The shaping of erosional landscapes by internal dynamics

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Abstract | Erosional landscapes transport sediment downstream, host natural hazards and are geologically active. While perturbations in external forcing, particularly climate and tectonics, sculpt erosional landscapes, similar landforms can be created by internal dynamics, that is, feedbacks between topography, erosion and sediment transport that occur independent of external perturbations. Internal system responses, termed autogenic dynamics, can remain active as landscapes adjust to perturbations in forcing, allowing for complex responses to external perturbations that potentially obscure links between external forcing, topographic form and sedimentary archives. Autogenic dynamics are being increasingly recognized in depositional systems, yet understanding of autogenic dynamics in erosional landscapes is nascent. In this Review, we discuss the mechanisms that contribute to internal dynamics in erosional landscapes. We use examples of autogenic terrace formation, knickpoint formation and river-basin reorganization to show how autogenic dynamics that occur over spatial scales of metres and temporal scales of hours can influence the evolution of mountain ranges over Myr periods. Unravelling the mechanics of autogenic processes allows the interplay of internal dynamics and external forcing to be explored and provides a framework to assess the influence of erosional processes in the geologic record.

Erosional landscapes
Landscapes in which the morphology and rate of evolution are set by bedrock erosion.

Knickpoints
Sections of a river channel that are locally steeper than the sections above and below.

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Erosional landscapes (FIG. 1) reflect a balance between tectonic processes that build mountains and erosional processes that sculpt topography, deliver sediment downstream, store and direct the flow of water and nutrients, and produce natural hazards that threaten human life[1–8]. The topography and erosion rates of such landscapes are often assumed to respond directly to external forcing, such as climate and tectonics, following a clear cause-and-effect relationship[9]. For example, large magnitude storms can induce landsliding, which scars hillslopes and transiently increases downstream sediment yield over months to years[10–12]. Similarly, externally forced drops in relative base level can accelerate river incision over kyr timescales and create steepened river reaches, or knickpoints, that retreat upstream. Examples of external perturbations to erosion rates, which sculpt distinct topographic features such as landslide scars and knickpoints, are well documented[8,13–15]; however, similar landforms and variability in erosion rate can also emerge without external perturbations[16–20].

Under temporally steady and spatially uniform external forcing, internal feedbacks between erosional processes and landscape components (such as adjacent drainage basins) can lead to variable erosion rates that modify topography[21]. The cumulative effects of such feedbacks, referred to as autogenic dynamics[22], are ubiquitous across erosional landscapes. For example, landslides can occur under constant external forcing as oversteepened hillslopes become unstable[23–25]. The deposition of hillslope debris in channels can initiate several internal feedbacks, including transient increases in sediment flux and channel narrowing as landslide material is exported[10,11], river terrace formation[26,27] and the creation of landslide dams that can cause rivers to shift course and erode new valleys[28,29]. Furthermore, landslide dams can influence speciation and habitat connectivity[27,30]. Subsequent catastrophic failure of dams can produce large floods that undermine hillslopes, initiate further landsliding and send sediment pulses downstream[31–33]. Internal feedbacks remain active as landscapes respond to changes in forcing, meaning that topography and erosion rates reflect the interplay between both autogenic dynamics and external forcing[34–38]. As such, autogenic dynamics might obscure the direct cause-and-effect relationship expected following tectonic or climatic perturbation[9,21,22,39–41] (FIG. 1).

Examples of the interplay between external forcing and autogenic dynamics highlight a need for analytical tools that can disentangle the complex effects of both processes. In particular, mechanistic understanding of landscape evolution that accounts for autogenic dynamics is needed to decipher the extent to which climate and

Key points

- Erosional landscapes reflect both internal dynamics and external forcing.
- River terraces can form autogenically by a meandering river undergoing constant, vertical incision.
- Autogenic knickpoints may form from the generation of bedrock bedforms, bedrock meander cut-offs and long-lived landslide deposits.
- Imbalances in the rate of surface-elevation change across drainage divides causes divide migration and can produce complete landscape reorganization.
- Autogenic dynamics in erosional landscapes can occur over spatial scales of metres to hundreds of kilometres and temporal scales of days to millions of years.
- Increased understanding of autogenic dynamics will benefit from explicitly accounting for feedbacks between autogenic dynamics and external forcing in physical and numerical models.

tectonic variability is recorded in topography[15,42,43] and sedimentary archives[9,21,22,41,44]. However, despite decades of work examining the response of erosional landscapes to external forcing[7,42,45,46], the majority of studies do not explicitly consider autogenic dynamics[15,46]. In depositional landscapes, it is increasingly recognized that defining the spatial and temporal scales over which autogenic processes operate provides criteria to separate internal dynamics from external forcing in the geologic record[9,22,39,41,47,48]. Defining such spatial and temporal scales first requires a mechanistic understanding of the processes that drive autogenic dynamics; yet, in erosional landscapes, there have been few efforts to fully characterize either the mechanisms that cause autogenic dynamics or how they interact with perturbations in external forcing[17,18,34,35,38,49–52].

In this Review, we discuss recent progress that has been made in understanding the mechanisms that contribute to internal feedbacks within erosional landscapes and their impacts on topographic form. In particular, we consider the profiles of bedrock rivers, which are commonly related to variations in external perturbations[8,15,43]. Therefore, we focus on several related processes within the river network, namely, autogenic river terrace and knickpoint formation, and autogenic river-basin reorganization. We note that, as integrators of water and sediment fluxes across erosional landscapes, rivers are intimately linked to adjacent and upstream hillslopes, which may have their own autogenic processes[11,29,31,37,53]. For each topic, we review the mechanisms that drive autogenic behaviour and the spatial and temporal scales over which the internal processes influence landscape evolution. We also discuss the potential for preservation of autogenic dynamics in the geologic record. Finally, we advocate for the development of new numerical and physical models to test the interplay of external forcing and internal dynamics in controlled settings, thereby providing a guide to craft field-testable hypotheses and interpret natural landscapes.

Autogenic dynamics
Internal feedbacks between topography, erosion and sediment transport that result in non-steady-state behaviour, even under constant external forcing.

River terrace generation

Over millennial timescales, rivers in erosional landscapes respond to rock uplift by eroding downwards. Lateral erosion can then lead to the formation of river terraces: low-gradient, abandoned riverbeds and floodplains stranded above the reach of recent floods[7,52,54] (FIG. 2). River terrace taxonomy distinguishes strath terraces — with a thin layer of sediment overlying eroded bedrock — from alluvial (fill or fill-cut) terraces formed entirely by sediment[52,55–58]. In addition, terraces can be paired, with terraces at matching elevations on both sides of the channel, or unpaired, with opposing terraces offset in elevation. Terraces often occur at multiple elevations above the channel, thereby preserving a partial record of channel vertical and lateral erosion over millennia[54].

Terrace formation requires that channels shift their banks, either by lateral migration or channel-width change[59], and erode vertically to abandon previously occupied surfaces, forming stepped, cross-valley profiles (FIG. 2). Commonly, terraces are interpreted to form during a pulse of river vertical erosion, driven by a change in external boundary conditions[57,59,60].

The downstream boundary condition, that is, the river base level, is influenced by global to regional perturbations in tectonic uplift, subsidence and eustatic sea level[52,57,61,62]. The river base level can also change on a more local scale, owing to the formation and breaching of natural dams[27,63], interaction of river longitudinal profiles with alluvial fans[36] and co-seismic surface rupture[64]. In addition, tectonic activity and/or changes in climate can influence the upstream boundary condition by altering water and sediment flux, thereby driving fluvial erosion or aggradation[3,57,60,65–67]. As the strath terrace record spans a dated range of ~10^2–10^7 years[54,68–70], it can, therefore, track the influence of climatic changes on 10^4–10^5-year timescales (such as Milankovitch cycles) and long-term changes in tectonic uplift[59].

Autogenic terrace formation. Conceptual models for autogenic terrace formation are long-standing[49]; yet, with occasional exceptions[52,71–73], autogenic river terraces are assumed to be rare and have a weak geomorphic expression as unpaired terraces with limited, along-stream extent[74]. Emerging work, however, shows that autogenic terraces can form via multiple mechanisms and could be common in erosional landscapes[18,75,76]. As outlined above, terraces can form following stochastic landsliding, as landslide-derived debris overwhelms the river's ability to transport sediment, forcing transient channel aggradation or shifting of a river's course[10,11,28,29], which can leave behind fill terraces when rivers resume vertical incision[26].

