

The influence of climate on the tectonic evolution of mountain belts

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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 tested¹⁸. 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

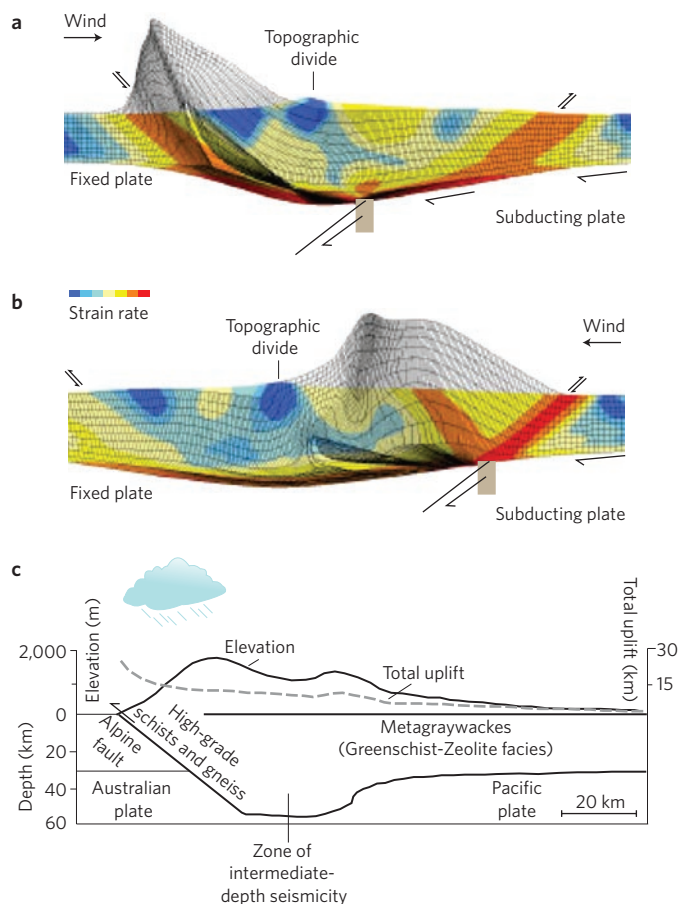


Figure 1 | Unidirectional moisture flux and mountain-belt evolution. **a, b**, Results of numerical models aimed at understanding the exhumational and structural response of mountain belts to unidirectional moisture flux. Tectonic convergence velocity and subduction direction in the models match conditions 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 details³⁰.

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 Nevada³⁷ or the Appalachian Mountains³⁸.

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 achieved⁴⁰. Under this condition, both topography and crustal thickness are steady⁴¹ 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 relief⁴² (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:

