Available online at www.sciencedirect.com
SCIENCE DIRECT
Earth and Planetary Science Letters 243 (2006) 218 – 228
EPSL
www.elsevier.com/locate/epsl

Orogen response to changes in climatic and tectonic forcing

Kelin X. Whipple [a,*], Brendan J. Meade [b]

[a] Department of Earth, Atmospheric and Planetary Science, Massachusetts Institute of Technology, Cambridge, MA 02139, United States
[b] Department of Earth and Planetary Science, Harvard, Cambridge, MA 02138, United States

Received 29 June 2005; received in revised form 21 December 2005; accepted 21 December 2005
Available online 15 February 2006
Editor: E. Boyle

Abstract

Despite much progress, many questions remain regarding the potential dynamic coupling between atmospheric and lithospheric processes in the long-term evolution of mountain belts. As a complement to recent efforts to discover the interrelationships among climate, topography, erosion, and rock deformation under conditions of mass-flux steady state, we explore orogen response to changes in climate and tectonic influx. We derive an analytical model that predicts a powerful climatic control on orogen evolution and distinct, potentially diagnostic, responses to climatic and tectonic perturbations. Due to isostatic compensation, the near-surface rock uplift rate during transients is tightly coupled to climate-modulated erosional efficiency. System response is approximately exponential, with a characteristic response timescale that is inversely proportional to the climate- and lithology-modulated erosional efficiency, and is largely insensitive to initial conditions, tectonic influx, and both the sign and magnitude of perturbations.

Keywords: climate; erosion; rock uplift; tectonics; critical wedge

1. Introduction

The potential of climate, and climate change, to importantly influence the pace and style of mountain belt evolution has been much discussed and debated, particularly during the past 15 years. Numerical models that include the coupling of tectonic and surface processes have demonstrated that climate-modulated erosion could exert a first order control on the geodynamics of active orogens [1–5]. Field evidence for significant feedback between erosion and tectonics is harder to come by and, although tantalizing, leaves many questions unanswered [6–14]. Much uncertainty remains as to the nature and strength of the role of climate-driven erosion in orogen evolution, and whether or not a diagnostic signature of such can be resolved in the field. For instance, much debate has centered on the role of climate and climate change in the evolution of the relief of mountain ranges [15–19] and in setting erosion rates [20–22].

Recently simplified analytical steady-state models have been used to quantify the strength of coupling among climate, erosion, and deformation [23–25]. Steady-state conditions in an orogen are defined by the balance between erosional efflux and accretionary influx and statistically invariant mean topography [26]. Both laboratory experiments and numerical models have demonstrated that orogenic systems evolve toward steady-state conditions when boundary conditions are constant [2,4,27–29]. However, although there is

* Corresponding author. Tel.: +1 617 253 2578; fax: +1 617 252 1800.
E-mail address: kxw@mit.edu (K.X. Whipple).

0012-821X/$ - see front matter
doi:10.1016/j.epsl.2005.12.022

evidence that some orogenic systems may have evolved to quasi-steady-state conditions [11,26,30,31], the concept has proven difficult to test rigorously with field data. Moreover, it is important to consider the possibility that the relations among climate, topography, erosion rate, and tectonics may differ markedly during transient evolution of a mountain belt.

To better understand the role of climate and climate change in orogen evolution we address four questions that have emerged from this debate: (1) how are the predicted relationships among climate, erosion rate, tectonics, and rock uplift rate different away from steady state, (2) what parameters control the timescale of orogen response to step-function changes in erosional efficiency or accretionary flux, (3) how likely are steady-state conditions to be attained given the frequency of changes in climatic and tectonic boundary conditions, and (4) what are robust measures of whether a quasi-steady-state has developed? Our approach is to derive an approximate analytical solution for the transient evolution of an orogen from one steady state to another. This model allows us to quantify the relative importance of the variables defining erosional efficiency, orogen geometry, and the tectonic accretionary flux.

2. Evolution of orogen cross-sectional area

We develop a model for the transient evolution of a two-dimensional, two-sided, frictional orogenic wedge by building on our earlier work on the hypothetical steady-state condition [24]. By considering the conservation of mass we can relax the steady-state assumption and derive relationships for the time evolution of wedge area, topographic relief, and rates of erosion, surface uplift, and near-surface rock uplift. Throughout this analysis we assume self-similar wedge growth and decay as seen in both analog sand-box experiments [27,32–34] and in numerical simulations using a Coulomb-plastic rheology [35]. As such, our model is most applicable to narrow, thin-skinned orogenic wedges. Departures from self-similar growth, due to rheologic effects, or temporal evolution of critical taper, will incur some error. Our aim is to model the first-order behavior of the transient evolution of orogens at critical taper.

