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The influence of climate on the tectonic evolution of mountain belts

Kelin X. Whipple

Simple physical arguments, analogue experiments and numerical experiments all suggest that the internal dynamics of actively deforming collisional mountain ranges are influenced by climate. However, obtaining definitive field evidence of a significant impact of climate on mountain building has proved challenging. Spatial correlations between intense precipitation or glaciation and zones of rapid rock-uplift have indeed been documented in numerous mountain ranges, and are consistent with model predictions. More compelling evidence — such as tectonic changes in response to (rather than just coincident with) climate change — has, however, rarely been documented. Triggered by a climate-driven increase in erosion rate, friction-dominated mountain ranges are expected to show a number of simultaneous responses: a decrease in the width of the range, a temporary increase in sediment yield, a persistent increase in the rate of rock uplift and a reduction in the subsidence rate of surrounding basins. The most convincing field evidence for such a coordinated response of a mountain range to climate change comes from the European Alps and the St Elias range of Alaska.

In the mid-1980s, advances in understanding the mechanics of the fold-and-thrust belts that flank many collisional mountain ranges set the stage for a fundamental change in our appreciation of the role of erosion in the tectonic evolution of mountain ranges. A combination of sandbox experiments, analytical treatments of stress state and field observations showed that fold-and-thrust belts form tapering wedges[1–3]. A growing wedge deforms internally until a critical surface slope (taper) — governed by its material properties and basal-thrust geometry — is established. At this point, the wedge has sufficient internal strength to allow slip on the basal thrust, as required by ongoing tectonic convergence[1–3]. Erosion tends to thin orogenic wedges, changing the stress state and thereby inducing a deformational response to restore the critical taper. Thus, in such critical-taper wedges, erosion is not simply a passive process occurring in response to tectonically driven rock-uplift and relief-production; rather it exerts a direct first-order influence on the tectonic evolution of the system.

A few years after the advent of critical-taper theory, researchers had demonstrated, at least qualitatively, that the rate and pattern of erosion of critical-taper orogenic wedges effectively dictates many aspects of the tectonic and structural evolution of mountain belts. These aspects include the width of the mountain range, structural style, the longevity of exhumational structures, the rate and pattern of internal strain, near-surface rock uplift rate, the pressure–temperature–time pathways of rocks and the spatial distribution of metamorphic facies in exposed rocks[4–7].

These pioneering researchers also evaluated the effects of asymmetry of erosional efficiency on orogenic evolution. Erosional efficiency determines the rate of erosion for a given topography, and depends on rock type, debris size and climate. The expected deformational and exhumational response to such asymmetry — induced by enhanced precipitation on windward slopes and rainshadow development on leeward slopes — is well matched by near-surface rock-uplift patterns and the metamorphic grade of exposed rocks in several active mountain ranges, such as the Southern Alps of New Zealand, the Olympic Mountains of Washington State, and the Himalaya[4,7,8]. Over the next decade, numerical experiments quantitatively demonstrated these concepts, supporting the contention that the tectonic asymmetry of the Southern Alps in particular is largely attributable to the pattern of rainfall[7–12] (Fig. 1). The development of the Central Andean Plateau and the limited late-Cenozoic deformation along its western margin is similarly consistent with the expected response to low erosion rates in the Atacama Desert[6,13,14].

Although most easily quantified for critical-taper wedges, erosion is expected to be equally or even more significant in thicker, hotter collisional systems, including plateaus. Whereas critical-taper theory assumes frictional deformation throughout the wedge, thermally activated viscous deformation becomes important as depth and temperature increase. Moreover, such thermally activated, and potentially strain-rate dependent, viscous deformation may trigger additional positive feedback loops between erosion, geothermal gradient, exhumation pathways, strain rate and strain concentration[15–17]. Beaumont *et al.*[15] showed that ductile extrusion of a belt of high-grade metamorphic rock from under the Tibetan Plateau could be facilitated by rapid erosion at the plateau margin and could explain many key observations pertaining to the tectonic history of the Himalaya (Fig. 2). Zeitler *et al.*[17] and Koons *et al.*[16] showed that similar mechanisms could explain geological observations of intense local domal-uplift and exhumation in the Himalayan syntaxes at Nanga Parbat and Namche Barwa.

The need for field evaluation

By the start of the twenty-first century these provocative ideas about the role of climate in the tectonic and structural evolution of active collisional mountain belts were becoming widely appreciated. Indeed, the essential argument had been demonstrated to be insensitive to the details and specific limitations of the various numerical and analogue experiments. These model-inspired ideas, however, remained to be rigorously tested[18]. This brief review focuses on the question of how to formulate effective field tests of the hypothetical links between climate and the tectonic evolution of active collisional mountain belts, and presents an assessment of the progress in such efforts so far. Although models (analogue, analytical or numeric) are necessarily simplified abstractions of reality, they yield specific, testable hypotheses and can be effectively

School of Earth and Space Exploration, Arizona State University, Tempe, Arizona 85487, USA. e-mail: kxw@asu.edu

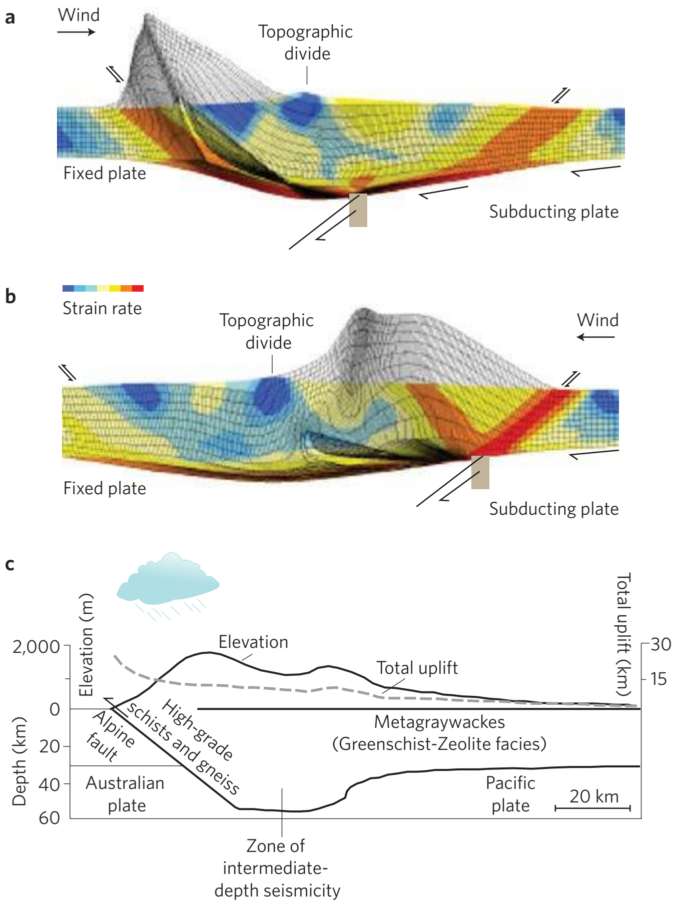

Figure 1 | Unidirectional moisture flux and mountain-belt evolution. **a**,**b**, Results of numerical models aimed at understanding the exhumational and structural response of mountain belts to unidirectional moisture flux. Tectonic convergence velocity and subduction direction in the models match conditions for the Southern Alps of New Zealand. In **a**, moisture-laden winds arrive from the west (left). Uplift and exhumation, indicated by the extension of the Lagrangian tracking mesh above the topographic surface (top of the coloured domain), is focused over an active thrust fault (orange band to the west, indicating high strain rate). In **b**, moisture-laden winds arrive from the east (right). Both uplift and exhumation are focused east of the drainage divide. The western thrust fault (the same as in **a**) is nearly inactive. **c**, The observed topography and pattern of total uplift and exhumation (difference between topography and total uplift) in the Southern Alps closely match the numerical experiment shown in **a**. Panels **a** and **b** used with permission from ref. 8 (© 1999 AGU); panel **c** reprinted with permission from ref. 7 (© 1990 GSA).

used as a guide to what observations are needed to determine whether a climatic influence on the tectonic evolution of active mountain belts is demonstrable, and over what time and space scales data are most needed.

Analogue laboratory experiments clearly document that the rate and pattern of erosion directly and significantly influence the style, pattern and rate of rock deformation in a manner generally consistent with expectations for critical-taper wedges. Analogue experiments have demonstrated erosional control of several factors: the relative concentration of strain on pro- and retro-thrusts[19,20]; particle trajectories, and by implication the pressure–temperature–time paths and the associated distribution of metamorphic rocks exposed at the surface[7,20]; the steepness and lifetime of frontal thrusts[20–22]; and the rate and location of underplating and the associated development of structural duplexes[21,23]. Both analogue and numerical experiments on critical-taper wedges have further demonstrated the potential for highly localized deformational response to concentrated erosion[22–25]. Similar experiments have explored temporal, semi-periodic variation of deformation in fold-and-thrust belts[20,26]. Thus, analogue experiments provide a partial, but important, test of model predictions in a controlled laboratory setting, and highlight potential influences on the evolution of individual faults poorly captured in most continuum models.

Recent advances — that explicitly quantify the strength of interactions between erosional efficiency, mountain-belt width and rock uplift rate in space and time[27–32] at mountain-range scale in frictional critical-taper wedges — provide an effective template for highlighting the field observations required to definitively test the core hypotheses outlined above. These models are highly simplified to allow analytical solution and are most suited to provide illustrative guidance to expected behaviour. Moreover, model predictions discussed below are resolved at the mountain-range scale, not at the scale of individual thrust faults. Essential results are a consequence of mass balance and the notion that erosion rates increase with topographic relief[28,33,34], and therefore are robust to model details[30].

Published solutions are limited to frictional rheology, but one may turn to numerical models of hot, viscous orogens to highlight how feedbacks between erosion and rheology may alter climate–tectonic interactions. In the following sections, I review the fundamental behaviour of three types of orogenic systems: fixed-width or inactive systems; narrow, frictional critical-taper wedges (such as Taiwan's Central Range and the Southern Alps of New Zealand); and large, hot orogenic systems (such as the Himalaya and Tibetan plateau). The fixed-width orogenic system is not realistic, except for inactive ranges, but serves as a useful tool for comparison. This comparison highlights what observations can and cannot be taken as supporting the proposed climatic control of orogen evolution.

