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# Preservation of inner gorges through repeated Alpine glaciations

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**Extensive valley glaciers have repeatedly covered the inner gorges of the Swiss Alps during Quaternary glaciations. Two controversial explanations of the development of the features have been proposed. In the first, the gorges would have formed anew each time the glaciers receded, through fluvial incision of the previously glaciated surfaces. Alternatively, the valleys could be palimpsest features, carved through successive glacial–interglacial cycles. Here we use topographic data derived from LiDAR measurements to show that fluvial erosion rates of 8.5–18 mm yr$^{-1}$ would be required to create the current relief of Swiss gorges solely during the present interglacial period. Such high rates exceed the long-term average bedrock erosion rates of even the most tectonically active regions. This scenario would also require that previously incised valleys were erased during successive glaciations by commensurately high glacial erosion rates, a suggestion that is incompatible with available constraints of exhumation from thermochronometry. We therefore suggest that the gorges observed in the Swiss Alps are resilient to repeated glaciations. Our data are most consistent with the hypothesis that gorges are progressively incised below the elevations of glacial trough valleys through multiple glaciations.**

Inner bedrock gorges have a distinct 'valley-in-valley' cross-section, and can form by various mechanisms, including transient response to localized uplift or base-level fall[1,2] that promotes increased river downcutting and preferential landsliding on neighbouring hillslopes[3,4]. The common perception that Alpine gorges are the sole result of post-glacial fluvial bedrock incision is rooted in the notion that erosion rates by glaciers greatly exceed those of rivers in mountain belts[5]. Although many studies assume that rivers rapidly cut deep gorges after deglaciation[6–11], it remains speculative as to whether the conspicuous and deep bedrock gorges that are common throughout the Alps were entirely carved since the Last Glacial Maximum (LGM; refs 12–15). Arguments in favour of post-glacial incision have been based on gorges being inset into the floors of U-shaped trough valleys, whereas arguments for preservation of gorges through multiple glacial cycles draw on local exposures of glacial and glaciofluvial deposits preserved within gorges. We build on prior work to determine the location and depths of gorges in relation to major lithologic units and use new LiDAR data to calculate the mean fluvial bedrock incision rates necessary to cut V-shaped inner gorges into lower-relief glacial surfaces and formerly ice-covered valleys assuming incision began at post-LGM glacial retreat. We then project the relative depths of fluvial and glacial erosion required to create and eradicate gorges during post-glacial and glacial periods, respectively, and report geomorphological mapping that together with thermochronometric data constrains the timing of gorge incision.

We focus on the northern Swiss Alps, which, except for isolated mountain peaks, were glaciated repeatedly throughout the Quaternary and are underlain by crystalline basement rocks of the Mesozoic Infrahelvetic complex, and the less erosion resistant Mesozoic–Oligocene metasediments of the Penninic nappes[16,17]. We restricted our analysis to the northern Alps because the origin of inner gorges in the southern Alps is complicated by development of prominent knickpoints and overdeepened bedrock valleys associated with the Messinian salinity crisis and base-level fall[18]. Major glaciation in the Alps accompanied by a phase of valley incision along large European rivers appears to have initiated about 1 Myr (refs 19,20).

## Distribution of Alpine gorges

Mapping of inner gorges over a total length of ~1,350 km confirms that gorges preferentially occur in mechanically weak rocks such as those of the Molasse foreland basin and the Penninic Schistes Lustrés and Flysch[4] (Fig. 1, Supplementary Information S1). Many inner gorges are continuous for several kilometres, and their steepness correlates with rates of historic rock uplift $U_h$, which vary severalfold across the Alps[17,21,22]. We find that gorges in stronger crystalline rocks, particularly gneisses, exhibit significantly less relief than those in the highly erodible Schistes Lustrés and Flysch (Fig. 2a). Historic gauging records show that fluvial suspended sediment yields are highest from catchments draining these lithologies[9]. Geomorphic evidence further indicates that Holocene erosion rates are on average at least four times higher than in the neighbouring crystalline lithologies[17], although they are too high to be purely derived from gorge incision alone.

