = swath profile in FIGURE 5.

Alps, with extensive glacier coverage (FIG. 1B) (Ehlers and Gibbard 2004). Cyclic variations between glacial and interglacial conditions and associated transient responses of the geomorphic processes (i.e., erosion and deposition) have shaped modern Alpine topography and relief.

Today, tectonic horizontal shortening from plate convergence appears to be active only in the Eastern Alps; the Western and Central Alps are currently subject to limited shortening, and even extension in some areas (Serpelloni et al. 2016). However, geodetic measurements (from Global Positioning System measurements and 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).

Here, we review the key evidence for the topographic evolution of the European Alps. We present developments in topographic, geochronologic and modeling methodologies that have quantified long-term erosion and relief development. Such a quantitative framework is needed to assess the relative contributions of internal and external forcings in the evolution of the European Alps and to diagnose the potential drivers for modern rock-uplift.

## OLIGOCENE–MIOCENE EVOLUTION OF THE ALPS

The main Alpine collisional phase started at ~35 Ma with the rapid development of mountainous topography, major drainage reorganization (Lu et al. 2018), and the 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 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 threefold: (1) sediment preservation and possible remobilization after deposition or the recycling of sedimentary rocks derived from earlier stages of orogeny; (2) changes in the river drainage patterns (which can confuse the 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) and shows two main periods in the sediment yield history: at 35–15 Ma and at 15–0 Ma (FIG. 2A). There is a significant increase in sediment yield between ~30 Ma and 25 Ma, reflecting topographic building with the onset of active geomorphic processes and efficient sediment production. Between 25 Ma and 15 Ma, sediment yields remained high and were punctuated by short pulses, which may reflect changes in tectonic forcing and migration of the drainage divide (Kuhlemann et al. 2002). The mobility of the drainage divide is also evidenced by source variations in sediment discharge between the Northern and Southern Alps. The 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, starting just before 15 Ma, for both the Western/Central and Eastern Alps, followed by steady sediment flux for only the Western and Central Alps. For the Eastern Alps, a trend of modestly increasing sediment yield over time can be observed during the middle Miocene. Finally, the most striking observation from Kuhlemann et al. (2002) is the trend of a significant increase in sediment yield beginning at ~5 Ma (Miocene/Pliocene transition) (FIG. 2A) and which is observed for the entire European Alps but that is apparently more pronounced in terms of sediment volume for the Western and Central Alps.

Records of sediment yield indicate that the Alpine orogeny underwent major changes in topography and erosion rates. However, given the large-scale spatial integration of sediment records, assessing the spatio-temporal patterns of erosion at the scale of individual massifs has remained challenging. Thermochronometry records the time since a rock passed through an effective closure temperature and can directly quantify times and rates of exhumation through erosion and tectonic unroofing. In addition, the thermal field of the upper crust is sensitive to exhumation and to the vertical amplitude and horizontal wavelength of surface topography. Low-temperature thermochronometry (thermochronometers that have closure temperatures <250 °C) can be used to quantify rock exhumation at a timescale provided by the respective rock cooling ages. Thermochronometry of detrital minerals from modern river sediments or from past sediment records provides an integrated overview of Alpine erosion rates. Despite fragmentary records for the early construction stages, detrital thermochronometry confirms erosion pulses during the Oligocene but suggests an overall steady