The rate of change of wedge cross-sectional area, A [m^2], is given by the difference between total mass influx, F_A [m^2/yr], and total erosional efflux, F_E [m^2/yr]

$$\frac{dA}{dt} = F_A - F_E \tag{1}$$

where F_A includes any sediment recycled back into the orogen through cannibalization of the foreland. The total influx (accretion plus recycled material) may be related to the far-field tectonic influx, F_{A_0}, by the relation $F_A = F_{A_0} + \xi\lambda F_E$, where λ denotes the fraction of total erosional efflux that is eroded off the pro-wedge side of the orogen, and ξ the fraction of this material that is recycled back into the orogen (Fig. 1). Eq. (1) tracks the volume fluxes of rock, with any density correction to recycled material absorbed into ξ. In the limiting case where $\lambda = 1$ and $\xi = 1$, the wedge grows without bound because all eroded material is continually recycled. Whipple and Meade [24] defined λ as the fraction of accretionary flux eroded off the pro-wedge. That earlier definition is consistent with our refined and more general definition when the system is at mass-flux steady state. Note that although we hold the recycling efficiency, ξ, constant, it can be expected to increase during orogen growth as the foreland is cannibalized, and can be expected to decrease during orogen decay.

Erosional processes remove material from the wedge at a rate defined as

$$F_E = E_p W_p + E_r W_r \tag{2}$$

where E_p and E_r are the average erosion rates (positive downward) on the pro-wedge and retro-wedge sides, respectively, and similarly W_p and W_r are the widths of the pro-wedge and retro-wedge sides of the orogen (Fig. 1). Under the conditions of mass-flux steady state, F_E equals F_A and the rock uplift rate is determined by the

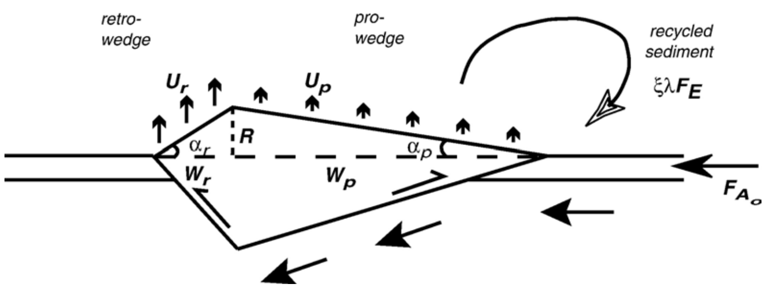

Fig. 1. Definition sketch defining assumed self-similar geometry of the wedge and key variables discussed in the text.

local erosion rate [1,24]. However, away from steady state it is important to distinguish between erosion rate and rock uplift rate as they exhibit different, but strongly coupled, transient behaviors.

Long-term, regional-scale erosion rates are set by rates of river incision into bedrock [36]. To model the spatially averaged erosion rate on the channel network, we use the orogen-scale erosion rule derived by Whipple and Meade [24]. The derivation of the erosion rule rests on three assumptions: (1) equilibrium river profiles are well-described by Flint's Law, $S=k_s A^{-\theta}$, where S is local channel gradient, A is upstream drainage area [m^2], k_s is the steepness index [$m^{2\theta}$], and θ is the concavity index (e.g., [37,38]); (2) there is a power–law relationship between the steepness index, the mean rock uplift rate (U), and erosional efficiency (C'), $k_s \propto (U/C')^f$; and (3) the concavity index (θ) is invariant with both rock uplift rate and erosional efficiency. Given these assumptions, steady-state fluvial relief (R_f) is set by the steepness index and wedge width, $R_f \propto k_s(W^{1-h\theta})$, where h is the inverse of the Hack exponent [39,40]. The orogen-scale erosion rule [24] is found by equating wedge relief, $R=W\tan\alpha$, with fluvial relief (R_f) (thus $k_s \propto W^{h\theta}\tan\alpha$), solving for U, and noting that $E=U$ at steady state:

$$E_{p,r} = C_{p,r}(\tan\alpha_{p,r})^b W_{p,r}^a \tag{3}$$

where the subscripts p and r indicate the pro- and retro-wedge sides, respectively (Fig. 1), $a=h\theta/f$, $b=1/f$, and C is linearly proportional to the coefficient of erosional efficiency (C') in the underlying fluvial incision rule (e.g., [40,41]). Erosional efficiency is a function of both climate and rock properties, and varies over at least three orders of magnitude (e.g., [42]) and $0.4 \le a \le 1.4$ and $0.7 \le b \le 2.0$ are the expected ranges for the model exponents, see Eq. (23) of Whipple and Meade [24] for details. Whipple [38] has recently reviewed the current understanding of the myriad controls on erosional efficiency and the present difficulty of quantitatively relating this model parameter to measurable climatic and lithologic properties (see also references therein). However, Eq. (3) holds for any incision rule consistent with the three assumptions listed above.