## Rates of river incision for post-glacial gorge formation

Digital topography derived from airborne LiDAR scanning at 2.5-m resolution shows that inner gorge relief ranges from 20 to 500 m, forming up to 40% of the local valley relief. Field observations and previous work show that the rock-walled gorges are dotted by numerous landslide scars. Probabilistic slope-stability modelling points to strength-limited threshold hillslope conditions within gorges, particularly where they have attained high relief[4]. In order for downcutting to have occurred entirely since the most recent deglaciation, any associated base-level changes would require average rates of post-glacial fluvial bedrock incision of $8.5 \pm 5.0$ to $18.3 \pm 9.6$ mm yr$^{-1}$ ($\pm 1\sigma$), depending on the different

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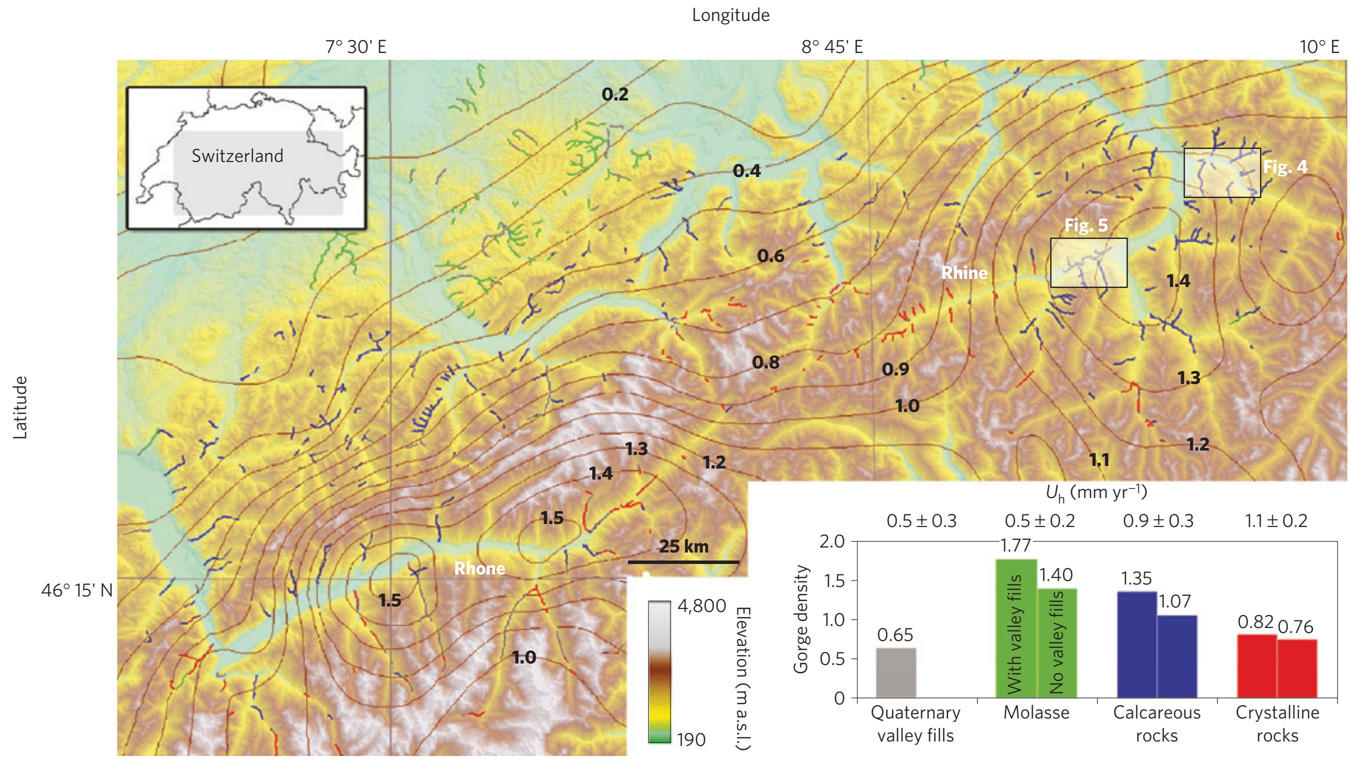

**Figure 1 | Topography of northern Swiss Alps with inner gorges mapped from 25-m digital elevation data.** Contoured rates of 20th century rock uplift $U_h$ (mm yr$^{-1}$) from repeat precision levelling of stable benchmarks[21,22] exhibit a pattern similar to exhumation rates indicated by apatite fission-track data[26]. Inset shows the fraction of total gorge length divided by the fraction of total area for the main lithologies (colour coded to map signatures). Ratio of unity indicates that the average gorge length scales with the relative abundance of rock-type. Left (right) hand bar includes (excludes) valley fills. Bold numbers above bars are mean values of $U_h$ ($\pm 1\sigma$).

lithologies, after valleys now featuring gorges became ice-free sometime between 10 and 15 kyr (ref. 23).