A river undergoing steady vertical erosion with steady external forcing can also form terraces owing to irregular lateral channel migration[49,52] (FIG. 2a). Numerical experiments reveal that terrace formation owing to irregular lateral migration is plausible for a river with typical lateral and vertical erosion rates (that is, for $E_{Vb}* = E_V h_c / w_c E_L < 1$, where $E_{Vb}*$ is the dimensionless vertical erosion rate, h_c the channel depth, w_c the channel width, and E_V and E_L are the mean vertical and maximum lateral erosion rates, respectively)[18,76]. In the numerical models, the time-averaged rate of channel migration is constant, but spatial variations in lateral erosion occur, owing to the growth of meander bends and drifting of the channel axis across the valley floor. The combination of both vertical river erosion at a steady rate and lateral channel migration creates a planation of strath terraces that are abandoned above the channel (FIG. 2a). Model results[76] indicate that, in landscapes with active lateral channel migration and vertical erosion rates <0.1 mm per year, autogenic terraces that are similar to terraces formed via pulses in vertical erosion induced by climate change will appear. In addition, the flights of autogenic terraces can have age differences of ~10^4 years, consistent with Milankovitch cycles timescales; will be paired, within typical measurement uncertainties (~10^3 years in age and ~1 m in terrace elevation); and can extend tens of channel widths downstream[76].

River terraces can also form autogenically when meander bends self-intersect, forming meander cut-offs (FIG. 2c). When meander cut-offs occur, the elevation drop that was previously accommodated over the entire loop must occur at the cut-off point, thereby forming a knickpoint that can propagate upstream (FIG. 2d). As the knickpoint retreats, it causes a pulse of vertical erosion, lowering the channel bed and increasing the likelihood that surfaces previously occupied by the river will be abandoned as terraces[75]. These terraces are usually unpaired, if the channel width is temporally constant, because planed surfaces preferentially develop on the inside of growing meander bends[75].

Distinguishing autogenic and externally forced terraces. Terraces with overlapping spatial and temporal scales can be constructed through both autogenic dynamics and perturbations in external forcing. However, terraces are used as a key feature for interpreting past changes in external drivers of local base level[57,59,60]. Therefore, it is necessary to create methodologies that can distinguish

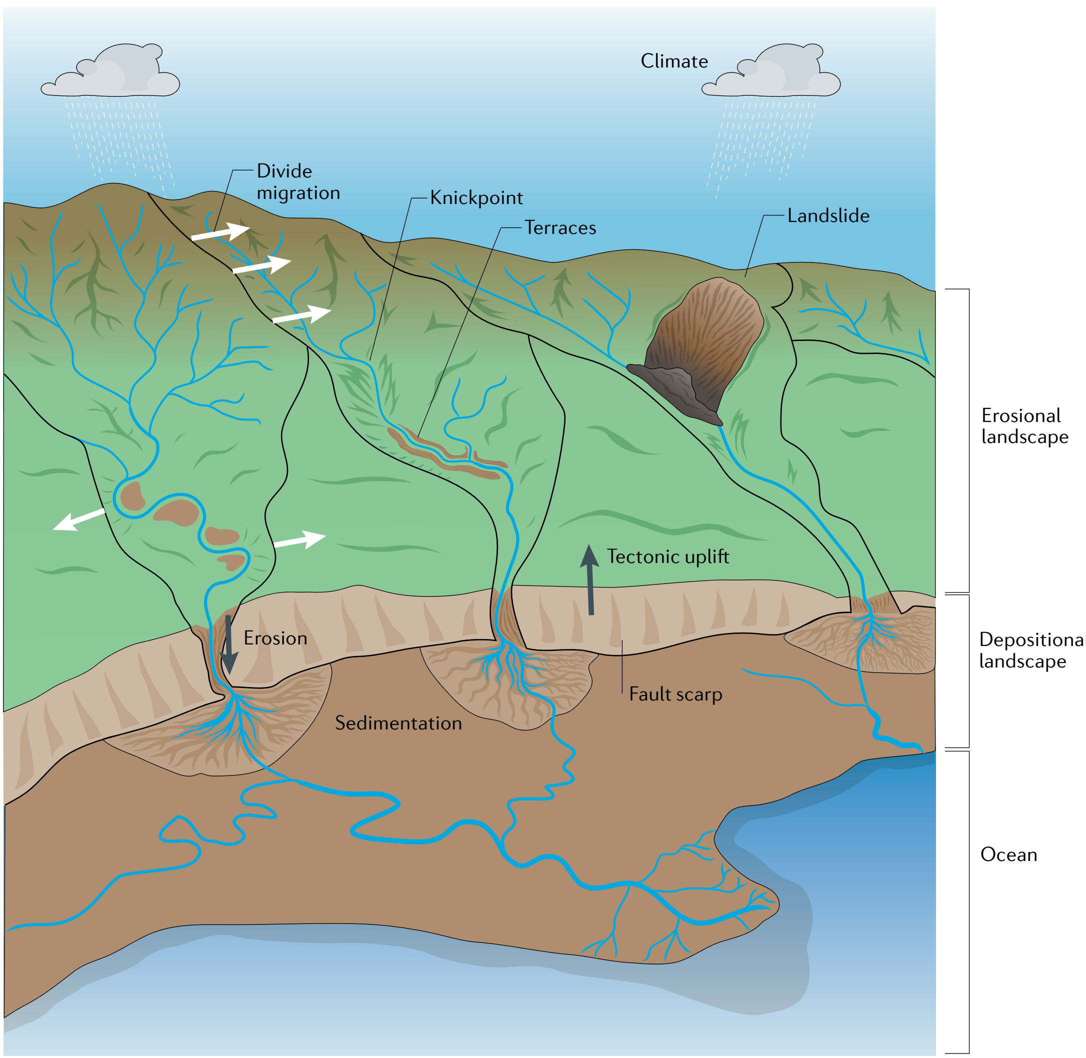

Fig. 1 | **Internal feedbacks in erosional landscapes.** Erosional landscapes are shaped under the combined influences of external forcing and internal dynamics. External forcing includes tectonics and climate, which can dictate the rate of rock uplift, set topographic relief and influence the fluxes of water and sediment. However, internal feedbacks, such as stochastic landslides that can dam rivers or alteration of erosional processes owing to river meandering, can also shape landscapes, even in the absence of perturbations in external forcing. Interaction between internal dynamics and perturbations in external forcing can cause formation of river terraces and knickpoints and the reorganization of drainage basins via divide migration. Distinguishing landscape features that arise from internal dynamics from those that form from perturbations in external forcing remains a major challenge.