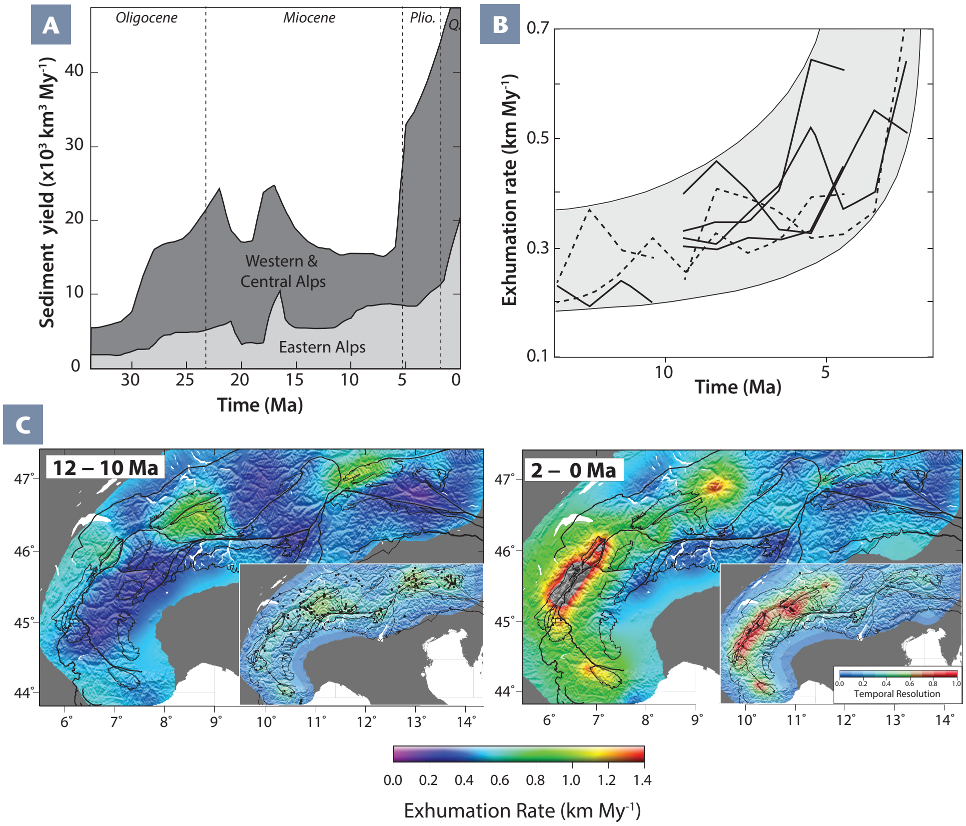

**FIGURE 2** Alpine erosion and sediment fluxes. (**A**) Late Cenozoic sediment yields for the Eastern Alps (light grey area) and the Western and Central (including Southern) Alps (darker grey area). Abbreviations: Plio. = Pliocene; Q. = Quaternary. AFTER KUHLEMANN ET AL. (2002). (**B**) Alpine exhumation rates of the Western Alps (thick lines) and Central Alps (dashed lines) extracted from the geometric reconstruction of bedrock thermochronometric iso-ages. Note the overall trend of increasing exhumation rate since ~5 Ma (grey envelope), similar to the trends in sediment yields shown in FIGURE 2A. AFTER VERNON ET AL. (2008). (**C**) Spatial distribution of Alpine exhumation rates from linear inversion of thermochronometric data. (LEFT) Alpine exhumation during 12–10 Ma. LEFT INSET shows the statistical resolution in inferred exhumation rates. (RIGHT) Alpine exhumation during 2–0 Ma. RIGHT INSET shows the statistical resolution in inferred exhumation rate. Note temporal variability for both time intervals. Black lines indicate the main Alpine massifs and the tectonic lineaments (Schmid et al. 2004). BASED ON FOX ET AL. (2016).

erosion over the European Alps since ~15 Ma at rates of 0.1–0.4 km My$^{-1}$ (Bernet et al. 2001). Within this apparent steady setting, major changes in sediment provenance have been constrained and reflect a reorganization of river drainage patterns for the Eastern Alps (at ~20 Ma) and for the Western/Central Alps (at ~13–10 Ma).

Bedrock thermochronometry directly quantifies erosion rates and topographic history. Since the 1970s, over 3,000 bedrock cooling ages (including multiple thermochronometers on individual bedrock samples) 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 high erosion rates began early (early to middle Miocene) in the Eastern Alps (Tauern Window and Austroalpine units) and in the Southern Alps (Bergell and Adamello Massifs). These high erosion rates can be linked to pulses of crustal thickening, followed by overall moderate erosion rates since the middle Miocene. An increase in erosion rate during the late Miocene has also been documented for the Southern Alps but has not been observed in bedrock thermochronometry in the Eastern Alps.