These average incision rates based on simple linear extrapolation exceed those in all but the most tectonically active regions and appear extremely high given that they would have to be sustained over $10^3$-yr timescales (Supplementary Fig. S2). However, pulses of transient or catastrophic incision following outburst floods from glacial or landslide-dammed lakes, as well as higher glacial meltwater discharges, may have contributed to gorge cutting during the dramatic shift from the glacial to post-glacial environment. Consequently, it is difficult to rule out extremely rapid incision solely on the basis of the need to invoke extraordinary rates. In the Swiss Alps this possibility is indicated by the effects of 20th century channel straightening[24] that resulted in the local metamorphosis of formerly braided river-channel reaches to incised bedrock reaches with up to 5-m deep inner gorges. Preliminary assessments suggest that these reaches, which are underlain by Schistes Lustrés and Flysch, transiently incised at rates >30 mm yr$^{-1}$ for several decades after river training exposed an undissected bedrock valley floor. An even more extreme example of rapid bedrock incision comes from a modern catastrophic flood in Texas that excavated up to 7 m of limestone in just three days (ref. 25). However, rapid transient incision over shorter durations would require rates proportionally greater than the long-term averages, and well above documented rates for bedrock river incision (Fig. 2b).

A key geomorphic constraint on the timing of gorge formation is that if gorges are solely post-glacial features then glacial erosion must eradicate any trace of the fluvial gorges carved in each successive interglacial period. In other words, the instantaneous glacial erosion rates integrated over the time that ice occupied the locations of inner gorges ($T_{\mathrm{glac}}$) must equal or exceed the integral of fluvial incision rates over the fraction of time that rivers were able to cut gorges ($T_{\mathrm{fluv}}$, Fig. 3a). Any intervening periods of valley aggradation would protect bedrock from erosion, thus requiring correspondingly higher glacial incision rates, including any contribution from glacial outburst floods or significantly different discharge regimes, to make up for the delay and to still arrive at the inner gorge relief observed today.

Independent long-term constraints on total erosion rates are set by apatite fission-track ages, which in the study area range from 2 to 8 Myr (compiled in refs 26,27). These ages imply mean Quaternary erosion rates remained <2 mm yr$^{-1}$ throughout our study area. This is consistent with estimates of Pleistocene trunk-valley incision of 1.2 mm yr$^{-1}$ on average[20], and Late Glacial denudation rates of 1.5 mm yr$^{-1}$ derived from volumetric reconstructions of Alpine valley fills based on well, borehole and geophysical data[28].

## Duration of fluvial versus glacial erosion

A further critical constraint is that the glacial erosion efficacy necessary to obliterate fluvial gorges must be consistent with the ratio of $T_{\mathrm{fluv}}/T_{\mathrm{glac}}$. Accepting a scenario in which post-glacial fluvial bedrock incision could be maintained at mean rates of 10 mm yr$^{-1}$ on average would necessitate $T_{\mathrm{fluv}}/T_{\mathrm{glac}} \sim 0.11$. In other words, if rivers eroded nine times faster on average than glaciers, as implied by these hypothetical post-glacial fluvial gorge incision rates, then glaciers would have to have covered the gorge reaches for nearly 90% of the duration of a given glacial–interglacial cycle to facilitate glacial erosion. This conflicts with the Quaternary geochronological record of Alpine glaciations, which indicates $T_{\mathrm{fluv}}/T_{\mathrm{glac}} > 1$, and probably between 1.1 and 1.3, over the last four major Alpine glaciations[19]. The corollary is that net average erosion rates during glacial periods would need to be 1.1–1.3 times higher than those of mean fluvial bedrock incision during interglacials to fully remove fluvial inner gorge relief. Moreover, we observe that the deepest