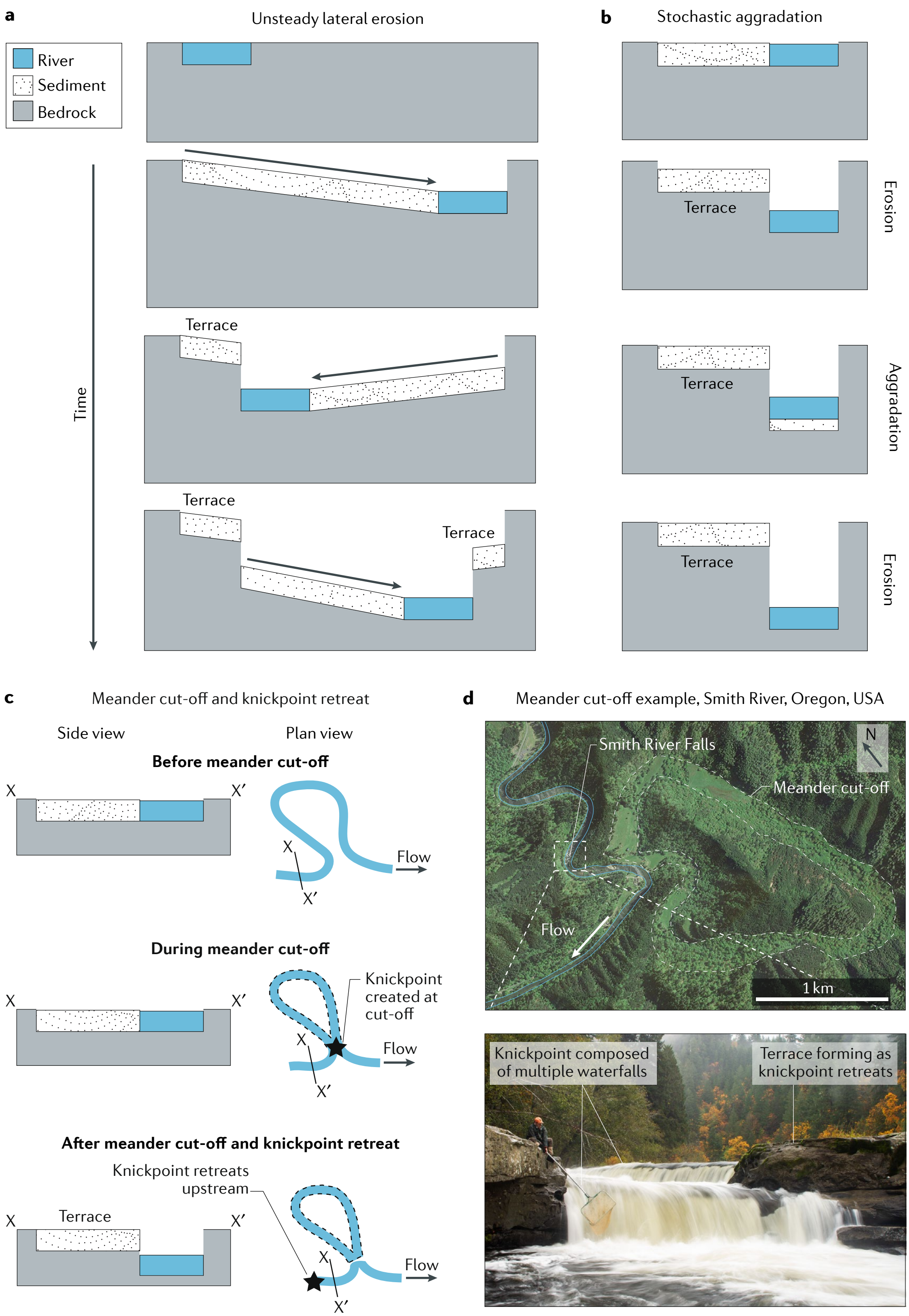

Fig. 2 | **Formation of river terraces by autogenic dynamics. a** | Cross-section view of autogenic terrace formation under constant vertical erosion and unsteady lateral erosion (lateral erosion rates can change in space and/or time). **b** | Cross-section view of stochastic aggradation and erosion in rivers, which makes interpretation of the bedrock erosion rate from terraces sensitive to the timescale of the measurements. **c** | Cross-section and plan views demonstrate how meander cut-off results in autogenic knickpoint and terrace formation. **d** | A meander cut-off example from the Smith River, Oregon, USA[75]. Overview image in panel **d** courtesy of Michael Campbell and the Bureau of Land Management (released under CC BY 2.0).

whether terraces record changes in external forcing or autogenic dynamics, and to explore interactions between external forcing and autogenic processes in terrace formation and preservation (for example, though laboratory studies)[35,77,78].

Clues to disentangling the two possibilities might lie in the spatial patterns of terraces. For example, predictions from numerical modelling of the age and geometry of terraces formed by autogenic processes provide null hypotheses with which to test the significance of terrace features. River meandering models indicate that flights of apparently paired strath terraces separated in age by more than 10^4 years are difficult to form by channel migration under a steady vertical incision rate (that is, without the influence of external perturbations). In fact, the shortest time interval between terrace levels formed through autogenic channel migration is inversely proportional to the vertical incision rate ($t_{vert} = \Delta z/E_V$, where Δz is the typical, metre-scale offset used to distinguish terrace levels), such that, in erosional landscapes (where E_V is typically >0.1 mm per year), $t_{vert} < 10^4$ years[79]. Therefore, paired terraces that are separated in age by $>10^4$ years likely record past perturbations in external forcing[76].

Furthermore, perturbations in climate or tectonics are likely to exert near-equivalent forcings across adjacent drainage basins and, therefore, likely result in consistent terrace ages across multiple basins[60]. By contrast, autogenic dynamics may create unique flights of terraces in adjacent catchments. For example, fill terraces along the San Gabriel River, California, USA were originally ascribed to changes in regional climate[60]; however, new analysis suggests that the terraces are better explained by sediment input from large landslides, as the terrace ages do not correlate with known external perturbations and adjacent catchments do not exhibit terraces of similar age and geometry[26].

It might also be possible to distinguish autogenic and externally forced terraces in sediment flux and erosion rate records. For example, changes in climate or tectonics that cause river downcutting typically result in regionally increased erosion and sediment flux, which might be quantifiable in downstream depositional basins[48,80,81]. By contrast, erosion rates and sediment flux should be constant for autogenic terrace formation via a migrating river eroding vertically at a constant rate.

Even when terrace formation is directly caused by perturbations in external forcing, autogenic processes can obscure the vertical erosion history recorded in flights of terraces. Terraces are commonly used to estimate vertical erosion rates over geological timescales using the elevation difference between a strath terrace surface and the modern river and the age of alluvium that caps the bedrock strath[59,65,66,82]. However, the calculated erosion rates are sensitive to periods of non-erosion (including aggradation)[66]. A compilation of vertical erosion rates estimated from strath terraces demonstrates that the apparent rates of vertical river erosion generally decrease as the temporal baseline of the measurement increases (that is, the age of the terrace). As a result, an increase in apparent erosion rates towards the present is observed[54], consistent with a model of vertical erosion overprinted by stochastic periods of fluvial aggradation (FIG. 2b) and analogous to timescale-dependent sedimentation rates, owing to depositional hiatuses in alluvial systems[83,84].

In studies of river vertical erosion, determination of the ages and elevations of multiple strath terraces across several adjacent river basins will allow more meaningful comparisons of apparent changes in vertical erosion rate and help to identify when stochastic processes modify the vertical erosion history recorded by terraces[54]. Stochastic processes can be autogenic, such as landsliding, or might reflect variability in external forcing (for example, a large magnitude storm or earthquake). Explicitly reporting measurement timescales for river vertical erosion rates can allow the diagnosis and potential correction of stochastic bias in vertical erosion rates[54]. However, it is more challenging to determine whether external forcing or internal dynamics is the source of stochasticity. Identifying the spatial and temporal scales over which autogenic dynamics can induce stochastic variability in sediment flux will aid understanding of whether internal or external processes drive variations in vertical erosion rates and remains a target for future work.

Knickpoint generation

Aside from river terraces, there are several other landscape or bedrock features that can form through autogenic dynamics but are typically interpreted to result from perturbations in external forcing. One critical example is the formation, and propagation, of knickpoints. Under steady, uniform forcing, bedrock rivers develop smooth, concave-upwards longitudinal profiles, where the channel vertical erosion rate balances tectonic uplift[3,7]. Such channels are defined as being in an equilibrium or steady state; however, processes that create spatially variable erosion can break the steady-state form and create locally steeper channel sections, or knickpoints, which can then propagate upstream.

Knickpoint formation is conventionally associated with external perturbations that disrupt the balance between erosion and uplift, owing to changes in tectonically driven uplift[46,85–88], sea level[7,89,90] or climate-induced changes in erosional efficiency[13,35,91]. The linkage between changes in external forcing building relief, for instance, by increasing fault slip rate, and knickpoint creation has led to the idea that knickpoint position and distribution can be inverted for the timing and magnitude of past changes in external forcing[15,92]. The influence of fault slip on knickpoint generation and location has been observed and modelled over scales $>10^1$ km (REFS[85,93–96]), with results demonstrating that knickpoint position and elevation scale with fault displacement rate, the time since generation and catchment drainage area[7,42,43,97,98].

Knickpoint generation near faults occurs at the timescale of co-seismic surface rupture[64] or via exposure of slip along buried faults during river incision[36,37]. The time-integrated effect of small, individual events sums to the larger-scale tectonic forcing over kyr to Myr periods[42], creating knickpoints extending over 10^2–10^4-m length scales. At scales $>10^2$ km, formal inverse approaches have quantitatively used river