In the Western and Central Alps, thermochronometric data highlight contrasts in exhumation rates, with the onset of middle Miocene erosion linked to the exhumation of the External Crystalline Massifs (i.e., Aar–Gotthard, Mont Blanc, Belledonne–Pelvoux) (Schmid et al. 2004) and within the more internal parts of the orogen (the Lepontine Dome), followed by an apparent increase in erosion rates during the late Miocene (FIG. 2B). This acceleration in erosion rates at ~5 Ma resembles the sharp rise in sediment accumulation rates (FIG. 2A) and has raised long-lasting discussions about the potential contributions of tectonics versus climate. For the Western and Central Alps, both hypotheses have been postulated, either calling on (1) a climate shift at the Miocene–Pliocene transition, with enhanced climatic variability and possibly increased precipitation favouring efficient erosion, sediment production and export (e.g., Vernon et al. 2008); or (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 hypothesized to be a result of changes in regional tectonics (i.e., inversion of the Pannonian Basin) (e.g., Ruszkiczay-Rüdiger et al. 2020 and references therein).

Recent developments in thermal(-kinematic) models and advances in numerical and inversion modeling approaches (e.g., Fox et al. 2016) (FIG. 2C) have allowed researchers to include multiple low-temperature 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 a middle Miocene onset of high erosion rates (FIG. 2C) simultaneous with tectonic uplift from crustal thickening, and also evidence for a subsequent decrease in erosion rates towards the late Miocene–early Pliocene. Temporal trends in erosion rate from bedrock thermochronometry (FIG. 2C) slightly differ from the sediment yield records for the late Miocene (FIG. 2A). The progressive exhumation and exposure of crystalline and highly resistant rocks at this time could have caused an overall decrease in bedrock erosion rate (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 rates since ~2 Ma (Fig. 2C) for the Western and Central Alps, although the resolution of both current thermochronometric data and imaging of the Earth's interior via inversion of seismic data have not yet allowed scientists to distinguish between either tectonic *or* climate forcings, nor to recognize possible feedbacks that may have triggered this increase in erosion rates (Fox et al. 2015).

## ALPINE TOPOGRAPHY AND PLIOCENE–QUATERNARY GLACIATION

Alpine landscapes present typical glacial landforms, including classic glacial cirques and U-shaped wide, steep, and deep valleys, but also "hidden" features such as overdeepenings, which form major lakes and sediment infills in the present-day topography. Although the Pliocene–Quaternary (Plio-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 occurred during the initial Plio-Quaternary 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 postglacial landscape readjustment, or do they evolve through multiple glacial/interglacial cycles?

Results of numerical landscape evolution suggest that glacial erosion in the Western and Central Alps 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, quantifiable data for the impact of Plio-Quaternary glaciation on Alpine erosion and topography has remained difficult for two reasons: (1) the relatively short timescales involved (1–2 My for the Quaternary and 10–100 ky for individual glacial/interglacial cycles) compared to the current temporal resolution of thermochronometric methods (which provide averaged rates over approximately 1–2 My timescales for the Alps); and (2) the preservation of, and/or access to, continuous sedimentary records or geomorphic markers for individual glaciations.

For the European Alps, initial Plio-Quaternary glacial phases appear to have been limited in extent, leaving only scarce sediment records in the internal parts of the Alpine massifs. A major environmental and stratigraphic change has been reported at ~0.9 Ma, with the development of extensive and long-lasting glaciers that reached the Alpine forelands (e.g., Muttoni et al. 2003). The mid-Pleistocene transition (~1.2 Ma), due to orbital eccentricity, promoted global climate change with the switch from low-amplitude, short (symmetric 40 ky) to high-amplitude, long (asymmetric 100 ky) glacial/interglacial cycles.

In the Western and Central Alps, there is quantitative evidence for the impact of glaciation on Alpine topography (Fig. 3). In the Swiss Central Alps, Haeuselmann et al. (2007) used cosmogenic $^{26}$Al/$^{10}$Be dating of buried cave sediments to quantify the deepening of the Aare Valley with respect to the cave system. Dating results show two valley deepening periods over the Plio-Quaternary, with limited deepening at ~0.1 km My$^{-1}$ until ~0.9 Ma, followed by abrupt valley deepening at >1 km My$^{-1}$. 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, Valla et al. (2011) highlight a quiescent erosion phase during the Plio-Quaternary followed by subsequent valley incision (i.e., topographic change by spatially focused erosion) at a rate of 1 km My$^{-1}$ since ~1 Ma (Fig. 3). These outcomes not only point towards a major shift in erosional pattern and rate since ~1 Ma for the Western and Central Alps but also reveal a topographic change with significant increase in relief which can be interpreted as glacial valley deepening. Such a topographic response to glaciation was negligible or had limited magnitude in the Eastern and Southern Alps, despite similar glacial landforms (Sternai et al. 2012).