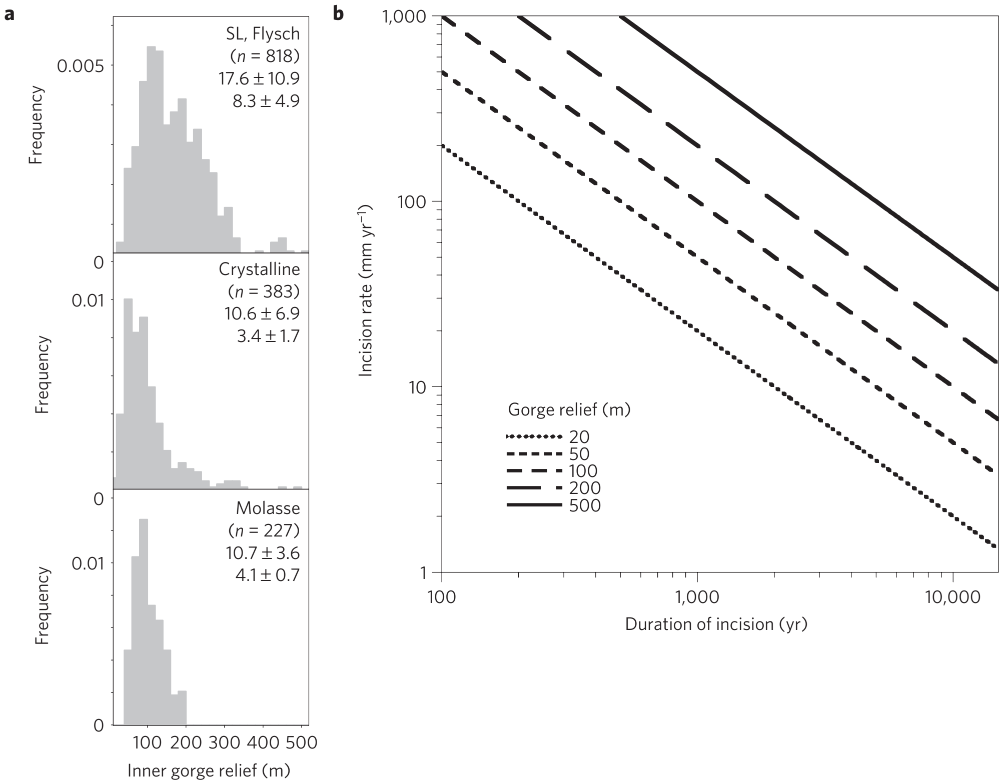

**Figure 2 | Rates of inferred post-glacial gorge incision.** **a**, Histograms of inner gorge relief stratified by major rock type, northern Swiss Alps (SL = Schistes Lustrés), including sample number *n* and average rates of post-glacial bedrock river incision inferred from dividing these relief values by 10 kyr and 15 kyr (mm yr$^{-1}$, $\pm 1\sigma$). **b**, Erosion rate (mm yr$^{-1}$) as a function of duration over which that rate would need to be maintained (yr) to account for post-glacial incision of 20–500 m, the observed range of inner gorge relief.

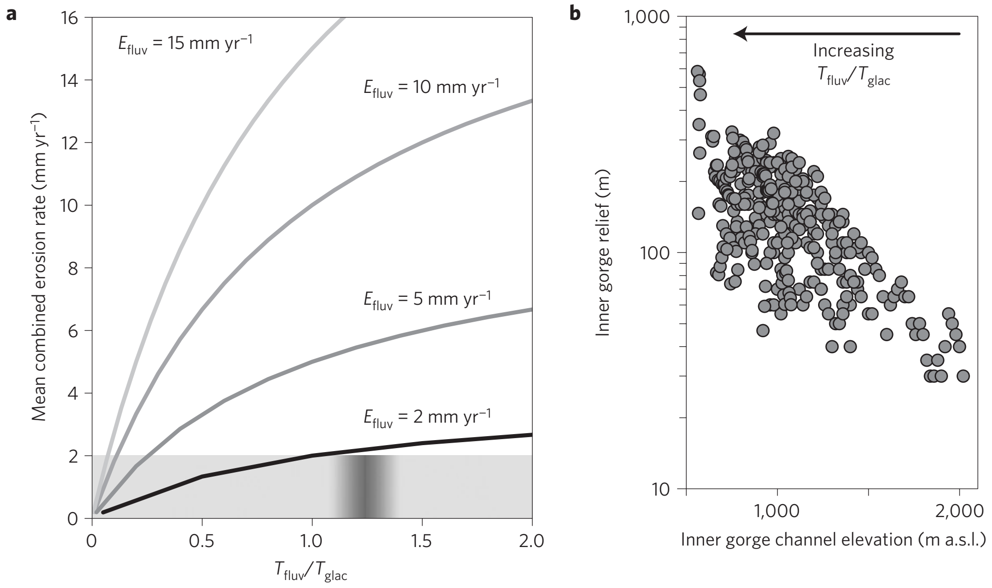

**Figure 3 | Quaternary erosion rates necessary to erase interglacially carved gorges.** **a**, Long-term erosion rate as a function of the ratio of the time that a location is subjected to fluvial and glacial erosion, $T_{\mathrm{fluv}}$ and $T_{\mathrm{glac}}$. Lines are mean rates of river incision $E_{\mathrm{fluv}}$ for four scenarios of post-glacial gorge formation (2–15 mm yr$^{-1}$). Grey shading indicates thermochronometric constraint limiting Quaternary erosion rates to $<2$ mm yr$^{-1}$, and darker grey shading indicates $T_{\mathrm{fluv}}/T_{\mathrm{glac}} = 1.1-1.3$ from the last glacial–interglacial cycle[23]. **b**, Inner gorge relief inferred from digital elevation models as a function of channel-bed elevation.