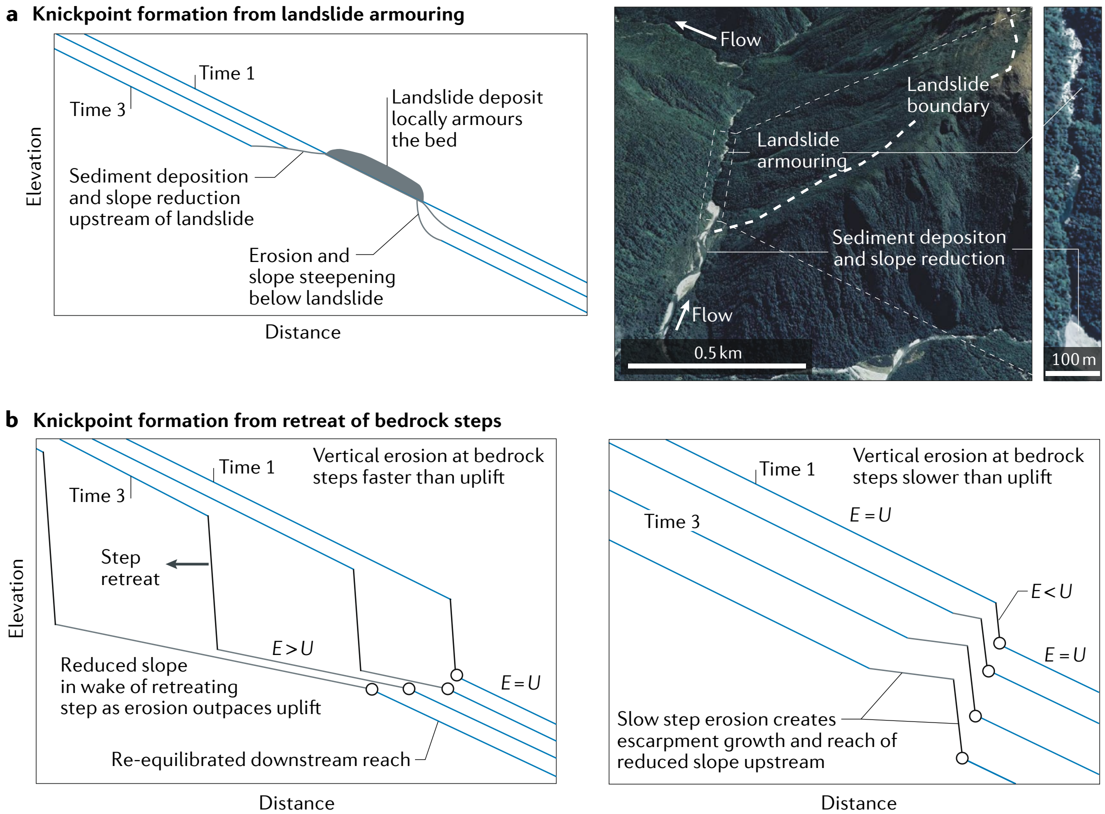

Fig. 3 | **Autogenic knickpoint development. a** | Schematic of knickpoint formation following a large bedrock landslide (left panel) and Google Earth perspective image from the Southern Alps, New Zealand, of a landslide that has caused sediment aggradation with potential for downstream knickpoint development[53]. **b** | The potential changes in channel slope following the formation of bedrock steps with vertical erosion rates (E) faster (left panel) and slower (right panel) than the local rock uplift rate (U). In the slow erosion case (right), vertical incision above the step can create an overdeepened channel, allowing sediment deposition and reducing channel slope. In all schematics, blue lines indicate equilibrium channel reaches, grey lines indicate reaches in disequilibrium and black lines are bedrock steps. Panel **b** adapted with permission from REF.[85], Geological Society of America.

longitudinal profiles to extract uplift-rate variation over Myr timescales[92,99,100]; however, the assumption of a fixed drainage basin configuration that underlies such inversions is often violated[19,101].

In addition, both stationary and migrating knickpoints can be generated by the presence of lithologic heterogeneity in the underlying bedrock[102–104]. Stationary knickpoints are commonly found at boundaries between different rock types, whereas during transient river profile adjustment following external perturbations, contrasts in rock strength owing to changes in rock type, jointing and/or fracturing can create erosion rate gradients that generate migrating knickpoints[102–105]. Rock strength variations can also influence knickpoint propagation rates and landscape response times to base level changes[42,106,107], thereby modulating the expression of external forcing.

Autogenic knickpoint formation. Internal feedbacks following the formation of bedrock bedforms[17,20,35,50,75] and/or sediment input from hillslopes[29,53] can lead to the autogenic formation of knickpoints. Bedrock bedforms, such as repeating bedrock steps, can form under steady, uniform forcing from at least two processes. First, as described above, meander bend cut-off forms bedrock steps with heights equal to the product of channel slope and cut-off loop length[75]. On the Smith River, Oregon, USA, such steps are common and range from ~4 m to 16 m tall[75] (FIG. 2d). Second, experiments and theoretical considerations suggest that bedrock incision in rivers with Froude supercritical flow can lead to the autogenic development of cyclic steps[20,35,50,108–111], which tend to occur with a characteristic spacing set by the flow Froude number, channel geometry and sediment supply[108,110].

Bedrock steps formed through autogenic processes are likely to occur in series and follow a characteristic ratio of drop height to spacing, set by cyclic step formation or meander cut-off frequency[20,75,110]; by contrast, bedrock steps formed from perturbations in external forcing or lithologic heterogeneity are likely to lack such characteristic distributions[85]. However, the geometry of bedrock steps cannot be used to identify knickpoint origin, because autogenic bedrock bedform formation can locally change the processes and rate of bedrock incision, creating complex, non-linear feedbacks that can influence channel slope over regional scales. For example, bedrock step formation locally changes flow hydraulics and sediment transport[112], allowing erosion to proceed either faster or slower than in adjacent reaches[85,113], possibly changing channel slope over km

Supercritical flow
Flow in which the downstream water velocity is greater than the wave speed.

Complex, non-linear feedbacks
System responses that are not in direct proportion to external forcing, owing largely to internal system feedbacks.

scales[85] (FIG. 3). Furthermore, autogenic bedrock steps can form in response to external forcing, for example, increases in tectonic uplift can raise channel slopes and allow the development of cyclic steps; in this case, the increase in channel relief occurs owing to external forcing, but the bedrock bedforms are the result of internal feedbacks[20].

Autogenic knickpoints can also emerge from feedbacks between hillslope erosion, sediment supply and channel incision[29,53]. The sediment deposition in rivers following stochastic landsliding can create a so-called armour layer[114], preventing bedrock incision[29,53,115]. If landslide deposits are long-lived relative to river erosion rates, river reaches shielded by deposits will not erode, while reaches immediately downstream from deposits will experience vertical incision. As a result, the relief between the eroding and non-eroding channel sections increase, creating km-long knickpoints with a scale set by the downstream river incision rate and the duration over which the landslide deposits limit erosion[29,53,115] (FIG. 3a).

Outburst floods from catastrophic failure of landslide dams can also generate periods of rapid river incision, knickpoint formation and large pulses of sediment flux that might potentially be preserved in sedimentary basins downstream[27,32,33,116]. Landslide-initiated knickpoints fulfil the definition of autogenic behaviour if landslides are triggered via internal dynamics rather than external forcing (for example, from stochastic landsliding in an otherwise steady-state landscape or from the retreat of autogenic knickpoints, which can undermine hillslopes)[31,117,118]. However, landslides arising from internal dynamics and perturbations in external forcing both illustrate the complex feedbacks that can occur as hillslopes and channels respond to external forcing and internal dynamics.

Distinguishing autogenic and externally formed knickpoints. The spatial distribution of knickpoints between adjacent catchments or within tributaries of a single catchment provides clues to distinguish autogenic and externally forced knickpoints. For example, knickpoints formed from pulses of uplift along a fault may be spatially correlated with the fault trace across multiple tributaries[15,91,95,119], while a base level change at a catchment outlet can create knickpoints at similar elevations in multiple tributaries of the basin[43]. Autogenic dynamics, by contrast, will not always produce consistent knickpoint distributions within or between catchments. For example, knickpoints formed following stochastic landsliding are unlikely to occur at similar locations in adjacent basins.

Distinguishing autogenic versus externally forced knickpoints along a single river profile, without comparison to adjacent tributaries and basins, remains a challenge. Autogenic knickpoints can form at m to km length scales, where river profiles are characterized by both gentle slopes, where meander cut-off might occur, and steep slopes, where bedrock bedforms and landslides are common. Knickpoints might form as single, steepened reaches, as expected downstream of a landslide deposit, or more complex patterns owing to the generation of bedrock bedforms or the presence of multiple landslides. Similarly, external forcing and lithologic variations can create complex knickpoint distributions within a single catchment. For example, knickpoints formed following landslide events are likely to have similar morphologies to those formed at lithologic contacts, as both cases have a more erodible channel section downstream from a less erodible section. Knickpoint formation following landslides and lithological contacts can be distinguished by the correlation of the former with landslide scars, while the latter should be correlated with changes in rock strength.

Explicit control of external forcing in physical and numerical models can isolate the influence of autogenic processes, allowing the relevant spatial and temporal scales over which knickpoints form to be defined, along with testable predictions of autogenic knickpoint morphology[35,50,86,120]. As an example, knickpoint formation owing to the growth of bedrock bedforms can be explored using numerical models[20,110,111].