The fixed-width system

The fixed-width is a simple, hypothetical system in which no interactions between the rate and style of deformation and climate-driven erosion are allowed, as is assumed in most landscape-evolution models forced with prescribed patterns of rock uplift[35,36]. As in some of these models, it is also assumed that topography is isostatically compensated in the fixed-width system. Analogous to an iceberg, most of the mass of a mountain range is in its crustal root (Fig. 3a), in proportion to the relative densities of the crust and mantle. In accord with the Archimedes principle, rocks will rise vertically to restore isostatic balance in response to erosional removal of mass in both tectonically active and inactive settings. If accretionary flux, F_A, is set to zero, the fixed-width system is a good analogue for inactive mountain ranges such as the Sierra Nevada[37] or the Appalachian Mountains[38].

For simplicity, the fixed-width system assumes simple block-uplift at a rate determined by the tectonic mass influx. In the case of no erosion, the near-surface rock uplift rate, U, is equal to cF_A/W, where c is the isostatic compensation factor ($c \sim 1/5$ for Airy isostasy)[39] and W is the width of the range (Fig. 3a) — most of the mass added must contribute to the crustal root to maintain isostatic balance. In the presence of erosion that increases with regional slope or topographic relief, the range grows in height until the erosion rate is equal to F_A/W, at which point a balance between tectonic influx and erosional efflux, F_E, is achieved[40]. Under this condition, both topography and crustal thickness are steady[41] and the near-surface rock uplift rate balances the erosion rate ($U = F_A/W$ everywhere).

The climate-modulated erosional efficiency dictates the relief required to erode at this rate. Higher erosional efficiency (wetter climate) means lower steady-state relief[42] (Fig. 3a), but no difference in steady-state rock uplift rate (F_A/W in all cases). An east–west difference in erosional efficiency can be expected to produce a topographic asymmetry with a steeper slope corresponding to lower erosional efficiency, but again with no effect on the tectonics:

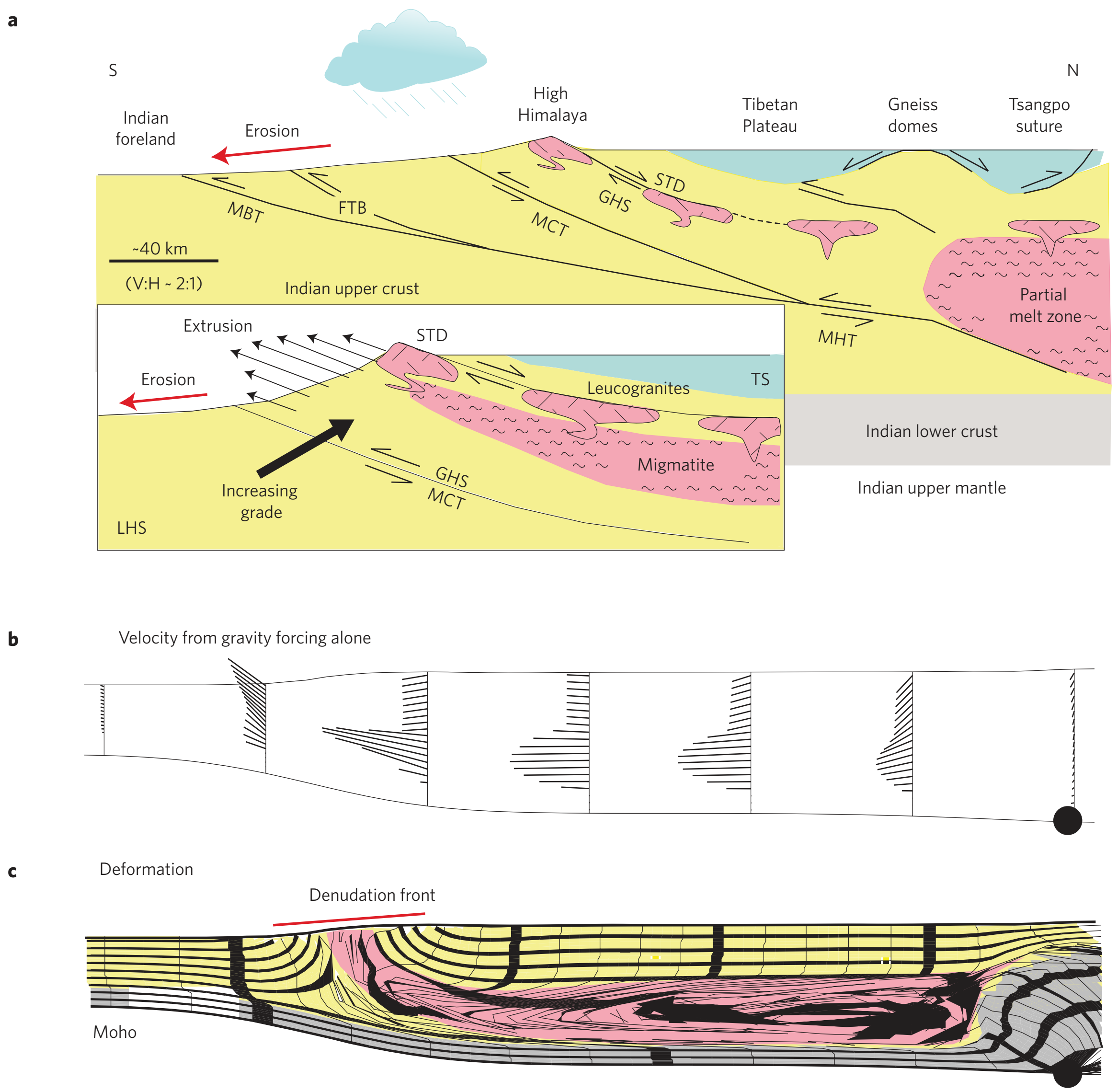

Figure 2 | Erosionally driven channel flow in the Himalaya. **a**, Schematic cross-section perpendicular to the Himalayan orogen. MBT, FTB, MCT, STD, LHS and GHS refer to main boundary thrust, fold-thrust belt (Siwaliks), main central thrust, south Tibetan detachment, lesser and greater Himalayan sequence metamorphic rocks, respectively. Note 2:1 vertical exaggeration (V:H – 2:1). Rapid erosion and removal of material at the southern margin of the Tibetan Plateau allows the movement of a channel of hot, weak ductile rock (pink regions) from beneath the plateau to its margins, as detailed in the inset. The channel-flow hypothesis[15] can explain a number of key attributes of Himalayan geology, such as extrusion of the GHS by means of contemporaneous slip on the MCT and STD, the conditions and timing of metamorphism in the GHS and LHS and, plausibly, the formation of the chain of gneiss domes north of the Himalaya. **b**,**c**, Numerical model results. The model domain is similar to that in **a**; the black circle shows position of modelled mantle–lithosphere subduction. Lines in **b** show the component of rock velocity due to erosion and gravitational effects alone (velocity vectors are in the vertical columns), illustrating channel flow. The pink zone in **c**, with greatly disrupted Lagrangian tracking mesh, shows the deformation pattern resulting from channel flow. Colours in **c** are as in **a**. All panels reprinted with permission from ref. 15 (© 2001 NPG).

$U = F_A/W$ everywhere as prescribed by the block-uplift kinematics. During a transient response to an increase in erosional efficiency, however, there will be a passive isostatic rebound in response to erosional unloading. For a time, the erosion rate will exceed F_A/W and the excess volume of rock previously stored in the topography and crustal root will be delivered to surrounding depositional basins, temporarily increasing F_E to greater than F_A (Fig. 4b,c).

Observations of quasi-steady balance between erosion and rock uplift rate (in Taiwan, the Southern Alps of New Zealand and the Olympic Mountains, among others)[43–46] and documentation of an isostatic rebound in response to accelerated erosion have at times been offered as evidence for a climatic influence on tectonics. However, both of these arise in the hypothetical fixed-width system characterized by simple block-uplift driven by independent tectonic processes. Thus, neither observation provides a test or demonstration of the dynamic interactions seen in coupled models, whereby the climate-modulated erosional efficiency directly affects internal deformation patterns, structural configurations and the rates and patterns of rock uplift. A demonstration of isostatic rebound[47,48] and/or increase in sediment delivery to basins[49,50], in response to the onset of Quaternary glaciation, supports the argument that this climate change enhances erosional efficiency, but does not lend support to the hypothesis that there is a profound link between climate and tectonics. We must look for evidence of connections beyond the well-established isostatic rebound to erosional unloading which operates even in inactive mountain ranges[51].

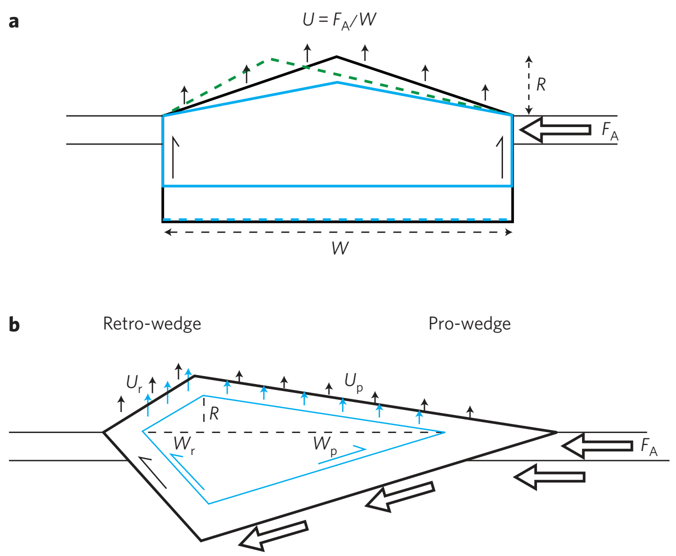

Figure 3 | Analytical landscape-evolution models. Solid lines in both panels show topography and crustal root for low (black) and high (blue) erosional efficiency. **a**, Fixed-width orogen. The width of the orogen (W) and the accretionary flux (F_A) remain constant. Arrows show invariant steady-state near-surface rock uplift rates (U; assuming simple block-uplift). Climate-induced changes in erosional efficiency may lead to changes in relief (R) but do not affect the tectonics. Similarly, asymmetry in erosional efficiency leads to asymmetric topography (dashed green line), but no change in rock uplift rates. **b**, Critically tapered wedge. U_r and U_p are near-surface rock uplift rates (the length of the arrows are proportional to the uplift rates) on the retro- and pro- sides of the wedge, which have widths W_r and W_p, respectively. For constant accretionary flux, a climate-induced increase in erosional efficiency leads to a reduction in wedge size (blue lines) and a commensurate increase in the steady-state near-surface rock uplift rates (blue arrows).