inner gorges preferentially occupy low-lying parts of the landscape, which are subject to shorter periods of glacial cover (lower $T_{\mathrm{glac}}$) than headwaters (Fig. 3b). Hence, the deepest gorges in lower parts of the landscape have had commensurately more time for fluvial incision (higher values of $T_{\mathrm{fluv}}/T_{\mathrm{glac}}$) than glaciated high-elevation regions during Quaternary glacial–interglacial cycles. Substantially thicker, and hence potentially more erosive, trunk glaciers would need to scour bedrock at even higher rates than the hypothesized

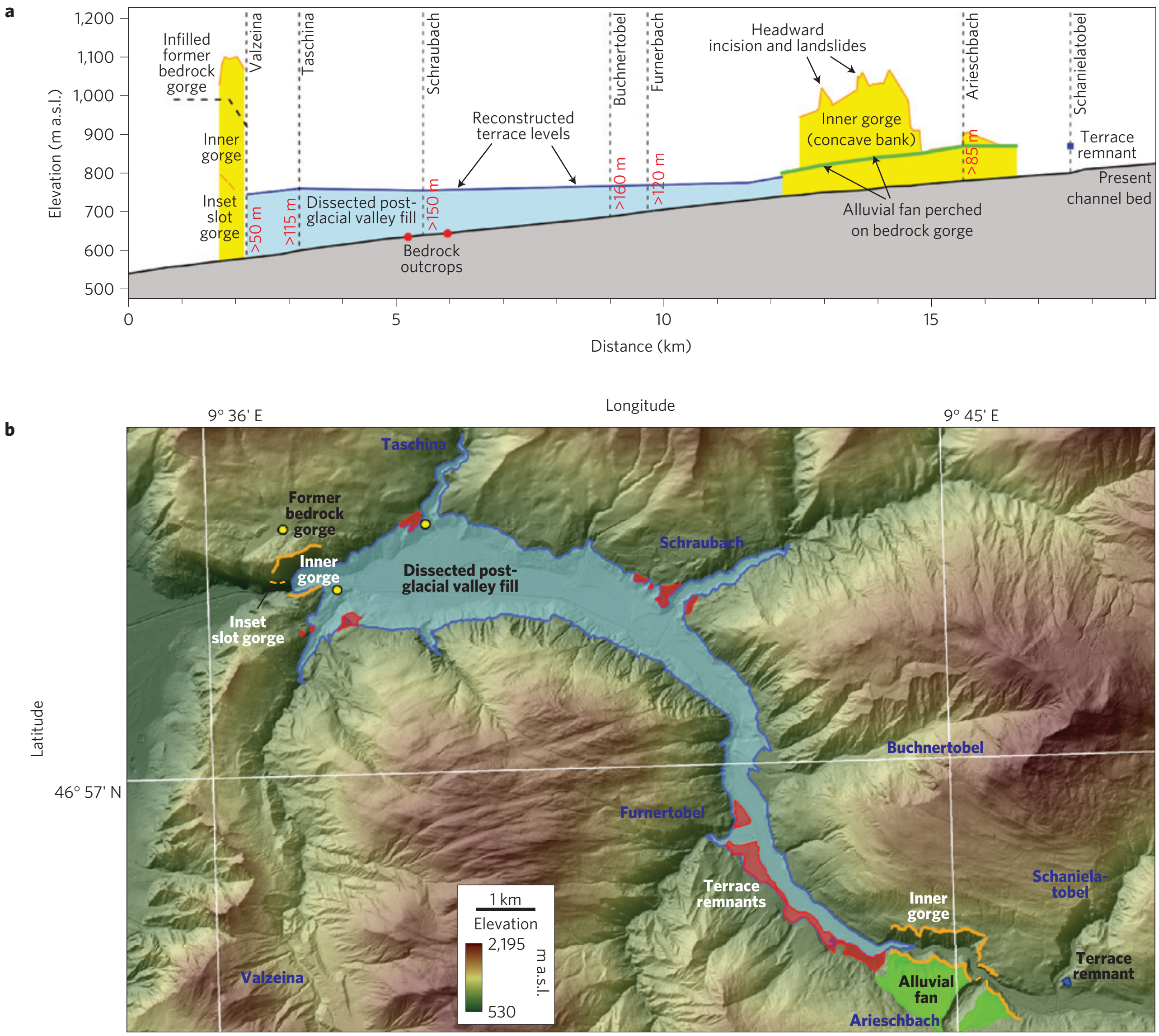

**Figure 4 | Geomorphic and sedimentary evidence of post-glacial valley infill and dissection of inner gorges, Landquart River (see Fig. 1 for location).** **a**, LiDAR-derived river longitudinal profile showing inset gorges (yellow) and the infilled remnant of former bedrock gorge ~400 m above the present channel (thick dashed line). Red vertical figures are the minimum inner gorge relief on tributaries (vertical dashed lines). **b**, Topographic map showing remnants of fill terraces (red) and alluvial fan (green) that cap former inner gorge confluence, and is graded to post-glacial valley fill with a maximum depth of ~180 m. Yellow dots are abandoned bedrock gorge segments flanked by truncated bedrock spurs.

interglacial fluvial incision (that is $>10\,\mathrm{mm\,yr^{-1}}$) to produce hanging valleys at the end of each maximum advance. Accordingly, hillslope processes would need to maintain similar process rates were topographic relief not to increase substantially with each glacial–interglacial cycle[9]. Thus, full resetting of interglacially carved gorges by glacial erosion would entail long-term denudation rates $>10\,\mathrm{mm\,yr^{-1}}$, a pace well above recorded rates of long-term exhumation and erosion. This would have removed >10 km of upper crust during the last 1 Myr, something incompatible with thermochronometric data[26,27].