While a full description of the autogenic dynamics requires a physics-based model capturing the complexity of a fluvial system[110], it is difficult to model such dynamics for the Myr timescales and km spatial scales over which bedrock rivers evolve. Until detailed, process-based models are developed, simplified treatment of autogenic behaviour can serve as a bridge towards developing more quantitative, physics-based theory. Here, a detachment-limited longitudinal profile model, in which erosion rate follows a modified stream power formulation, is presented[46,121] (FIG. 4), where the vertical rate of change in river profile position is solved as:

$$\frac{dz}{dt} = U - KA^m S^n \tag{1}$$

where z is the elevation of the land surface, t is time, U is the uplift rate, A is the drainage area (which scales with distance along the channel following Hack's law[122]), S is the channel slope and the constants K, m and n lump the influence of rock type, climate and more[7,121]. Theoretical and experimental constraints[20,110,111] suggest that bedrock steps autogenically form when the river slope surpasses a critical value, S_c, resulting in either an increase or decrease in the erosion rates[85,113]. This assumption can be modelled by modifying Eq. 1 with a rate constant, F:

$$\frac{dz}{dt} = U - FKA^m S^n \tag{2}$$

F is set equal to unity for regions where $S < S_c$ and $F \neq 1$ where $S \geq S_c$.

We explored the development of autogenic knickpoints by holding external forcing constant and first allowing the channel to reach steady state under Eq. 1 with uniform uplift of $U = 0.3$ mm per year, $K = 10^{-6}$ per year, $m = 0.45$ and $n = 1$. We then allowed the evolution of autogenic knickpoints to proceed following Eq. 2 with $S_c = 0.08$ for the cases of $F = 0.5$ and $F = 2$ (FIG. 4).

When F is set as 0.5, the model simulates a halving of erosion rates owing to the development of bedrock bedforms and, as the portion of the profile with bedrock

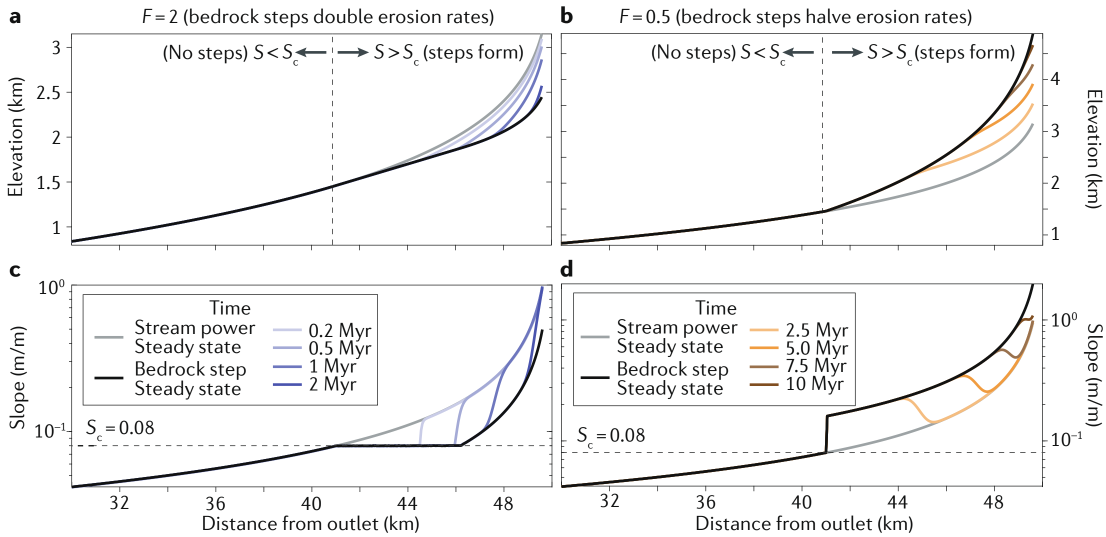

Fig. 4 | **Autogenic knickpoint development under steady and uniform forcing. a,b** | Evolution of river longitudinal profiles. The initial steady state is defined by Eq. 1 (grey lines). After allowing the autogenic development of bedrock steps (Eq. 2), a new steady state emerges (black lines), the morphology of which depends on whether bedrock steps cause erosion rates to increase (panel **a**) or decrease (panel **b**) relative to reaches without steps. **c,d** | The evolution of channel slope for cases where bedrock steps act to increase (panel **c**) and decrease (panel **d**) erosion rates relative to step-free reaches. Coloured lines show the transient profile forms at different times. In all simulations, we solved for drainage area as $A = 6.69x^{1.8}$, where x is distance along the channel. F, rate constant; Myr, million years; S, channel slope; S_c, critical value of channel slope for autogenic bedrock step formation.

steps erodes more slowly than the uplift rate, results in the formation of an autogenic knickpoint. The resulting autogenic knickpoint retreats slowly, leaving a profile steepened by a factor of F in its wake (FIG. 4b,d).

By contrast, when F is set to 2, the model simulates a doubling of erosion rate owing to the formation of bedrock bedforms, which results in the development of a rapidly retreating autogenic knickpoint (FIG. 4a,c). Increased erosion results in the formation of a new steady-state profile that is composed of three distinct sections: a downstream portion that follows Eq. 1 for $S < S_c$, a middle portion with $S \approx S_c$ and an upper portion where channel slope has been decreased by a factor of F relative to that predicted by Eq. 1 (FIG. 4a,c). The middle portion, which has a constant slope, is in a state of dynamic equilibrium, where sustained uplift continually increases channel slopes above S_c, causing enhanced erosion (as $F > 1$) that then reduces channel slope below S_c. For the scenario modelled in FIG. 4a,c, the middle section stretches ~6 km in length, but its extent lengthens with increasing U/K, increasing F or decreasing S_c. The geometry displayed here (that is, long channel segments with relatively constant slope that are downstream of steeper sections with periodic bedrock steps) might serve as a topographic signature of autogenic knickpoint formation and the nature of knickpoint retreat.

The numerical model presented here explores the simplest case of imposing autogenic dynamics under steady external forcing in an isolated river but can be modified to account for interactions between autogenic dynamics and perturbations in external forcing. Although simple numerical models typically prescribe internal feedbacks, rather than letting feedbacks emerge from basic principles[110], their utility lies in the ease with which they can be used to explore the interactions between autogenic dynamics and external forcing. Expanding on such models to generate predictions of landscape metrics that can be field tested and ground truthing model results against laboratory experiments where internal dynamics emerge organically[17,20,35,50,111] might provide a feasible approach to further differentiate autogenic and externally forced knickpoints.

River-basin reorganization

We have, so far, focused on how perturbations in external forcing and autogenic dynamics sculpt topography in isolated drainage basins. However, landscapes are composed of an interconnected network of drainage basins that are separated by drainage divides in the form of topographic ridges. Drainage divides can move gradually via divide migration, erasing the channel network in its path, while growing a new channel network in its wake, or by discrete jumps via stream capture, in which the channel network of one basin is transferred to a neighbour through a breached divide[123].

Even under steady and uniform external forcing, divide migration can take place and trigger internal feedbacks[16,19,124]. In addition, perturbations in external forcing and autogenic dynamics can both increase the level of inter-basin interaction, allowing wholesale river-basin reorganization[4]. Drainage area exchange between basins changes river basin configurations and can create terraces, knickpoints and altered river profiles. As such, the ability to read topographic records of Earth's history, and interpret the sedimentary record, requires an understanding of the disequilibrium landscape features and changing rates of sediment flux that arise through interactions between drainage basins.

Dynamic equilibrium
For river profiles, the case when rivers maintain constant profile form averaged over long timescales but can deviate from equilibrium form over short timescales, owing to ongoing geomorphic change.

Drainage divides
Ridges or hillslopes that create a boundary between two separate drainage basins.

River-basin reorganization
Changes in the geometry and topology of a network of drainage basins induced by gradual drainage divide migration or discrete capture of drainage area.

Drainage divide motion is initiated by differences in the rates of surface-elevation change, $dz/dt = U - E$, where E is the erosion rate[3,4,16,125]. If dz/dt is equal on both sides of a divide, the divide and river-network geometry are stable. However, changes in external forcing, lithologic variability or autogenic dynamics can create spatial variations in uplift and erosion that produce divide motion[4,16,19,38,104,126]. If erosion outpaces uplift within a landscape (leading to a negative value of dz/dt), drainage divides migrate from areas of high erosion to low erosion. By contrast, in regions where uplift outpaces erosion (positive dz/dt), migration is from areas of low uplift to high uplift[19,101].

River basin reorganization and basin-scale disequilibrium landforms are commonly associated with external perturbations that alter channel slope and divert flow across drainage divides. For example, channel flow can be diverted by deposition of rock following volcanic activity or the formation of ice sheets. Evidence of basin reorganization is present in the form of deep gorges cutting across ridges, changing sediment and water sources, or palaeo-valleys filled with volcanic rocks[127–129].