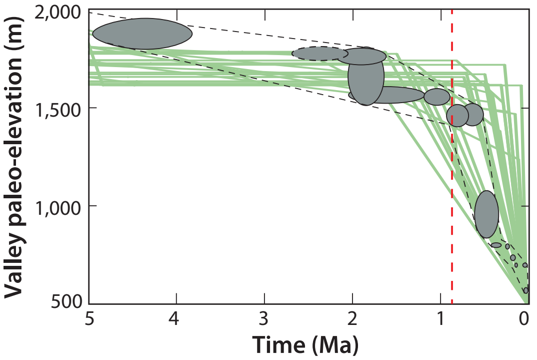

**Figure 3** Plio-Quaternary Alpine erosion and relief development. Palaeoelevation (a proxy for valley incision) of the valleys of the Aare (based on cave sediments dating, grey ellipses and black dashed lines; Haeuselmann et al. 2007) and Rhône (based on bedrock low-temperature thermochronometry, converted into valley floor palaeoelevations using thermal-kinematic modeling, green lines; Valla et al. 2011). Red dashed line indicates onset of major Alpine glaciation from stratigraphic evidence (Po River Basin; Muttoni et al. 2003).

Reconstructions of the pre-glacial Alpine topography 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., a constant drainage network throughout the Quaternary), they provide useful first-order estimates for evaluating glacial topographic changes in the European Alps and the associated isostatic response to non-steady erosional unloading (Fig. 5).

## 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 or the Global Navigation Satellite System) rock-uplift rates, averaged over the last 10 to 100 years, are highest in the Western and Central Alps at up to 2 mm y$^{-1}$ (Fig. 5) (Nocquet et al. 2016; Sternai et al. 2019). What is driving the observed spatial patterns of rock uplift in the European Alps? Differences in erosion rates between the Eastern and Western/Central Alps have been invoked to explain these patterns of rock uplift. However, it is necessary to quantify the spatial and temporal variations of erosion rates to recognize whether the European Alps are, or are not, actually experiencing surface uplift (i.e., the difference between the rate of rock uplift and that of erosion).

Modern Alpine erosion rates have been estimated using both sediment yield (river and reservoir gauges) (Hinderer et al. 2013) and cosmogenic $^{10}$Be in riverine sediments (Delunel et al. 2020). Modern sediment yield data only cover the last few decades and show an ~3-fold difference in erosion rates between the fast-eroding Western/Central Alps and the slow-eroding Eastern Alps. This is interpreted as reflecting enhanced chemical erosion of the carbonate sedimentary rocks that are abundant in the external

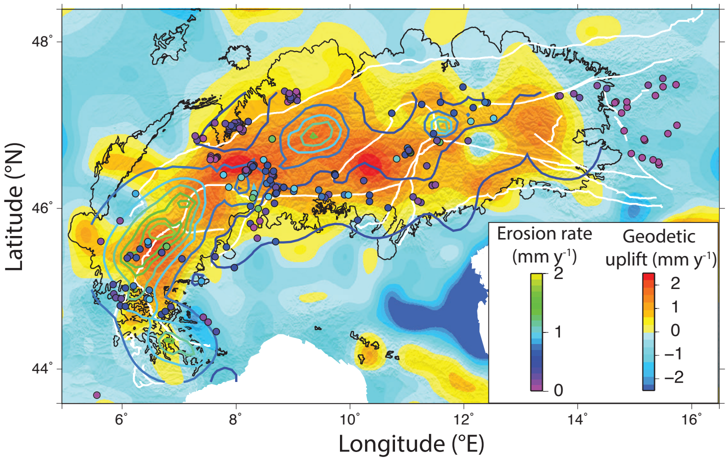

**FIGURE 4** Modern Alpine rock-uplift and erosion rates. The background solid-coloured map depicts the spatial distribution (at 30 km resolution) of modern geodetic rock uplift (Sternai et al. 2019) over decadal timescales. Coloured circles are locations of catchment outlets where averaged erosion rates have been measured based on riverine cosmogenic $^{10}$Be, which reflects millennial timescale rates (Delunel et al. 2020). Coloured lines are 2–0 Ma erosion rate estimates based on linear inversion of thermochronometric data (FIG. 2C) (Fox et al. 2016). Black lines are ice extent of the last glacial maximum. White lines are major Alpine tectonic lineaments.