## Local stratigraphic and geomorphological constraints

Several independent observations imply a pre-LGM origin of Alpine inner gorges. Most compelling is the local evidence for remnant deposits such as indurated and weathered glaciofluvial sediment or till within a number of Alpine gorges[14,15] (Supplementary Fig. S3). On the basis of the elevation of glacial deposits preserved within the Gorge du Guil in the Hautes-Alpes of France, Tricart[29] estimated a maximum of only 5–8 m of post-glacial gorge incision in calcareous rocks. Similarly, De Graff[15] reported that cemented Pleistocene valley fills in gorges of Vorarlberg, Austria, located below the modern streambed, indicate post-glacial (Holocene) fluvial incision has not yet excavated the gorge back down to the depth attained in a prior interglacial. He also reported direct measurements of modern incision rates that support the case for modest post-glacial incision, as field-based measurements of abrasion in bedrock channels cut into sedimentary rocks in the area yielded five-year rates of $1–3\,\mathrm{mm\,yr^{-1}}$, which could account for just 10–45 m of post-glacial incision since 10–15 kyr (ref. 15).

Further LiDAR-derived geomorphological mapping and topographic analysis from the northern Alps show evidence for substantial (>100 m) valley fills such as fluvial and lake terraces that would have helped preserve gorges even in mechanically weak rock types. If deposited during post-glacial times, these sediments would require even higher net bedrock incision rates to cut the gorges since the LGM and make up for the time during which valley