Friction-dominated, narrow mountain-belts

Quantitative comparisons of system response to tectonic or climatic change in the hypothetical fixed-width model and the well-studied critical-taper wedge system (Fig. 3b) can provide insight into specifically what criteria can be used to diagnose a dynamic response of active tectonics to climate or climate change. Figure 4 illustrates system responses to both climatic and tectonic perturbation using the relations in Whipple and Meade[29]. Note that all variables in Fig. 4 are reported in non-dimensional form (see Supplementary Information). Interestingly, the non-dimensional signal of total sediment delivery to adjacent depositional basins (F_E^*; Fig. 4c) is identical in the fixed-width and critical-taper wedge systems and thus provides no evidence for or against dynamic interactions between climate and tectonics. However, both analytical[29] and numerical[31] models have shown that a tectonically driven increase in F_E would be associated with an increase in the width and relief of the mountain belt, the opposite of expectations for a climatically driven increase in F_E.

Thus, a diagnostic criterion for a climatic influence on tectonics is that an increase in sediment delivery to basins, driven by climate change, should be accompanied by a retreat of active deformation to the interior of the range, and a commensurate reduction in the foreland subsidence rate or even the flexural-isostatic uplift of the foreland[6,7,31,52] (Fig. 4a). Conversely, a tectonically driven increase in sediment delivery should be accompanied by progradation of the deformation front into the foreland and accelerated subsidence in response to the increased topographic loading. The advance or retreat of the deformation front will often be preserved in the structure and stratigraphy of foreland basins and, together with information on sediment flux into the foreland, may be diagnostic of a dynamic tectonic response to climatic forcing.

Quaternary evolution of the St Elias range of Alaska and Mio-Pliocene evolution of the European Alps are examples of the importance of the stratigraphic record of deformation for diagnosing a tectonic response to climate change. Berger *et al.*[53] document a contemporaneous Quaternary increase in sediment yield and a cessation of deformation at the toe of the wedge that they associate with an increase in the intensity of glaciation at 1 Myr. Similarly, Willett *et al.*[54] document that an increase in sediment yield[49,55] associated with climate change at ~5 Myr[47,56] was synchronous with retreat of the active deformation front on the southern flank of the European Alps. Both studies infer that continued deformation was concentrated in the interior of the range. These responses are precisely what is expected for a narrow convergent mountain range subjected to an increase in erosional efficiency[6,28,29,31,52] (Fig. 4). Although both examples lack a definitive demonstration of enhanced slip on interior faults, they do seem to make a strong case for tectonics responding to climate. However, there is a complication in the European Alps: convergence rate has declined since the Late Miocene[57–59]. If this decline was roughly synchronous with climate change, as is plausible[57], this coincidence of tectonic- and climatic-forcing could explain the simultaneous increase in sediment flux and retreat of the deformation front even without a tectonic response to erosion. This seems an unlikely coincidence given the close timing of events[54]. Nonetheless, additional criteria for a tectonic response to climate should be explored.

A second diagnostic criterion is that responsive critical-taper wedge systems experience a persistent change in the near-surface rock uplift rate that is sustained well beyond the initial isostatic response to erosional unloading. Both the critical-taper wedges and the fixed-width mountain belt experience identical, isostatically induced initial changes in rock uplift rate (Fig. 4d). The difference is that in the fixed-width, non-responsive system, rock uplift rate relaxes exponentially back to its pre-perturbation value ($U = F_A/W$). The magnitude of the persistent change in rock uplift rate in the critical-taper wedge depends on many factors, including: the particulars of erosion process mechanics[28,30–32], the degree to which the strength of rocks and fault surfaces at depth are strain-rate and temperature dependent[11,16] and whether the inclination of the basal decollement adjusts with range size[27,28]. Thus, the curves shown in Fig. 4 are illustrative examples only — the magnitude of the persistent change in rock uplift rate, relief and range width could be greater or smaller than shown.

The shared initial isostatic response means that if the second diagnostic criterion was considered in isolation, only observations of accelerated rock uplift that persist for more than twice the characteristic system response time ($T^* > 2$, Fig. 4d) after a pronounced climate change can be considered strong evidence for a climatic influence on tectonics. The controls on system response time are therefore critically important. Perhaps surprisingly, the response time (τ) is predicted to depend primarily on the post-perturbation erosional efficiency and only secondarily on wedge size or convergence velocity[29].

Knowledge of the system response time is required to assess whether the post-Miocene evolution of the European Alps, for example, satisfies this second criterion for a tectonic response to an increase in erosional efficiency. An example calculation for Taiwan's Central Range (τ ~1 Myr; ref. 29) probably represents a minimum given the vigorous erosional environment[60,61]. Tomkin and Roe[32], using an analogous formulation for glaciated ranges, estimate τ ~1.5 Myr for the Southern Alps of New Zealand where erosion is similarly vigorous (probably also applicable to the St Elias range), but τ ~5.5 Myr for the European Alps. If these estimates are even approximately correct, this implies that only in areas experiencing the most vigorous erosion (moderately weak rocks, extreme precipitation and/or glaciation) will it be possible to demonstrate a tectonic response to Quaternary climate change based on exhumation-rate data alone (subject to uncertainties in estimating exhumation