mountainous parts of the Western/Central Alps (Hinderer et al. 2013). Erosion rates derived from cosmogenic $^{10}$Be integrate over millennial timescales and present similar patterns: higher erosion in the Western and Central Alps (2–3-fold difference) (FIG. 4) compared to the Eastern Alps. Moreover, both erosion rate datasets show no evidence for modern climatic control on the spatial erosion distribution (i.e., there is no relationship to present-day precipitation patterns), but instead reveal a significant dependence of erosion on slope or relief, which reflects the intense glacial preconditioning of the Alpine topography as well as ongoing glacier retreat (Hinderer et al. 2013; Delunel et al. 2020). Patterns of erosion over millennial timescales appear to follow an expected geomorphic response since the last glacial maximum at ~20 ka, characterized by high postglacial erosion rates and transient hillslope and fluvial topographic readjustment (e.g., Valla et al. 2010). It remains debated how long Alpine 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 trend: increasing from the Western to the Central Alps, followed by a decrease towards the Eastern Alps. This agrees with the hypothesis that rock uplift is driven by erosion across the European Alps (Champagnac et al. 2009). However, while patterns of erosion and uplift do correlate with one another, 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 observations of erosion and rock uplift, or alternatively it may highlight that modern rock uplift integrates multiple 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, including the sublithospheric mantle's viscosity, the sublithospheric mantle's structural or chemical variations (both laterally and vertically), the timing and spatial variability in deglaciation, and the importance of topographic change versus 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 rock uplift, suggesting isostatic adjustment could be the only mechanism for uplift in this region. However, this scenario is unlikely for two reasons: (1) the Eastern Alps are still experiencing shortening and associated tectonic rock uplift, as also suggested by local examples of compressive tectonics since ~3 Ma (e.g., Ruszkiczay-Rüdiger et al. 2020); and, (2) mantle upwelling below the Pannonian Basin is likely to involve dynamic uplift in the Eastern Alps, while sediment loading within the Pannonian Basin is likely to involve subsidence in the Eastern Alps (FIG. 5). Modern and 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 ~50% of the observed geodetic rock uplift (FIG. 5). Given the limited tectonic shortening that is occurring there, deeper mechanisms that involve lithospheric and sublithospheric mantle flow (and related dynamic uplift) must be at play. Convective processes due to detachment of the lithospheric slab below the Western Alps are particularly debated (Lippitsch et al. 2003; Zhao et al. 2016), because the occurrence, timing and spatial extent of such event(s) are still poorly constrained. For the Central Alps, the contribution of sublithospheric mantle flow to rock uplift appears significant (FIG. 5) and can explain the high observed rock-uplift rates (up to 2 mm y$^{-1}$) when combined with the isostatic adjustments to external forcing.

## SUMMARY AND OUTLOOK

Our review of the late Cenozoic evolution of the European Alps is based on different methodologies, ranging from sediment yield analyses (modern and past records), to geochronology (mainly low-temperature thermochronometry and terrestrial cosmogenic nuclides), to geodesy or geophysics combined with numerical modeling. This diversity in methodology allows us to assess the different spatial and temporal scales of Alpine erosion and topographic evolution.

The existing data show that the topography of the European Alps has evolved in a complex way, starting with the onset of topographic construction in the early Oligocene, followed by significant tectonic controls on erosion and topographic building via crustal thickening and drainage-pattern changes into the middle Miocene. The erosion and topographic evolution of the Plio-Quaternary appear to have been controlled by climatically driven geomorphic processes, glaciation having a major impact on topography since ~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 reflects the interplay between external (climate) and internal (solid Earth) mechanisms.