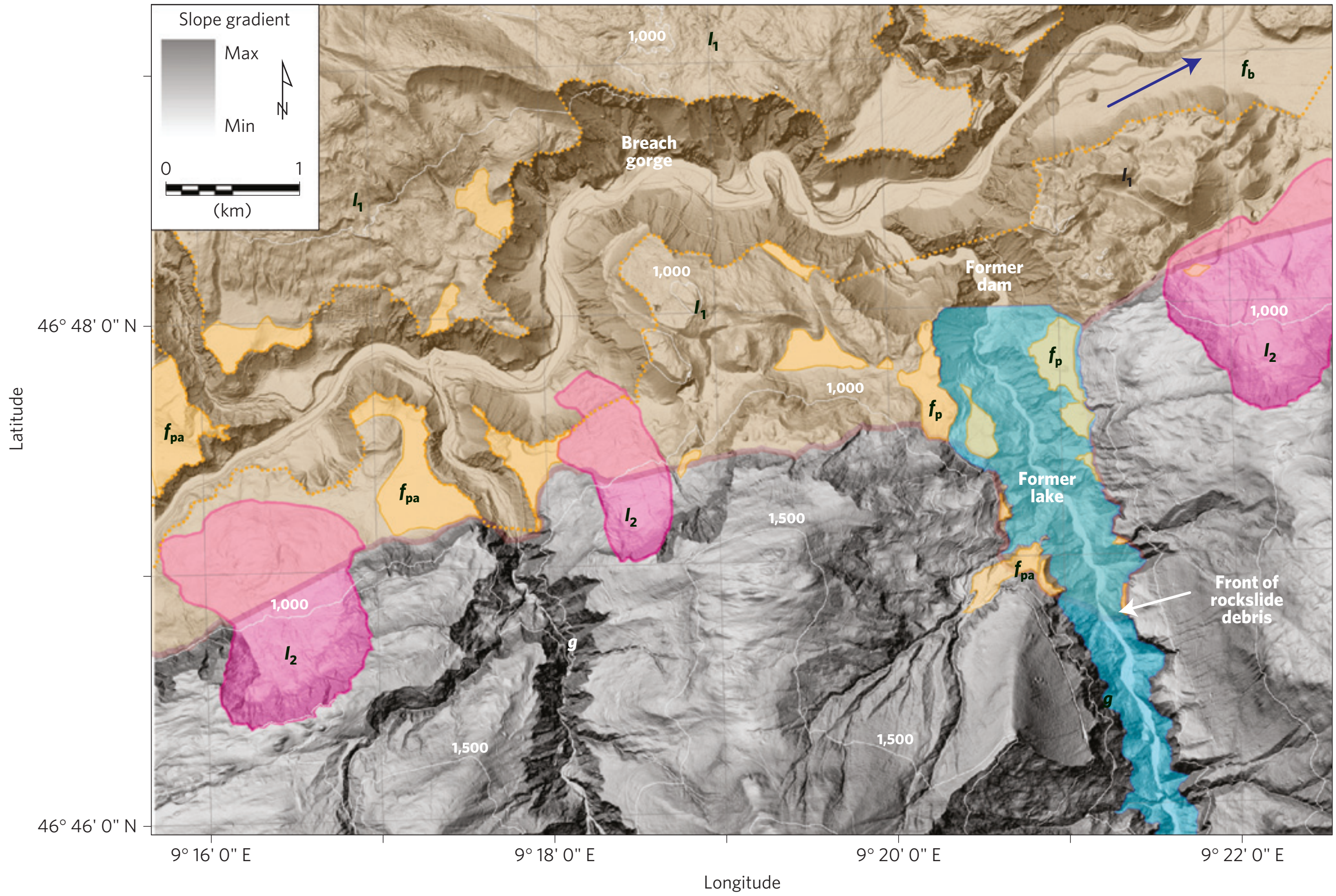

**Figure 5 | LiDAR-derived topography of southern front of the ~9 kyr Flims rockslide (yellow brown shade, $l_1$; see Fig. 1 for location).** Local slope gradients indicated by greyscale hue. Rockslide motion was SSE, with highly mobile fragmented debris entering tributary valleys, causing ephemeral blockage (former dam, former lake) and deposition of backwater ($f_p$) and alluvial ($f_{pa}$) sediments capping >100-m thick rockslide debris emplaced in pre-existing V-shaped bedrock inner gorge ($g$). Younger landslides ($l_2$) cover the southern margin of Flims rockslide deposit.

fills shielded the underlying bedrock from incision. Moreover, this would call for a mechanism that allowed for episodes of alternating rapid incision and massive aggradation of major valley floors. Also, we detected a number of truncated bedrock spurs and knobs with polished surfaces adjacent to infilled bedrock gorges stranded up to 400 m above modern channels (Fig. 4). If post-glacially incised, these fossil inner gorges would necessitate maintaining bedrock incision at $>23$ mm yr$^{-1}$ for up to 17 kyr, and proportionally higher rates if carved transiently during deglaciation or over some fraction of the Holocene. Similar high-level perched gorge segments and sediment-filled slot gorges have been reported from the famous Via Mala gorge, which is cut >70 m deep into Schistes Lustrés[13]. Finally, in the Alpine Rhine valley, the Flims rockslide, the largest in the Alps ($\sim 1.2 \times 10^{10}$ m$^3$), catastrophically filled in 100-m to >200-m deep pre-existing bedrock gorges in tributary valleys about 9 kyr (ref. 30, Fig. 5, Supplementary Information S4). There, $>10^8$ m$^3$ of pervasively fragmented rockslide debris entered steep V-shaped gorges and caused ephemeral blockage, as shown by extensive backwater terraces that continue to mantle the underlying bedrock. Hence, any post-glacial excavation of these infilled and now partly re-incised gorges would have necessitated fluvial bedrock incision from 10–15 kyr to 9 kyr at an average rate of 17–200 mm yr$^{-1}$ for 1–6 kyr.