The dependence on wedge width in the orogen-scale erosion rule reflects the fact that to maintain the same regional topographic gradient (critical taper [1,24]), rivers in larger catchments must be steeper at any given drainage area than rivers in smaller catchments. Generally catchment size will increase in proportion with wedge width and therefore erosion rate will increase with wedge width, even for fixed climatic and lithologic conditions [24]. Stolar et al. [35] have demonstrated that numerical simulations of coupled mechanical deformation (Coulomb-plastic rheology) and surface process (fluvial and hillslope processes operating in a 2D representation of topography) models predict the same relations among steady-state wedge width, accretionary flux, rock uplift rate, and erosional efficiency as derived by Whipple and Meade [24] and Roe et al. [25], thus confirming the validity and utility of Eq. (3) (and the closely related derivation of the steady-state scaling laws in Roe et al. [25]). Here we make the further assumption that Eq. (3) applies during transient adjustment of orogen size, consistent with self-similar wedge growth and decay. We do not model the co-evolution of orographic precipitation and topography.

Using (2) and (3), the fraction of eroded material derived from the pro-wedge is:

$$\lambda = E_p W_p / F_E = C_p / (C_p + C_r W_*^{a+1-b}) \tag{4}$$

For self-similar wedge growth the ratio of pro-wedge to retro-wedge widths, $W_* = W_r / W_p = \tan\alpha_p / \tan\alpha_r$, is constant. Using this geometric constraint, the total erosional efflux can be written in terms of the pro-wedge width alone as:

$$F_E = C' W_p^{a+1} \tag{5}$$

where $C' = (\tan\alpha_p)^b (C_p + C_r W_*^{a+1-b})$. C' is linear in both C_p and C_r, but is weighted toward C_p because of the larger size of the pro-wedge (Fig. 1). We assume that wedge geometry is consistent with the maintenance of Airy isostasy, so that pro-wedge width is related to wedge area by $W_p = \sqrt{A/\Gamma}$, where $\Gamma = \tan\alpha_p[\rho_m/(\rho_m - \rho_c)](1+W_*)/2$, and ρ_m and ρ_c denote the density of mantle and crust, respectively. Using the orogen-scale erosion rule and the above geometric relations we can re-write the mass balance evolution equation as

$$\frac{dA}{dt} = F_{A_0} - K^* A^p \tag{6}$$

where $K^* = (1-\xi\lambda) C' \Gamma^{-p}$ and $p=(a+1)/2$. At steady state, $dA/dt=0$ and wedge area is given by $A=[F_{A_0}/K^*]^{1/p}$. The expected range for the wedge-area exponent is $0.7 \le p \le 1.2$ [24], and K^* has units of m^{2-2p} yr^{-1}.

3. Orogen response time

Consider the response of an orogenic wedge initially at flux steady state to an instantaneous change in either tectonic forcing (accretionary influx, F_{A_0}) or climate (reflected in the coefficient of erosion, K^*). For $p=1$, a solution to the area evolution equation from initial steady state, A_i, to final steady state, A_f, is

$$A(t) = A_f + (A_i - A_f)e^{-\kappa t} \tag{7}$$

where t is time since the change in climatic or tectonic forcing and $\kappa = K_f^*$ (coefficient of erosion of the final state). The transition from A_i to A_f is exponential with an e-folding time $T_{1/e} = 1/\kappa$. Remarkably, for the $p=1$ case, the response timescale, $T_{1/e}$, is set entirely by K_f^*, which is linearly dependent on the climate-modulated coefficient of erosion, K, in the bedrock channel incision model [24,40]. Thus, for $p=1$, the response timescale is independent of the initial and final cross-sectional areas, the accretionary flux, and both the magnitude and sign of the perturbation. Note that the case where accretionary flux is reduced to zero, and thus $A_f=0$, would be better treated by relations for a constant-width orogen (see below and Pazzaglia and Brandon [43]) because in the absence of an accretionary flux, the orogen ceases to deform as a critical taper wedge. Moreover, Baldwin et al. [44] have discussed the role of a critical threshold for channel incision in preserving significant post-orogenic residual relief (with low gradient channels, very low erosion rates, but potentially steep hillsides) for for hundreds of millions of years (see [45,46,47,48]). Thus our model is restricted to actively deforming orogenic wedges.

For arbitrary values of p, we are unaware of an exact closed form solution to Eq. (6). However, one may anticipate that the solution will have an approximately exponential form in the vicinity of $p=1$. Accordingly, we seek to find a generalized definition of the decay constant, κ, in Eq. (7) that is approximately valid for the expected range of the wedge area exponent, $0.7 \leq p \leq 1.2$. This is accomplished by deriving two relations for dA/dt, evaluating them at time $t=0$ (the onset of tectonic or climate change), equating them, and solving for the effective value of the decay constant, κ.