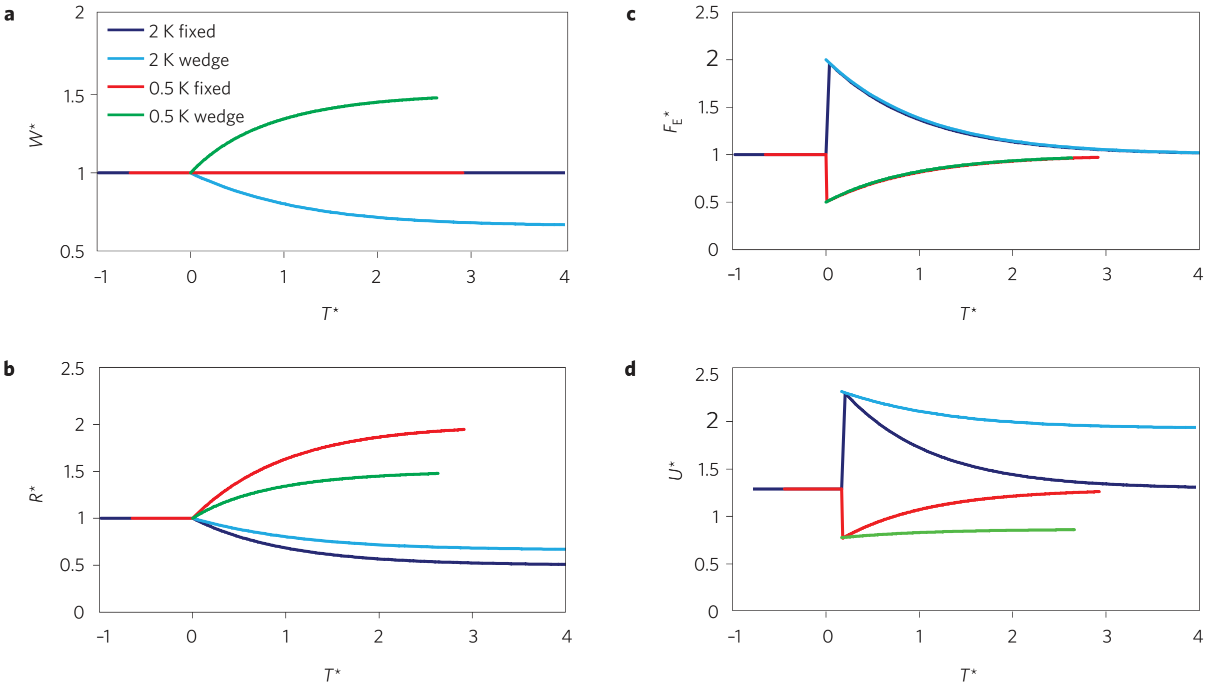

Figure 4 | Mountain-belt response to erosional efficiency changes. Response to both an increase (twice; 2K) and decrease (half; 0.5K) in erosional efficiency are tested using an analytical model[29]. Predicted variables include: **a**, normalized mountain belt half-width (W^*), **b**, normalized topographic relief (R^*), **c**, normalized total erosional efflux (F_E^*) and **d**, normalized rock uplift rate (U^*). All variables are normalized by their initial steady-state values and are plotted against dimensionless time (T^*), which is the ratio of time to system response time (τ). Curves are shown for both the simple fixed-width model ('fixed') and a coupled erosion-tectonic model ('wedge')[29]. See Supplementary Information for details.

rates)[62]. However, when considered together with other data, firmer conclusions can be reached, as discussed below.

Quaternary structural, thermal, and erosional evolution of the St Elias range seems to satisfy most of the criteria outlined above: contemporaneous increase in sediment flux, narrowing of the deformation zone and acceleration of cooling rates. Berger and colleagues[53] have argued that the observed acceleration of cooling rates records an increase in exhumation rate rather than simply a change in particle trajectory on entering the deforming wedge[12]. The pattern of cooling ages implies enhanced slip on thrust faults in the interior of the range and there is no indication of a change in the tectonic mass influx to the wedge in this time interval[53]. For the case of the European Alps, the decline in convergence rate post 5 Myr and the long estimated response time[32] complicate the interpretation. Several studies have found evidence for an acceleration of exhumation rates to > 0.4 mm yr^{-1} (~1 mm yr^{-1} favoured) in the past 2–3 Myr (refs 63–65). These thermochronometer-derived exhumation rates are in good agreement with the sediment yields compiled by Kuhlemann[49], and are consistent with expectations for exhumation sustained by isostatic rebound[47,48] that could prevail for the next ~9 Myr, even without an active deformational response to erosion. Demonstration of an acceleration of active shortening on specific structures in the interior of the range synchronous with the retreat of the deformation front is required for either case to be considered definitive.