## The case for pre-glacial gorge formation

In summary, even conservative regional estimates of inner gorge relief demand extraordinary rates of fluvial bedrock incision, as well as similar if not higher rates of valley lowering by glacial erosion, to support the hypothesis of an exclusively post-glacial gorge cutting. Although such towering bedrock erosion rates have been recorded from transient response to rapid uplift or base-level drop[25], sustaining such average rates is inconsistent with long-term exhumation rates of 1–2 mm yr$^{-1}$ in the Alps. Catastrophic or highly episodic incision of gorges would require even greater rates to achieve the same physiographic result over shorter periods.

We conclude that the relief of inner gorges characteristic of weak rocks of the Penninic nappes began developing before rather than since the LGM. This implies either that glaciers protect inner gorges through gradual infilling with glaciofluvial sediment and/or till during glacial advances[15], or that glacial valley bottom erosion does not keep pace with fluvial incision over multiple glacial cycles, resulting in progressive gorge development over successive interglacial periods. The partial ‘sealing’ of bedrock gorges with sedimentary fills below the snouts or flanks of prograding glaciers may be a viable mechanism of protecting gorge topography from glacial obliteration, especially where weak lithologies such as Schistes Lustrés and Flysch readily provide high amounts of debris. Moreover, subglaciofluvial erosion by pressurized meltwater in conjunction with subglacial solution weathering of these and other calcareous rocks may further accentuate existing gorges. All of these mechanisms are consistent with a counter-intuitive resilience of inner gorges in some of the weakest rocks in the Alpine orogen through multiple glacial–interglacial cycles. Such preservation provides an explanation that is consistent with sedimentological and geomorphological characteristics of inner gorges in the eastern Swiss Alps, whereas solely post-glacial incision does not. Consequently, conventional notions and contemporary models about the role of glaciers and bedrock rivers in Alpine relief production warrant re-examination in regard to the post-glacial erosional efficacy of bedrock rivers and the capability of glaciers to remove pre-existing fluvial gorges.

## Methods

**Regional pattern and relief of inner gorges.** We mapped the spatial distribution of ~1,350 km of inner bedrock gorges, defined as continuous areas with more or less symmetric 'valley within valley' morphology[1] from a 25-m digital elevation model (Swiss DHM25) covering the northern side of the Swiss Alps (exclusive of the Jura Mountains). Inner gorges <1 km in length and those inundated by hydropower reservoirs were excluded. We used a laser altimetry (LiDAR)-derived digital terrain model at 2.5-m grid size (Swiss DTM-AV) to inspect the morphology of inner gorge walls in detail. Valley cross-sections were extracted from the DHM25 at representative locations along incised fluvial gorges, yielding a total of 1,627 individual measurements of inner gorge relief. We quantified this inner gorge relief (Supplementary Fig. S1) by projecting the elevation of the formerly glaciated surface or trough wall over the incised gorge to ascertain the elevation difference between this 'surface' and the present floor of the gorge. We avoided measurements across well-defined head scarps of landslides that detached from gorge walls, and caused local but substantial upslope extensions of the valley-in-valley morphology, to avoid overestimating inner gorge relief.

**Rates of bedrock incision, catchment erosion and rock uplift.** Rates of inferred bedrock incision required for post-glacial gorge development were determined by dividing inner gorge relief by the time since deglaciation. We conservatively assigned an age range of 10–15 kyr, which spans the range of the estimated onset of major deglaciation and the chronology of proglacial lakes that were extensive in many of the Alpine trough valleys[9,23,28]. To create a generalized lithologic map of the northern Alps we lumped geologic units into three categories: hard crystalline rocks, weak sedimentary rocks, and carbonate rocks. Rock uplift rates were derived from precision repeat surveys of fixed benchmarks during the 20th century; close spatial correlation with inferred exhumation indicated by apatite fission-track data suggests that the pattern and rates of rock uplift can be assumed as comparable for the Quaternary[26].

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## Author contributions

O.K. mapped bedrock gorge distributions, conducted terrain analyses, and fieldwork; both authors contributed to conceptualizing, interpreting and writing.

## Additional information

The authors declare no competing financial interests. Supplementary information accompanies this paper on www.nature.com/naturegeoscience. Reprints and permissions information is available online at http://npg.nature.com/reprintsandpermissions. Correspondence and requests for materials should be addressed to D.R.M.