From Eq. (6) the rate of change of cross-sectional area at $t=0$ is

$$\left.\frac{dA}{dt}\right|_{t=0} = F_{A_f} - K_f^* A_i^p \tag{8}$$

The rate of change of cross-sectional area can be found independently by differentiating Eq. (7) and setting $t=0$

$$\left.\frac{dA}{dt}\right|_{t=0} = \kappa(A_f - A_i) \tag{9}$$

Equating Eqs. (8) and (9), solving for κ, we find

$$\kappa \approx \frac{K_f^*(A_f^p - A_i^p)}{(A_f - A_i)} \tag{10}$$

Eq. (10) reduces to the exact solution for $p=1$. The accuracy of this approximate solution can be demonstrated by comparison with numerical integration of Eq. (6) for a range of p (Fig. 2). The approximate analytic solution is quite good, with deviations from the numerical results of less than 5% for up to factor of 2 changes in F_A or K. Significant departures from the approximate analytical solution occur during later stages of orogen evolution when F_A is reduced by more than 90% of the initial steady-state value.

Note that K_f^* has units that depend on p. Careful tracking of units and calculating appropriate values of K_f^* from the underlying relations for C_p and C_r (Eq. (23) in Whipple and Meade [24]) and for the coefficient of fluvial erosion in the stream-power river incision model, K (Eq. (8b) in Whipple and Tucker [40]) is required.

The sensitivity of response time ($T_{1/e} = 1/\kappa$) to the exponent p may be evaluated by computing the ratio of

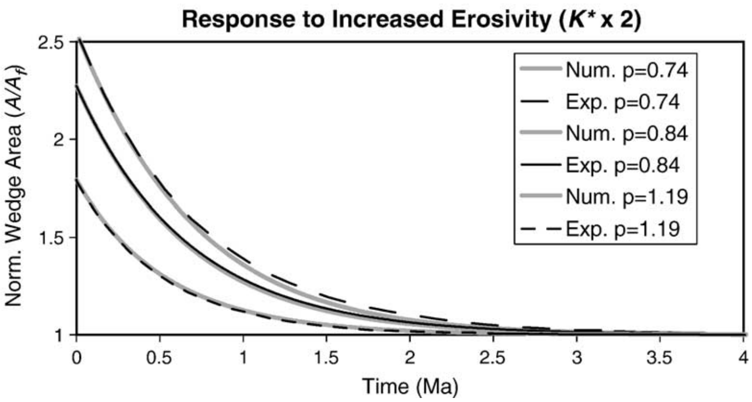

Fig. 2. Comparison of the approximate analytical solution for $p \neq 1$ (Eq. (10)) with direct finite-difference numerical integration.

response times (T_{p_2}/T_{p_1}) of wedges starting with the same initial cross-sectional area and subjected to the same magnitude change in erosional efficiency (ΔC) but with two different p values (denoted p_1 and p_2). Because K^* is a dimensional variable with dimensions that depend on p, the condition that initial cross-sectional areas are identical requires that initial values of K^* are related by:

$$K^*_{\mathrm{i}p_2} = \left(K^*_{\mathrm{i}p_1}\right)^{p_2/p_1} F_{\mathrm{A_i}}^{1-p_2/p_1} \tag{11}$$

With this condition, the ratio of response times can be derived from (10):

$$\frac{T_{p_2}}{T_{p_1}} = \frac{(\Delta C^{-1/p_2} - 1)}{(\Delta C^{-1/p_1} - 1)} \tag{12}$$

Recognizing that $A_{wf}/A_{wi} = \Delta C^{-1/p}$, we find that the ratio of response times is simply equal to the ratio of percent change in wedge size required to reach the new steady state for each value of p. Eqs. (10) and (12) indicate that for $p \neq 1$, response time is a weak function of accretionary flux, initial wedge size, and both the magnitude and sign of the perturbation. As shown in Fig. 3, $T_{1/e}$ is found to vary by less than a factor of two within the expected range of p (0.7–1.2), a surprisingly weak dependence.

4. Comparison with previous work

Within the last decade, several researchers have investigated the problem of orogen response time following perturbations in either climatic conditions or accretionary flux. Early treatments considered constant-width orogens [43, 49], and the three more recent papers considered critical taper orogenic wedges [35,50,51]. These are similar to our model set up, though only Stolar et al. [35] considered asymmetrical, two-sided wedges (a symmetrical two-sided wedge has the same solution as a one-sided wedge with a rigid backstop). Our analysis is consistent with these other works, but is founded on a more complete erosion rule, is more general, and is more explicit about the various factors that control response time.