Large, hot orogens

Climate–tectonic feedbacks may be even stronger under some circumstances in active deformational belts on the margins of large, high-elevation plateaus such as the Himalaya and the Central Andes[15–17,66,67]. In these systems there is the potential for localized rapid erosion — on plateau margins that receive abundant precipitation, for example — to draw large volumes of hot, low-viscosity middle-to-lower crustal rock out from under the plateau in either laterally continuous belts (so-called channel flow; Fig. 2) or into more localized domal uplifts[15–17,66,67]. In both cases, the upward and outward flow of rock is triggered by an erosional–rheological positive-feedback loop[15,17]. Deep in the thickened crust of high-elevation plateaus, radiogenic middle-to-lower crustal rocks can become heated to the point of incipient low-fraction partial melt[68]. This low-viscosity material will flow in response to any pressure gradient — such as that generated by the topographic margin of a plateau[15] — at a rate proportional to the square of its layer thickness and inversely proportional to its viscosity. Eventually, a record of the localized flow of hot, weak rock may reach the surface as a belt of rapidly exhumed high-pressure and high-temperature metamorphic rocks[15,66,67] (Fig. 2) or as a localized domal uplift[16,17,69].

If erosion rates are sufficiently high and act over a sufficiently broad region, erosion can provide an escape route for this highly pressurized ductile rock, effectively drawing the low-viscosity rock towards the surface[15,16,67]. Upward flow will initially result in an approximately isothermal decompression that may induce partial melting, further reducing viscosity and resistance to flow — a positive feedback. Rocks must cool near the Earth's surface, however, so there is always a brittle 'cap' to such a flow. Consequently, flow rates can be directly dictated by the erosion rate, up to a maximum set by viscosity, flow geometry and the lithostatic pressure gradient — the erosion dictates how fast the brittle cap can be moved out of the way.

Deformation rates can potentially respond in a 1:1 fashion to changes in erosion rate, with very little time-lag. A tectonic response in a large, hot orogen need not involve a significant change in the size or shape of the mountain range as required in frictional wedges, because internal deformation rates and patterns respond directly to the velocity boundary condition set by the erosion rate[15,67]. Beaumont *et al.*[70] have shown that Quaternary climate change could potentially re-activate Miocene channel flow in the Himalaya–Tibet system. However, the response of large, hot orogenic systems to climatic perturbation has not yet been systematically explored.

Scaling analyses of the strength of, and limits to, tectonic response to climatic forcing in these systems have yet to be developed.

Controversy in the Himalaya

Controversy surrounds arguments that erosional control of deformation rates and patterns is shown in the topography, geology and thermal history of the Nepalese Himalaya. Although the erosion-induced channel-flow hypothesis illustrated in numerical experiments[15,67] (Fig. 2) constitutes a mechanistically sound, internally consistent scenario capable of explaining many field observations, the data do not demand channel flow[71,72]. However, even if evidence against a Miocene (or younger) episode of channel flow is found, this would not preclude a climatic influence on deformation. Leaving this debate over the proposed channel flow aside, conflicting data and interpretations regarding the links between precipitation, erosion rate and deformation have arisen in studies aiming to test the hypothesis that climate can significantly influence the tectonic and structural evolution of mountain ranges.

In a single month in 2003, four papers were published that presented seemingly disparate views of the problem, including two papers that discussed data derived using similar approaches in neighbouring drainage basins in the Nepalese Himalaya[60,73–75]. These disparate views can be reconciled. Wobus *et al.*[75] showed that a strong break in exhumation rate and thermal history of rocks coincided with a pronounced physiographic transition and the associated orographic enhancement of precipitation. Indeed, there is a general correlation along 10° longitude (77°–87° E) between high rainfall[76], high relief, steep river gradients and rapid exhumation recorded in young apatite fission-track ages[77]. Wobus *et al.*[75,78,79], Thiede *et al.*[77] and Vannay *et al.*[80] argue that this correlation indicates an erosionally induced concentration of deformation in the interior of the mountain range. Although Dadson *et al.*[60] showed that decadal erosion rate patterns in Taiwan did not correlate well with topographic relief and runoff, as assumed in these Himalayan studies, thermochronological data confirm that long-term exhumation rate patterns in Taiwan do correlate with topographic relief, as expected[33,34,81].

The strongest evidence against a climatic influence on Himalayan tectonics is the fact that within the Greater Himalaya a pronounced northward decrease in annual precipitation is associated with uniformly young apatite fission-track ages. These data imply uniformly fast exhumation and rock uplift[73,82]. Burbank *et al.*[73] infer that erosion rate is driven by independent tectonic processes and is insensitive to precipitation rate; either erosion rate is independent of erosional efficiency, or erosional efficiency is not much affected by the observed variations in precipitation. An erosion rate independent of erosional efficiency is expected only if the topography adjusts to compensate for differences in erosional efficiency, as illustrated for the simple fixed-width system discussed above (Fig. 3a) — this is not supported in the Nepalese Himalaya[75,79]. An erosional efficiency unaffected by precipitation is directly contradicted by data from the Cascades that show a strong correlation between erosion rate and precipitation rate over a range of precipitation rates similar to that observed in the Himalaya[73,74]. Burbank *et al.*[73] provide the most satisfying plausible answer to this apparent paradox: the northward decline in precipitation rate in the Himalaya could be counteracted by the onset of glaciation in the higher terrain to the north. Glaciers are far more efficient erosion agents than rivers[83–85], thus the northward decline in precipitation rate need not equate to a northward decline in erosional efficiency.