There is still a need for higher spatial and temporal resolution in thermochronometric data for studies on the late-stage erosion of slowly eroding regions: current data only provide averaged erosion histories over long periods. Better resolution will be possible with the recent development of very low-temperature thermochronometers ($^4$He/$^3$He and luminescence thermochronometry). In addition, further geomorphic markers and sediment

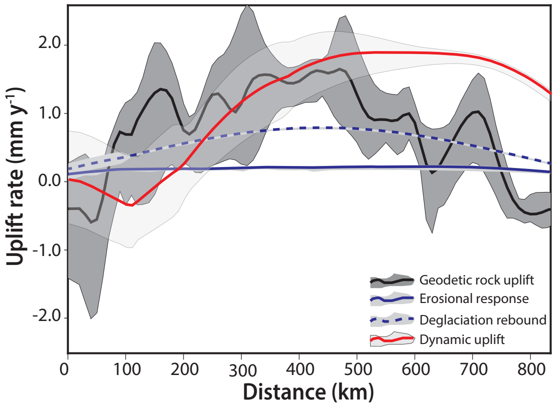

**FIGURE 5** Modern geodetic uplift of the Alps and potential uplift contributions. Graph shows swath profiles (see FIG. 1B for locations) of modern geodetic rock uplift (see also FIG. 4, black line and dark-grey envelope) and of the different forcings. The external forcings are as follows: blue continuous line (with grey envelope) = erosional adjustment to topographic changes (Sternai et al. 2012); blue dashed line (with grey envelope) = deglaciation rebound (Spada et al. 2009). The internal forcing is as follows: red line (with light-grey envelope) = dynamic uplift (Zhao et al. 2016). AFTER STERNAI ET AL. (2019).

archives need to be investigated and dated to improve the existing chronology for the progressive (or not) evolution of Alpine topography and for the fluctuations in timing and extent of glaciers during previous glacial/interglacial cycles of the Plio-Quaternary. Such improvements in topographic chronology would provide a quantitative framework by which to explain the recent erosion history of the Alps, which is required to then estimate the isostatic response to erosional unloading while considering both steady background erosion and topographic changes, in addition to deglaciation. Finally, sublithospheric mantle flow and potential slab detachment are likely contributors to modern geodetic rock uplift. Higher spatial resolution in tomographic models would provide important information for further constraining these contributions across the entire European Alps.

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## REFERENCES

Bernet M, Zattin M, Garver JI, Brandon MT, Vance JA (2001) Steady-state exhumation of the European Alps. Geology 29: 35-38, doi: 10.1130/0091-7613(2001)029<0035:SSEOTE>2.0.CO;2

Campani M, Mulch A, Kempf O, Schlunegger F, Mancktelow N (2012) Miocene paleotopography of the Central Alps. Earth and Planetary Science Letters 337-338: 174-185, doi: 10.1016/j.epsl.2012.05.017

Champagnac JD and 5 coauthors (2009) Erosion-driven uplift of the modern Central Alps. Tectonophysics 474: 236-249, doi: 10.1016/j.tecto.2009.02.024

Champagnac J-D, Valla PG, Herman F (2014) Late-Cenozoic relief evolution under evolving climate: a review. Tectonophysics 614: 44-65, doi: 10.1016/j.tecto.2013.11.037

Delunel R and 12 coauthors (2020) Late-Pleistocene catchment-wide denudation patterns across the European Alps. Earth-Science Reviews 211, doi: 10.1016/j.earscirev.2020.103407

Ehlers J, Gibbard PL (eds) (2004) Quaternary Glaciations - Extent and Chronology. Part I: Europe. Elsevier, 488 pp

Fauquette S and 17 coauthors (2015) Quantifying the Eocene to Pleistocene topographic evolution of the southwestern Alps, France and Italy. Earth and Planetary Science Letters 412: 220-234, doi: 10.1016/j.epsl.2014.12.036

Fox M, Herman F, Kissling E, Willett SD (2015) Rapid exhumation in the Western Alps driven by slab detachment and glacial erosion. Geology 43: 379-382, doi: 10.1130/G36411.1

Fox M, Herman F, Willett SD, Schmid SM (2016) The exhumation history of the European Alps inferred from linear inversion of thermochronometric data. American Journal of Science 316: 505-541, doi: 10.2475/06.2016.01

Haeuselmann P, Granger DE, Jeannin P-Y, Lauritzen S-E (2007) Abrupt glacial valley incision at 0.8 Ma dated from cave deposits in Switzerland. Geology 35: 143-146, doi: 10.1130/G23094A

Hinderer M, Kastowski M, Kamelger A, Bartolini C, Schlunegger F (2013) River loads and modern denudation of the Alps — a review. Earth-Science Reviews 118: 11-44, doi: 10.1016/j.earscirev.2013.01.001

Kuhlemann J, Frisch W, Székely B, Dunkl I, Kázmér M (2002) Post-collisional sediment budget history of the Alps: tectonic versus climatic control. International Journal of Earth Sciences 91: 818-837, doi: 10.1007/s00531-002-0266-y