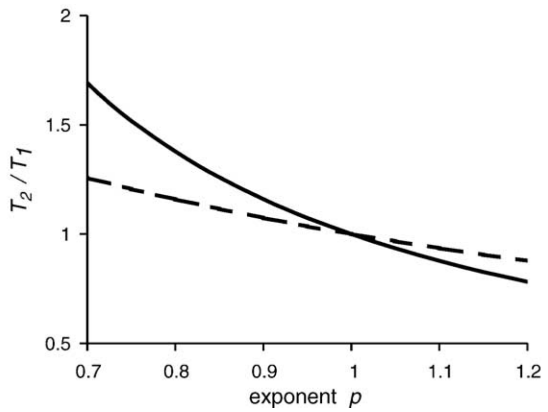

Fig. 3. Sensitivity of orogen response time to the Area exponent (p) in the erosion rule (Eq. (6)). The solid line is for a halving of erosional efficiency and the dashed line is for a doubling of erosional efficiency.

Constant-width orogens can be considered a special case of the deforming-wedge analysis. Pazzaglia and Brandon [43] present a relatively complete solution for a constant width orogen using the simple rule that erosion rate scales with mean elevation (or equivalently with total relief, R), which is consistent with (3) for the condition $a = b = 1$ and $C = C_l$. Their solution is directly analogous to ours:

$$R(t) = R_{\mathrm{f}} + (R_{\mathrm{i}} - R_{\mathrm{f}})e^{-C_l\left(\frac{\rho_{\mathrm{m}}-\rho_{\mathrm{c}}}{\rho_{\mathrm{m}}}\right)t} \tag{13}$$

where $R_{\mathrm{i}} = U_{\mathrm{i}}/C_{l\mathrm{i}}$ and $R_{\mathrm{f}} = U_{\mathrm{f}}/C_{l\mathrm{f}}$. As with our $p = 1$ case, the response time scales inversely with the coefficient of erosion and is independent of both tectonic mass-flux and orogen size.

Kooi and Beaumont [49] did not derive an expression for response time, but found through numerical simulations that it was sensitive to erosional efficiency and relatively insensitive to changes in rock uplift rate, consistent with Pazzaglia and Brandon [43] and our deforming-wedge solution. Kooi and Beaumont [49], however, did find a strong dependence on orogen width. This departure in model behavior stems from a difference in the channel incision rule they used. As orogen width becomes large, erosion rates predicted by their "under-capacity" channel incision rule become invariant with width because channel concavity index, θ, approaches zero at large drainage area [41] (recall that in Eq. (3) $a = h\theta/f$). Thus in their model, for large W mean erosion rate scales with regional slope only. As regional slope is given by R/W, the Kooi and Beaumont [49] erosion rule for large W becomes Eq. (3) with $a = 0$, $b = 1$ and $C = C_l/W$, resulting in the observed dependence on orogen width.

Hooke [50] set up his analysis much as we have, except with a symmetrical two-sided wedge (essentially the one-sided problem) and using simplified rules with erosion rate growing linearly with relief (e.g., Pazzaglia and Brandon [43]), or increasing exponentially with relief [52]. Hooke also found a response timescale that was sensitive to the erosion coefficient and insensitive to tectonic influx. However, his perturbation analysis did not yield the simple analytical solution we present. In addition, his analysis suggests a response time that is strongly dependent on initial relief, even for erosion linear in relief. This finding is at odds with both our analysis and that of Pazzaglia and Brandon [43].

Recent numerical integrations for one-sided and two-sided wedges conform closely to the predictions of our analytic model. Although Hilley et al. [51] did not derive relations for response time, the inverse dependence on erosional efficiency and insensitivity to accretionary flux that we predict are consistent with their results. One point of departure with their analysis, however, lies in the sensitivity of response time to the exponents in the erosion rule (p in Eq. (6)). As shown above in Eqs. (11) and (12), the claim by Hilley et al. [51] that response time is highly sensitive to erosion law exponents is in our view an artifact of independently varying these exponents in various model runs without regard to the dimensionality of the coefficient of erosion (K^*). The simulations of coupled mechanical deformation (Coulomb-plastic rheology) and surface process models presented by Stolar et al. [35] are consistent with our approximate analytical solution. Stolar et al. [35] find a close match between predicted response time using our solution and model output for simulations in which step-function increases and decreases in both erosional efficiency and accretionary flux were explored. Stolar et al. [35] used model parameters consistent with $p=0.85$ in these simulations.