Similarly, tectonic perturbations can reorganize river networks, for example, by diverting river headwaters into a closed basin, tilting the surface to reverse flow or diverting streams to facilitate passage around an area of rapid uplift[123,130,131]. In general, river basin reorganization is interpreted as a direct marker of the river network response to perturbations in external forcing, and changes in sedimentary facies, anomalous network geometry or abandoned river channels are used to infer the forcing perturbation.

Autogenic river basin reorganization. River-basin reorganization and associated disequilibrium landscape features can also occur without, or with little connection to, perturbations in external forcing. Such autogenic basin reorganization is commonly driven by imbalances in the distribution of drainage area among river basins, which is commonly referred to as geometric disequilibrium[19]. Differences in the drainage area of adjacent river basins lead to cross-divide differences in dz/dt, which mobilize divides and start a chain of feedbacks as adjoining basins interact. Geometric disequilibrium can be inherited as nascent river networks form on a pre-existing land surface or it can persist from ancient (>100-Myr) tectonic regimes[16,19,124]. Autogenic basin reorganization can also stem directly from internal dynamics[132,133], such as autogenic bedrock river meandering and knickpoint formation, which create cross-divide differences in dz/dt.

Stream capture, the process by which an 'aggressor' basin experiences a sudden increase in drainage area and basin length owing to the piracy of area and length from a 'victim' basin, demonstrates the complex feedbacks of basin reorganization (FIG. 5). Stream capture results in positive and negative feedbacks that simultaneously move the parts of the basin directly participating in the capture towards equilibrium and push all other parts of the basins temporarily further from equilibrium, as described via χ analysis (BOX 1; FIG. 5). Following stream capture, the increased drainage area in the aggressor basin causes the erosion rate to non-linearly increase, which can force the aggressor to vertically incise, abandoning terraces and forming knickpoints at tributary junctions that will then propagate upstream (FIG. 5). At the same time, the drainage-area decrease in the victim basin reduces its erosion rate, creating a cross-divide imbalance in dz/dt, where the aggressor basin can continue to migrate into the victim basin in a positive feedback loop.

'Aggressor' basin
A river basin that gains area owing to divide migration into a victim basin.

'Victim' basin
A river basin that loses area owing to divide migration from an aggressor basin.

The positive feedback loop driving continued divide migration is counterbalanced by a negative feedback driven by a change in the uplift-to-erosion ratio of each catchment. In the aggressor basin, erosion increases but uplift remains constant following divide capture, forcing the aggressor channel to reduce its slope, lower its erosion rate and move towards an equilibrium geometry. The opposite occurs in the victim basin, and channel slope will increase as equilibrium is approached. When both aggressor and victim basins have balanced erosion and uplift rates, cross-divide differences in dz/dt vanish and divide migration ceases.

In the mainstem channels of the aggressor and victim basins, the negative feedback dominates, which moves them towards geometric equilibrium. By contrast, tributaries to the main stem experience only an indirect change in area, which allows the positive feedback to go unchecked until the tributary knickpoints that carry the signal of area gain from the main stem arrive at the divide (FIG. 5). The end result is a pulse of erosion throughout the aggressor basin that moves the landscape in a single, non-uniform step towards geometric equilibrium.

The ubiquity of autogenic basin reorganization provides a potential mechanism to generate the scale independence, or fractal appearance, of river networks from small headwater catchments to continent-draining watersheds. The scaling between basin size and basin shape is remarkably uniform over much of the Earth's surface, and is best expressed in tectonically quiescent areas[122], leading to the idea that river-network geometry is self-organized[134]. Self-organization requires that drainage divides are mobile features, such that interactions between adjoining basins, and feedbacks from those interactions, create distinct network patterns[40,124,135,136]. Field studies[137], numerical landscape evolution models[101,138–140] and physical experiments[17,133,141,142] have all confirmed that drainage-divide motion, and ensuing non-linear interaction between basins, can create such self-organized networks.

Distinguishing autogenic dynamics and perturbations in external forcing. River-basin self-organization responds to both perturbations in external forcing and internal dynamics. The landscape-scale response, which depends on the relative rates of divide motion and channel erosion[4,101], can be quantified by a divide migration timescale, τ_{dm} (that is, the timescale required for basin geometry to reach a stable equilibrium configuration following a perturbation), and the timescale required for river profiles to return to equilibrium following a drainage-area change, τ_a (REF. [101]). In typical basins, τ_a, which is controlled by the ratio of erosion to uplift,

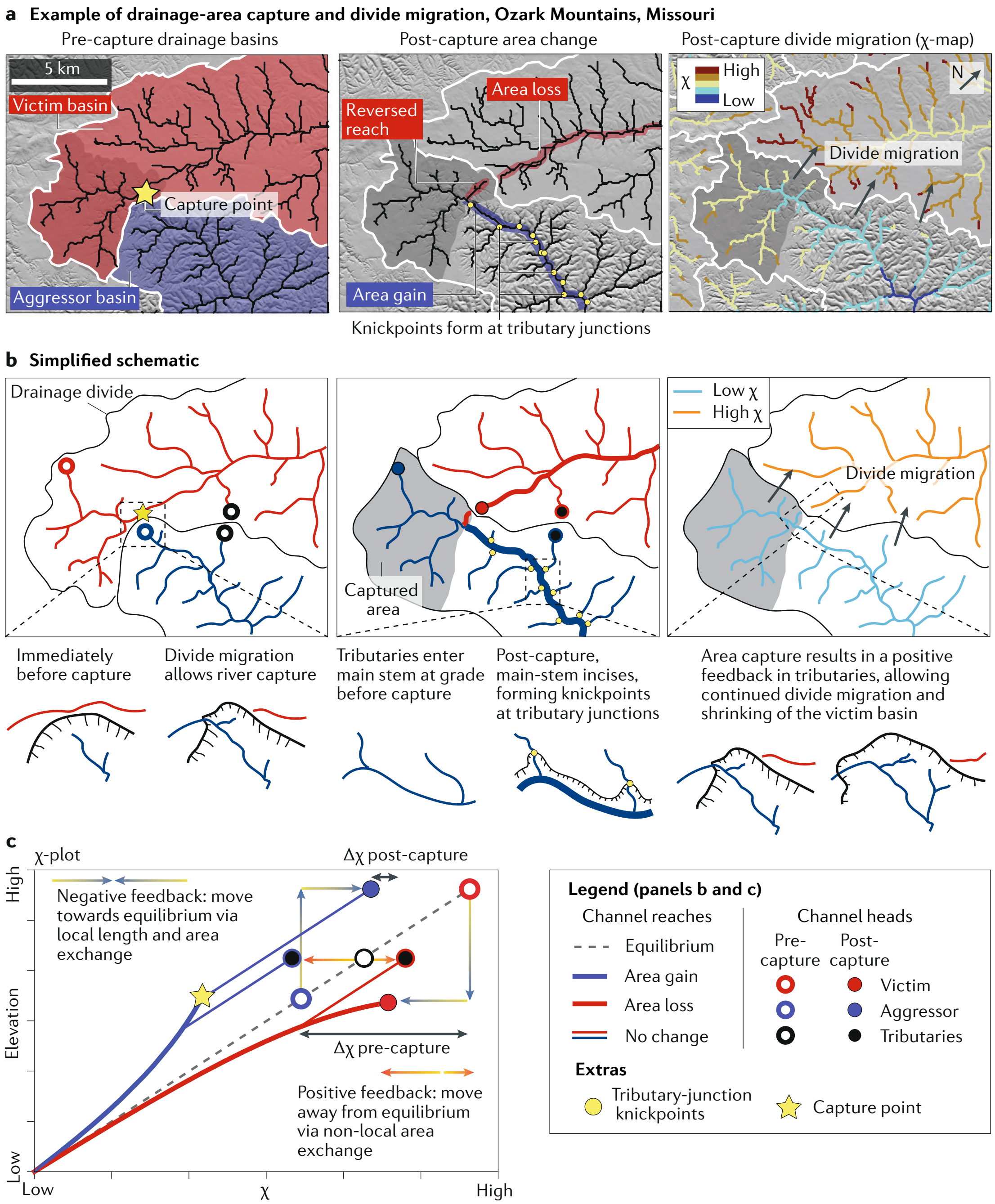

Fig. 5 | **The cascading, non-local feedbacks of stream capture. a** | Example of the capture of a 30-km^2 portion of Flat Creek by the White River in the Ozark Mountains, Missouri, USA[16]. **b** | Simplified schematic of the same event. The assumed pre-capture drainage networks are displayed in the left-hand column, with the drainage networks after capture presented in the middle column, highlighting areas that experience a change in drainage area. Tributaries have no change in drainage area, but in the basin that gains area, increased water discharge allows the main-stem channel to vertically erode, forming knickpoints that propagate throughout the network to communicate the area gain on the main stem. The right-hand column displays a χ-map of the post-capture topography and the likely direction of future divide motion (black arrows). **c** | χ-plot demonstrating the positive and negative feedbacks that occur following stream capture and the means by which the approach towards geometric equilibrium in one part of the basin (main stem) can temporarily move other parts of the basin (tributaries) further from equilibrium. Panel **a** adapted with permission from REF.[16], Elsevier.

is ~1–10 Myr (REF.[143]), whereas τ_{dm} can vary from <1 year in the case of stream capture to >100 Myr in landscapes where the divide-migration rates are vanishingly small and divide migration over several kilometres is required to reach a stable network configuration[16,101].