Leith K, Fox M, Moore JR (2018) Signatures of late Pleistocene fluvial incision in an alpine landscape. Earth and Planetary Science Letters 483: 13-28, doi: 10.1016/j.epsl.2017.11.050

Lippitsch R, Kissling E, Ansorge J (2003) Upper mantle structure beneath the Alpine orogen from high-resolution teleseismic tomography. Journal of Geophysical Research: Solid Earth 108, doi: 10.1029/2002JB002016

Lu G, Winkler W, Rahn M, von Quadt A, Willett SD (2018) Evaluating igneous sources of the Taveyannaz formation in the Central Alps by detrital zircon U–Pb age dating and geochemistry. Swiss Journal of Geosciences 111: 399-416, doi: 10.1007/s00015-018-0302-y

Montgomery DR, Korup O (2010) Preservation of inner gorges through repeated Alpine glaciations. Nature Geoscience 4: 62-67, doi: https://doi.org/10.1038/ngeo1030

Muttoni G and 7 coauthors (2003) Onset of major Pleistocene glaciations in the Alps. Geology 31: 989-992, doi: 10.1130/G19445.1

Nocquet J-M and 11 coauthors (2016) Present-day uplift of the western Alps. Scientific Reports 6, doi: 10.1038/srep28404

Ruszkiczay-Rüdiger Z, Balázs A, Csillag G, Drijkoningen G, Fodor L (2020) Uplift of the Transdanubian Range, Pannonian Basin: how fast and why? Global and Planetary Change 192, doi 10.1016/j.gloplacha.2020.103263

Schmid SM, Fügenshuh B, Kissling E, Schuster R (2004) Tectonic map and overall architecture of the Alpine orogen. Eclogae Geologicae Helvetiae 97: 93-117, doi: 10.1007/s00015-004-1113-x

Serpelloni E, Vannucci G, Anderlini L, Bennett RA (2016) Kinematics, seismotectonics and seismic potential of the eastern sector of the European Alps from GPS and seismic deformation data. Tectonophysics 688: 157-181, doi: 10.1016/j.tecto.2016.09.026

Spada G, Stocchi P, Colleoni F (2009) Glacio–isostatic adjustment in the Po Plain and in the northern Adriatic region. Pure and Applied Geophysics 166: 1303-1318, doi: 10.1007/s00024-004-0498-9

Sternai P and 5 coauthors (2012) Pre-glacial topography of the European Alps. Geology 40: 1067-1070, doi: 10.1130/G33540.1

Sternai P, Herman F, Valla PG, Champagnac J-D (2013) Spatial and temporal variations of glacial erosion in the Rhône valley (Swiss Alps): insights from numerical modeling. Earth and Planetary Science Letters 368: 119-131, doi: 10.1016/j.epsl.2013.02.039

Sternai P and 14 coauthors (2019) Present-day uplift of the European Alps: evaluating mechanisms and models of their relative contributions. Earth-Science Reviews 190: 589-604, doi: 10.1016/j.earscirev.2019.01.005

Valla PG, van der Beek PA, Lague D (2010). Fluvial incision into bedrock: insights from morphometric analysis and numerical modeling of gorges incising glacial hanging valleys (Western Alps, France). Journal of Geophysical Research: Earth Surface 115, F02010, doi: 10.1029/2008JF001079

Valla PG, Shuster DL, van der Beek PA (2011) Significant increase in relief of the European Alps during mid-Pleistocene glaciations. Nature Geoscience 4: 688-692, doi: 10.1038/ngeo1242

Vernon AJ, van der Beek PA, Sinclair HD, Rahn MK (2008) Increase in late Neogene denudation of the European Alps confirmed by analysis of a fission-track thermochronology database. Earth and Planetary Science Letters 270: 316-329, doi: 10.1016/j.epsl.2008.03.053

Whipple KX (2009) The influence of climate on the tectonic evolution of mountain belts. Nature Geoscience 2: 97-104, doi: 10.1038/ngeo413

Zhao L and 13 coauthors (2016) Continuity of the Alpine slab unraveled by high-resolution P wave tomography. Journal of Geophysical Research: Solid Earth 121: 8720-8737, doi: 10.1002/2016JB013310 ■