5. Surface uplift, rock uplift, and erosion

Surface and rock uplift are defined as positive upward and measured relative to the geoid at or near the earth's surface — rock uplift rate may be expected to vary significantly with depth [24]. The definition that near surface rock uplift rate equals the sum of surface uplift rate and erosion rate ($U \equiv U_s + E$) holds at all times [53]. Thus, provided we can write U_s and E as a function of time, we can solve explicitly for the time evolution of the near surface rock uplift rate. Further, as pointed out by Molnar and England [15], isostatic compensation of erosion is often the dominant contributor to total rock uplift rate during transient decreases in mean elevation and crustal thickness, suggesting the likelihood of a strong coupling between rock uplift rate and climate or climatic change [15].

The elevation of the range crest is $R = W_p \tan\alpha_p = \tan\alpha_p \sqrt{A/\Gamma}$ and the rate of surface uplift, U_s, is given by

$$U_s = \frac{dR}{dt} = \frac{\tan\alpha_p}{2\sqrt{A(t)/\Gamma}} \frac{dA}{dt} \tag{14}$$

where the time evolution of $A(t)$ is given by Eq. (7) and $dA/dt = \kappa(A_f - A_i)e^{-\kappa t}$. Surface uplift rates are the same on the pro- and retro-wedge sides of the orogen, as required for self-similar growth. The pro- and retro-wedge orogen-scale erosion rates (E_p, E_r) as a function of time can be found by substituting the final C values and the evolving wedge width ($W_p = \sqrt{A/\Gamma}$, $W_r = W_* W_p$) into Eq. (3):

$$E_p = C_{pf}(\tan\alpha_p)^b \left(\sqrt{A(t)/\Gamma}\right)^a;$$
$$E_r = C_{rf}(\tan\alpha_r)^b \left(W_* \sqrt{A(t)/\Gamma}\right)^a \tag{15}$$

The near surface rock uplift rate is the sum of surface uplift (Eq. (14)) and erosion rates (Eq. (15)) $U_{p,r} = U_s + E_{p,r}$ (Fig. 4).

Interestingly, whereas the evolution of A and F_E are uniquely described by K_f^* (Eq. (7)), regardless of the relative values of C_p and C_r, the evolution of the patterns of rock uplift rate and internal deformation is strongly influenced by the relative erosional efficiency on the pro- and retro-wedges. The controls on the relative sensitivity of $U_p(t)$ and $U_r(t)$ to changes in C_p and C_r are much the same as for the steady-state case and have been discussed in some detail by Whipple and Meade [24].

6. Application to the Taiwan orogen

As an example of system response to tectonic forcing, Fig. 5 shows the growth of an orogenic wedge from the onset of convergence through an asymptotic approach to mass-flux steady state. Model parameters are set to approximately represent conditions in the Taiwan Central Range (Fig. 5). This calculation predicts a steady-state configuration with ~88 km total range width, a ~2.3 km mean crest elevation, and ~5 mm/yr and ~7 mm/yr rock uplift rates on the pro-wedge and retro-wedge sides, respectively. These values are consistent with erosion rates estimated by Willett et al. [11] and with observations in the northern half of the Taiwan Central Range, where some authors have suggested the presence of steady-state conditions [11,54]. We calculate an expected e-folding time of 1.2 Ma, such that a close approach to steady-state conditions might be expected in ~3–4 Ma, provided tectonic and climatic conditions have remained steady. This time scale is short enough for the northern portion of the Taiwan orogen to have approached near-steady conditions (~95%) since the onset of collision, estimated

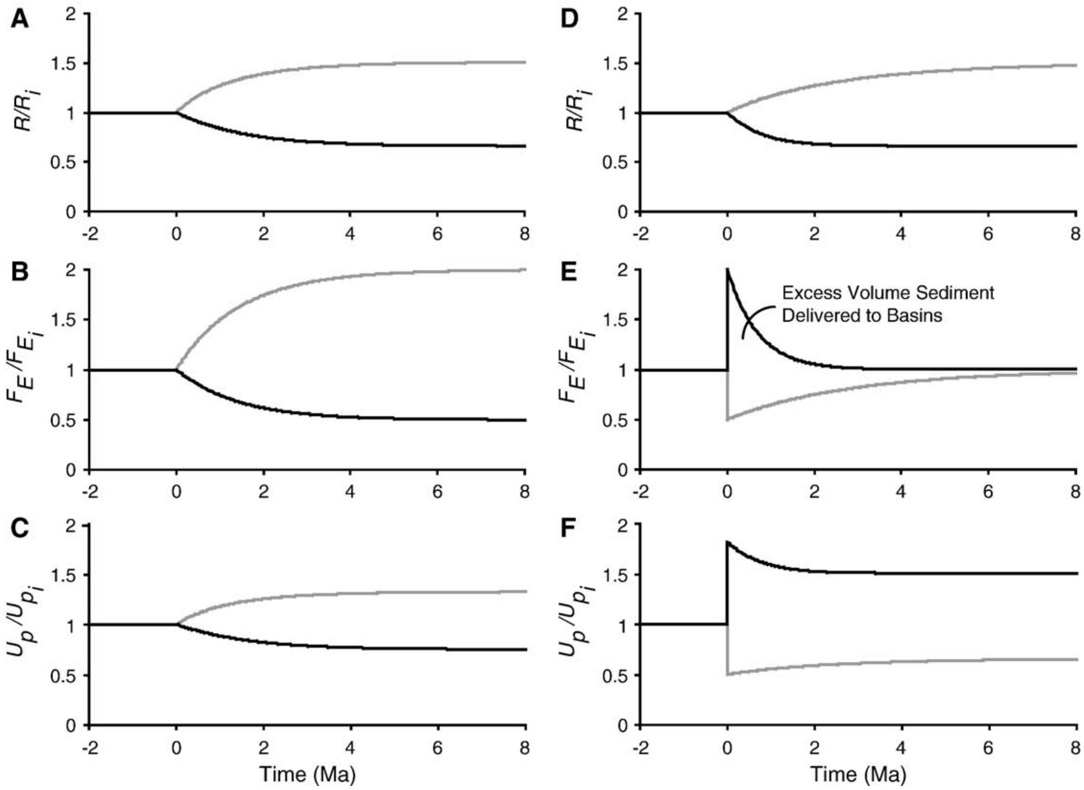

Fig. 4. Contrasting transient response to changes in accretionary flux (A–C) and climate-modulated erosional efficiency (D–F). Left column illustrates orogen response to either a factor of two increase (grey lines) or decrease (black lines) in accretionary flux at time $t=0$ in terms of (A) topographic relief (tracking surface uplift), (B) total erosional efflux, and (C) rock uplift rate on the pro-wedge side. Right column illustrates orogen response to either a factor of two increase (black lines) or decrease (grey lines) in erosional efficiency (K^*) at time $t=0$ in terms of (D) topographic relief (tracking surface uplift), (E) total erosional efflux, and (F) rock uplift rate on the pro-wedge side. All variables are normalized by their initial steady-state value, denoted by the subscript i.

at 3–5 Ma [11,55,56], provided steady tectonic and climatic forcing. It is worth noting, however, that systems with less erodible rocks and less rainfall (lower K^*) can have characteristic response times of tens of millions of years (e.g., [51]). Under such conditions, orogenic systems are unlikely to attain a steady-state configuration before accretionary flux or convergence geometry changes.

Given the frequency of climatic oscillations through the Quaternary, however, truly steady-state conditions are rarely achieved [57]. Although orogen size and long-term average rock uplift rates may adjust to the long-term mean climate state [58], erosion rate and sediment flux data over 10^2–10^3 year timescales are strongly influenced by high-frequency climatic, land cover, and seismic activity variations, and cannot be used to assess whether a system is approaching a long-term quasi-steady state [9]. However, assuming a sudden switch in mean climate at 2 Ma, the response time scale is sufficiently short for the Taiwan orogen to have adjusted to within ~85% of quasi-steady conditions reflecting the mean Quaternary climate state. This analysis does not include the effects of the evolving pattern of orographic precipitation. By choosing model parameters to represent modern conditions we predict a reasonable modern topography. However, it is likely that precipitation rates were lower in the early stages of orogenic growth; our response-time calculation is therefore a minimum estimate.

In addition to providing a quantitative estimate of the time required to reach flux steady-state conditions there are implications for the metrics used to test the steady-state assumption. Fig. 5 shows that while in this scenario the system requires 3–4 Ma for a close approach to steady-state conditions in terms of erosional flux and topography, the erosion rate approaches near-steady conditions in under 2 Ma, and the rock uplift rate nears steady conditions in less than 1 Ma. Thus, evidence of approximate temporal invariance in rock uplift, exhumation, or erosion rates may not be sufficient evidence