When $\tau_a \ll \tau_{dm}$, divides move slow enough that adjustment of the channel profile can keep pace with perturbations to the drainage area, thereby maintaining a balance between erosion and uplift rates, even when the landscape as a whole is in geometric

Avulsion
The natural process of river-channel abandonment as flow is diverted from an existing channel to a new channel.

Surface roughness height
A characteristic scale of topographic variation.

Geometric equilibrium
For drainage divides, a state in which divides are stationary because the topology and distribution of drainage areas have adjusted such that erosion rates in all rivers balance the rate of rock uplift.

disequilibrium[101]. River longitudinal profiles in such a system should reflect the combination of external forcing and smaller-scale autogenic dynamics. Nevertheless, because drainage divides are continually in motion, the possibility remains for both slow changes in sediment flux from basins and discrete river capture events, which could trigger autogenic knickpoint and terrace formation (FIG. 5). However, such events should be infrequent for regions with a small τ_a/τ_{dm} (REF.[101]).

Even in regions characterized by small τ_a/τ_{dm}, where perturbations in external forcing should be clearly recorded in river-profile form, persistent drainage-divide migration reduces the erosion rate of victim basins. If erosion falls below uplift rates, victim basins can be uplifted to higher elevations and form low-relief surfaces that are elevated above the surrounding basins. Critically, such elevated, low-relief surfaces could be similar in appearance to basins experiencing a transient response to relative base level fall[38]. Although there is continued debate as to whether or not persistent divide migration alone could be responsible for some of the low-relief surfaces found at high elevations in the Himalayas[144–146], elevated, low-relief surfaces highlight the potential for internal system dynamics to create large-scale landscape features that appear similar to those that arise from perturbations in external forcing.

If divides move rapidly, $\tau_{dm} \ll \tau_a$, river-basin reorganization will outpace the rate at which river profiles respond to perturbations. For example, consider the landscape response to a pulse of rock uplift. Under static drainage divides, bedrock rivers respond to uplift pulses by creating upstream-propagating knickpoints that incise the existing channels back to their equilibrium long profiles, causing no change to the channel network structure[7,15]. However, if mobile divides can modify the former channel network through divide migration before propagating knickpoints can reach a new, equilibrium channel gradient, a pulse of uplift might result in wholesale reorganization of the pre-perturbation channel network.

Such a scenario seems to be likely in the High Plains of North America, where, following an uplift perturbation, newly emerging river networks are replacing pre-perturbation networks, rather than simply entrenching the existing channels[4] (FIG. 6). Obliteration of the previous channel network through rapid divide migration effectively erases any prior topographic records previously recorded within the landscape. In addition, such rapid drainage area exchange can heavily modify topographic metrics that are typically associated with perturbations in external forcing[4,15,19,43]. However, in many landscapes, τ_a/τ_{dm} is likely to be small[101], allowing landscapes to record perturbations in external forcing and autogenic dynamics. Where τ_a/τ_{dm} appears large, the associated large degree of geometric disequilibrium can be easy to identify, as in the High Plains (FIG. 6). Further understanding of channel-network response under rapidly migrating drainage divides will help to identify areas of geometric disequilibrium and allow development of new metrics to read Earth history from topographic patterns[19].

Geologic record of autogenic dynamics

In principle, autogenic processes in erosional and depositional landscapes, as well as their interplay with external forcing, can be preserved in stratigraphic records. The sedimentary record can, therefore, reveal the history of autogenic processes in erosional landscapes whose topographic signatures have been erased. However, variations in sedimentation that are driven by autogenic processes in upland landscapes could be wrongly interpreted to reflect changes in sedimentary-basin or climate-driven dynamics[147,148]. Therefore, accurately interpreting the geologic record requires understanding the autogenic processes involved in both erosional and depositional landscapes[22,41,44].

In alluvial basins, autogenic processes (for example, channel avulsion and migration) create spatial and temporal variability in sediment deposition[22,149], thereby dictating the apportionment of time in stratigraphic records between deposition, erosion and stasis[47,150]. Laboratory experiments of fluvio-deltaic sedimentation indicate the minimum timescale over which sediment flux can be consistent across a basin, termed the compensation timescale[151], and is set by the ratio of surface roughness height to basin subsidence rate[152–154]. Therefore, if the timescales of autogenic dynamics in upland, erosional landscapes are shorter than the typical alluvial compensation timescales of ~10^3 years[155], signals arising from autogenic erosion are likely to be overprinted by autogenic deposition. Fully recognizing

Box 1 | χ analysis

The parameter χ characterizes the scaling between channel length and drainage area in river networks and is often used as a coordinate transformation that accounts for downstream increases in drainage area[174,175]. χ is commonly derived as a geometric term in the steady-state solution to Eq. 1 by setting $dz/dt = 0$, assuming U and K are uniform, introducing a reference drainage area, A_0, and solving for the steady-state elevation of the river network, z, to yield:

$$z(x) = z_b + \left(\frac{U}{KA_0^m}\right)^{1/n} \chi \qquad \text{(b.1)}$$

where

$$\chi = \int_{x_b}^{x} \left(\frac{A_0}{A(x')}\right)^{m/n} dx' \qquad \text{(b.2)}$$

z_b is the elevation at the river base level and x is the channel distance[175].

Eq. b.1 takes the form of a line with a slope equal to $k_s = (U/K)^{1/n}$ if $A_0 = 1$. The parameter k_s, or channel steepness index, represents the channel slope normalized for downstream increases in drainage area and scales monotonically with erosion rate[15,176,177]. Thus, in z versus χ plots, or χ-plots, equilibrium river profiles plot as straight lines[174,175]. Although river profiles are typically assumed to reflect uplift, rock type and climate subsumed into k_s (REFS[15,43]), Eq. b.1 demonstrates that steady-state elevation in a river network depends on both k_s and the basin geometry, which is captured by χ.

Mapping χ across a landscape, as in a χ-map (FIG. 5), can reveal if a landscape is in geometric equilibrium. Landscapes with small cross-divide differences in χ are predicted to be close to equilibrium, with stable divides. By contrast, areas with large cross-divide differences in χ indicate a disequilibrium geometry[19]. River basin reorganization can bring disequilibrium landscapes closer to equilibrium via divide motion that transfers drainage area from basins with low χ to basins with high χ, such that mapping χ allows the general direction and magnitude of divide motion that is required to reach geometric equilibrium to be assessed[19].