The best hope for definitively testing the proposed links between climate and tectonics is to develop records of the temporal evolution of deformation and climate together. Interpretations of spatial correlations between topography, rainfall, exhumation rate and active deformational structures are likely to remain speculative. Nature does not provide ideal experiments where climatic factors alone vary from one place to another. Consequently, demonstration of a cause-and-effect relationship between rapid exhumation and rainfall remains elusive. In the Himalaya, this is largely because orographic enhancement of precipitation[86] will produce spatial correlations between intense precipitation and rapid rock-uplift, even in the absence of a tectonic response to climate and erosion. This null hypothesis can be difficult to disprove, suggesting that observations of a temporal change in rock deformation patterns and/or rates in response to a major shift in local climate ultimately may prove more convincing than spatial correlations.

As in the St Elias range of Alaska and the European Alps, there is some evidence for tectonic responses to temporal changes in climate in both the Himalaya and the Andes. It has been argued that tectonic, geomorphologic and exhumational differences between eastern and western Bhutan are attributable to the Pliocene rise of the Shillong Plateau and the orographic rainshadow it casts on eastern Bhutan[87,88]. Although available data do not yet convincingly demonstrate that this is the case, studies in the Andes (recently summarized by Strecker *et al.*[89]) also highlight the effects of growing orographic rainshadows and this interesting idea should be pursued further.

Farther west in central Nepal, researchers[82,90] have documented an acceleration of long-term rock cooling rates starting between 0.9 and 2.5 Myr, roughly coincident with the onset of Quaternary glaciation. In the absence of evidence for either a far-field tectonic change or for a change in structural geometry over this time interval, Huntington *et al.*[90] have argued that this change in cooling rate represents a climatically triggered acceleration of exhumation rate. Given that the monsoon was well established in the Miocene[91,92], these data indicate that vigorous glacial erosion in the higher and drier mountain peaks to the north was important: consistent with the argument above that vigorous glacial erosion may counterbalance the northward decline in precipitation through the Himalaya[73].

As was the case in the European Alps, it is not possible to determine from exhumation-rate data alone whether they record more than a passive isostatic response to enhanced erosional unloading. Quaternary reactivation of thrust faults at the southern boundary of the rapidly exhumed zone[90,93] and the lack of evidence for a broad flexural-isostatic rebound of the crust point to a dynamic, localized tectonic response to accelerated erosion. However, tectonic response to climate change should be a regional, not local, phenomenon. So far there is no evidence that the inferred Quaternary acceleration in exhumation rate, thrusting and rock uplift documented in central Nepal[82,90,93] was regional in extent[94].

Model predictions as a guide to field verification

Definitive resolution of whether the tectonic evolution of collisional mountain belts is significantly influenced by climate, as suggested by coupled tectonic-surface process models (of analogue, analytical and numerical types), has proved rather challenging. As discussed above, efforts to test model predictions must take cognisance of several complicating factors, not least because there are no perfect natural experiments that isolate climatic effects on mountain-belt evolution. For example, an isostatic response to erosion is expected even if none of the proposed feedback mechanisms operate in nature, as is evolution towards a balance between near-surface rock uplift rate and erosion. Orographic enhancement of rainfall can produce spatial correlations between rapid rock-uplift and intense precipitation, even in the absence of any erosional influence on tectonics. Inactive, narrow and large/hot orogens can be expected to respond differently to climatic forcing. Finally, climate change and mountain building operate on very different timescales — short timescale variability in deformation is not necessarily a result of forcing due to climate change. With these factors in mind, a review of the implications, strengths and weaknesses of models and theory suggests some promising strategies for future research.

The relationship between measurable climate parameters and erosional efficiency should be studied. Coupled tectonic–surface process models predict that the tectonic and structural evolution of a mountain belt is sensitive to spatial and temporal variations in erosional efficiency. However, the underlying assumption that erosional efficiency increases monotonically with precipitation has not been demonstrated quantitatively. Only when this link has been quantitatively established can the assessment of spatial correlations between climate and deformation rates and patterns move beyond speculation. Although other factors will always potentially vary with climate, researchers will be able to test whether spatial variations in deformation histories can be explained without a tectonic response to climate or whether the data demand such a response.

Efforts should focus on possible re-configuration of active structures and deformation rates in response to late Cenozoic climate change that is independently inferred to have occurred. In narrow, frictional ranges, evidence can be sought for, or against, well-defined model expectations that are distinct for system response to changes in climatic and tectonic forcing (Fig. 4). Models are, of course, highly simplified abstractions and their predictions should be considered only as useful guidelines for exploration of these ideas. As mentioned before, an increase in erosional efficiency should be associated with several simultaneous responses: a retreat of the deformation front, a concentration of strain within the interior, a decrease in relief, an increase in rock uplift rate, isostatic rebound of the foreland and a temporary increase in sediment flux to the surrounding basins. The St Elias range of Alaska provides the most convincing case study so far. The opposite is expected for a decrease in erosional efficiency, whereas responses to changes in tectonic forcing are distinct from both (Fig. 4).

To be definitive, a combination of expected responses needs to be shown and their synchronicity demonstrated. Acceleration in rock uplift sustained for longer than twice the system response time (that is, sustained for 2–10 Myr minimum) seems to be required to rule out a simple isostatic rebound if exhumation-rate data are considered in isolation. Expectations are less well defined for large, hot orogenic systems. Further work is required to synthesize a set of testable hypotheses to guide field evaluation of the potential role of climate and erosion in shaping the evolution of such systems.

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Additional Information

Supplementary Information accompanies this paper on www.nature.com/geoscience.