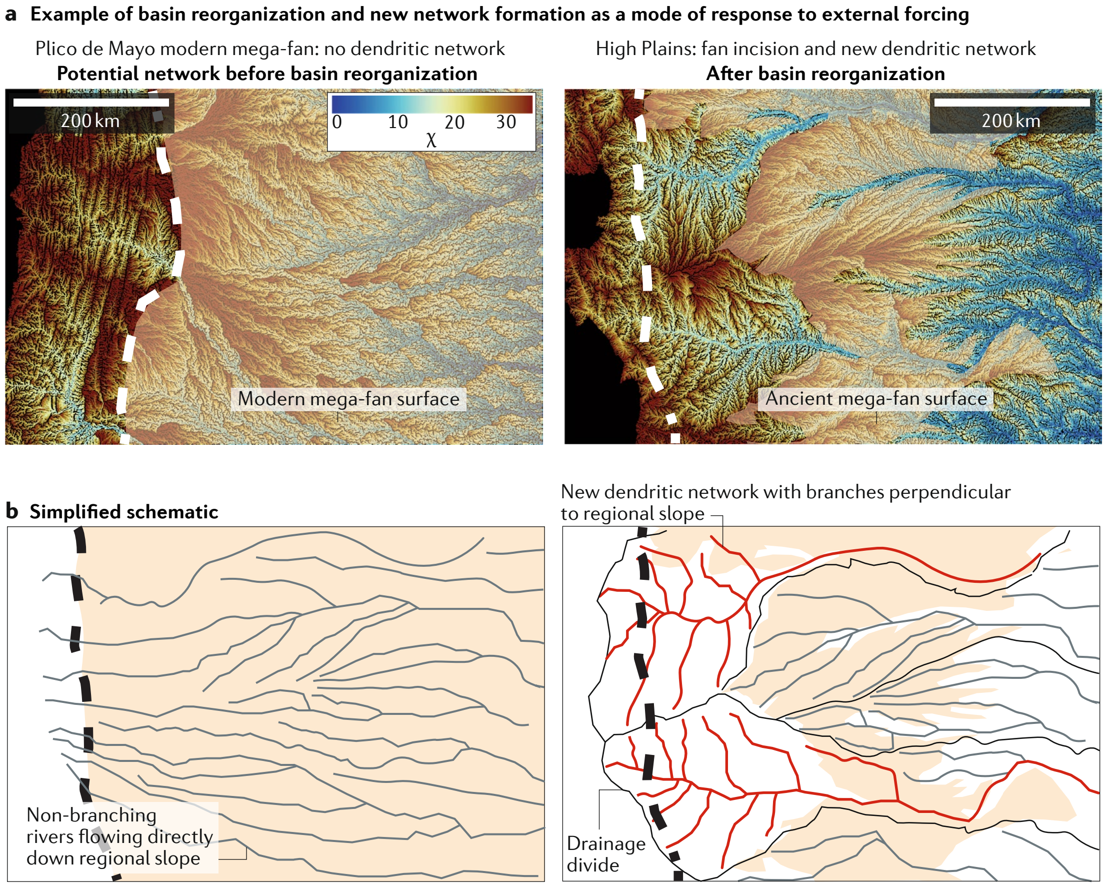

Fig. 6 | **Wholesale reorganization of drainage basins.** Field example of river-basin reorganization of a pre-perturbation channel network[4] (panel **a**) and a simplified schematic of the same process (panel **b**). The left column displays a χ-map of the distributary channel network on the Plico de Mayo megafan, South America. The Plico de Mayo megafan serves as a modern example of the type of network topology that was likely present in the High Plains of North America before the region switched from deposition to incision of the Ogallala megafans. χ-map of the High Plains, following a perturbation in uplift rate, is displayed in the right-hand column. Newly emerging dendritic river networks (with tributaries that flow perpendicular to the regional slope) replace and reorganize the pre-perturbation network (with non-branching rivers flowing directly down the regional slope), rather than simply entrenching the existing channels. The heavy dashed lines represent the approximate positions of the bedrock mountain front and the tan, semi-transparent polygons reveal the approximate extent of fan sediments.

the signals of autogenic erosion, thus, requires detailed depositional chronologies[148,156].

The temporal constraint on observing autogenic erosion in the depositional record indicates that, although short-term, autogenic erosion processes in erosional landscapes might impact alluvial-deposit growth, they might not leave traceable stratigraphic signatures, making their identification difficult. For example, if autogenic knickpoints retreat rapidly, they might increase sedimentation rates downstream; however, such increases will be short lived and cease once knickpoints have migrated through the drainage network[17]. By contrast, if knickpoints retreat slowly, sedimentation rates may be elevated over a longer time period. The increase in sedimentation, however, will be lower in magnitude than that caused by rapidly retreating knickpoints, thereby diminishing its detectability in sedimentary archives[21,22,44]. By contrast, the absence of a sedimentary signal might itself point to an autogenic process upstream, such as the formation of terraces by an incising, meandering river (FIG. 2a), which might impart no change in downstream sediment flux.

Geological preservation is most likely for long duration and large magnitude variations in autogenic sediment flux[21]. For example, disequilibrium in drainage-basin geometry can produce erosion rates that vary by a factor of three and could last over Myr timescales[16,19,138]. Now that some of the mechanisms driving autogenic erosion are recognized, detailed characterization of the timescales and magnitudes of sediment export by autogenic processes in erosional landscapes is possible and will help determine the likelihood that autogenic dynamics will be preserved in stratigraphic records.

Summary and future perspectives

The evolution of erosional landscapes is controlled by tectonic and climatic forcing, autogenic processes of erosion and deposition, underlying lithology and non-linear feedbacks between, and within, these processes and system components. Autogenic processes are ubiquitous across erosional landscapes. They can modulate simple topographic patterns, which are traditionally associated with tectonic and climatic forcing, and induce additional stochasticity in downstream sediment flux. By considering both the autogenic processes and external forcing that together shape erosional landscapes, we provide insights into the mechanistic origins of landscape form and the historical record that is preserved in topographic and stratigraphic records.

Despite ongoing progress in defining the mechanisms that drive autogenic dynamics in erosional landscapes, we largely lack criteria to distinguish the influence of internal dynamics and perturbations in external forcing in a variety of settings, including bedrock rivers. Although comparison of features such as terraces and knickpoints in adjacent basins might help to identify externally forced landscape features[26,157], autogenic dynamics can act to modify or overprint such features. We suggest that the most pressing work in erosional landscapes is to further define the spatial and temporal scales over which autogenic processes operate[9,22,41,44,47,48,158] and, thus, provide quantitative criteria to separate internal dynamics from external forcing. Once the impacts of individual autogenic processes are isolated, we can then investigate the more common scenario where interactions between multiple autogenic dynamic mechanisms, or between autogenic dynamics and external perturbations, modify landscape patterns and sediment flux.

Progress is difficult to accomplish by field data analysis alone, owing to the many processes and feedbacks present. While physical and numerical models can isolate aspects of autogenic dynamics and external forcing, applying the findings to full-scale, natural landscapes with multiple geomorphic processes provides an additional challenge.

Understanding the role of autogenic dynamics in landscape evolution is most likely to come through a two-pronged approach. First, we must identify the small-scale physics that drives autogenic dynamics through detailed experiments, fieldwork and theoretical development, as reviewed above. Second, although incorporation of autogenic processes into landscape-scale theory and experiments should be a fundamental goal of future research, application of more complicated models to large spatial scales or longer temporal periods can be computationally expensive and difficult where model inputs are poorly constrained. Instead, we suggest that more rapid progress will come through development of simplified landscape evolution theory, which can feasibly be applied to large spatial and temporal scales, while capturing the essence of autogenic dynamics and their interactions across landscapes[9,159].

For example, consider the case of autogenic knickpoint development from the generation of bedrock bedforms (FIG. 4). Applying existing theory[110] for bedrock bedform generation is not currently practical over continental spatial scales and Myr timescales. However, the simplified model presented above is guided by process-based theory, experiments and field observations[20,35,50,85,108,110,111], which enables autogenic behaviour to be modelled over landscape evolution scales. Such models create predictions for the spatial and temporal scales of autogenic dynamics, which can be tested through fieldwork and in experiments. Additionally, models of simplified landscape evolution can easily be modified to include interactions between autogenic dynamics and perturbations in external forcing.

Both numerical and physical experiments have already succeeded in exploring landscape evolution with simplified descriptions of autogenic dynamics. Simplified numerical models of bedrock river meandering have been used to reveal the autogenic dynamics of both knickpoint and terrace formation[18,75,76]. A future target is to further integrate such models within a landscape evolution framework; for example, to explore links between bedrock meandering and divide migration[132,160,161]. Similarly, inclusion of simplified river incision rules that depend on sediment flux has allowed numerical exploration of hillslope–channel coupling[37,51,120,162–169], which shows fundamentally different behaviours compared with cases that exclude such feedbacks.

Furthermore, in physical experiments, relaxation of rigorous scaling has allowed the evolution of entire mountain ranges to be explored[159]. For a bedrock analogue, such experiments typically use cohesive sediment that erodes via shear detachment from overland water flow[17,141,170,171], rather than from abrasion of impacting particles, as is common in bedrock rivers[3,114,172]. Despite the simplification, such experiments resemble natural landscapes and show complex autogenic behaviour, including drainage basin reorganization, stochastic sediment flux and the formation of knickpoints and terraces[17,141,159,170,171,173].

We emphasize that robust, physics-based theory, aided by rigorously scaled experiments and careful field observations, is a necessary prerequisite for generating simplified models that appropriately balance realism and practicality. Although such an approach is not a substitute for continued work that establishes small-scale physics within larger-scale contexts, simplified numerical and physical models can guide ongoing field studies and serve as a necessary bridge between ignorance of autogenic processes and their full integration in landscape evolution theory.

Ongoing work to describe how internal dynamics manifest in topography and drive temporal variability in erosion is leading to fundamental progress in our ability to predict landscape evolution, mitigate natural hazards and solve challenges from controls on speciation to the distribution of surface water across landscapes[1,2,4,76,101]. Research continues to reveal a number of previously unknown actors that rival the role of climate and tectonics in shaping topography and controlling landscape evolution, which have classically been considered to have leading roles. Further understanding the role of autogenic dynamics provides an exciting opportunity to better constrain how internal and external processes interact on the planetary stage.

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