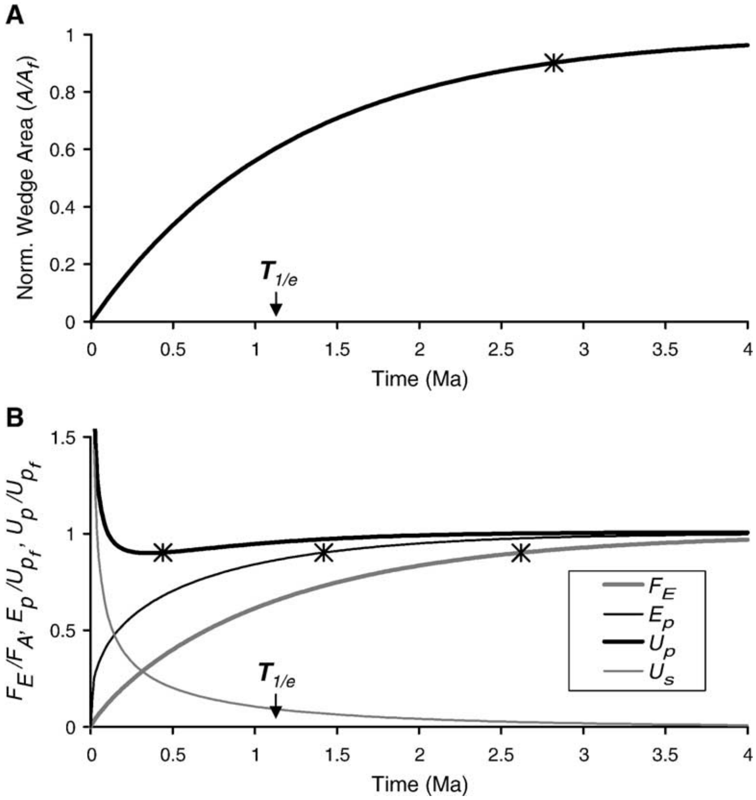

Fig. 5. Wedge growth to steady state from initial collision showing an exponential approach of A (a), and U_s, U_p, E_p, and F_E (b) toward steady-state conditions, roughly modeled after the Taiwan Central Range. The asterisk on each curve marks the point where 90% of the steady-state value is attained. We use the same erosion rule parameters chosen by Whipple [57] to describe fluvial incision in the Taiwan Central Range ($p = 0.84$; $K^* = 1.9e-5$). Topographic taper angles are measured from the GTOPO30 DEM [24]. We assume $\rho_m/(\rho_m - \rho_c) = 6$, and use published estimates of the total accretionary flux, $F_A \approx 500$ m^2/yr [23,54].

that an orogenic system has reached quasi-steady-state conditions.

7. Discussion and conclusions

Orogenic wedges are predicted to grow and shrink in response to changes in erosional efficiency (climate and rock properties) and accretionary flux (tectonics). Accordingly, changes in climate and tectonic forcing cause persistent changes in rock uplift rate [23–25,35]. Thus although the hypothesized climate-change-induced production of relief [15] has proven equivocal [16–19], climate change has the potential to alter rock deformation patterns and strain rates, inducing persistent increases in rock uplift rate [23–25,35], which is arguably a more interesting finding than the prospect of increased peak elevations due to isostatic compensation of enhanced surface roughness. Here we have shown that orogen response is approximately exponential and the response time is well characterized by an e-folding time, $T_{1/e}$ (Figs. 4 and 5). Our analysis of asymmetric, two-sided orogenic wedges considers both tectonic and climatic perturbations, accounts for recycling of sediments in the mass balance, encompasses the time evolution of topographic relief, erosion rate, rock uplift rate, and surface uplift rate, and shows that response time is primarily controlled by the final climate state as expressed by K_f^*, which is linearly dependent on the coefficient of fluvial erosion on both the pro-wedge and retro-wedge sides of the orogen. Note that one-sided or symmetrical wedges are a special case of our general solution. Because orogen response time is set by the final value of the coefficient of erosion, the response to an increase in the erosional efficiency will be faster than that to a change in accretionary flux, which in turn will be faster than that to a decrease in erosional efficiency (Fig. 4). In other words, the fastest way to increase mean elevation and relief is to increase the tectonic influx, and the fastest way to reduce them is to increase the erosional efficiency by way of a climate change.

Inversion of the stratigraphic record has long been hampered by the inability to differentiate between climatic and tectonic drivers of sediment supply (see for example Heller et al. [59]). Our analysis shows that orogen responses to climatic and tectonic perturbation are quite distinct, suggesting potentially diagnostic patterns in sediment efflux, exhumation rates, and orogen growth or decay (and therefore flexural loading or unloading of flanking basins). A step-function change in accretionary flux induces a simultaneous smooth, exponential transition in topographic relief, erosional efflux, and rock uplift rate to new steady-state values with a common response time, regardless of the sign and magnitude of the perturbation (Fig. 4A,B,C). Abrupt, step-function increases in rock uplift, erosion rate, and total erosional efflux (F_E) are generally not possible responses to changes in tectonic accretion flux. Analyses of steady-state conditions [23–25] have shown that topographic relief and rock uplift rate responses are damped compared to the magnitude of the perturbation (compare Fig. 4A,B,C) because roughly 50% of the enhanced accretionary flux is absorbed by widening of the orogenic wedge.

There are significant differences in system response to climatic rather than tectonic perturbation (Figs. 4 and 5). First, equilibration is much faster in response to an increase in erosional efficiency and slower in response to a decrease in erosional efficiency (Fig. 4D,E,F). Second, only topographic relief and wedge cross-sectional area show a smooth, monotonic transition to the new steady-state condition (Fig. 4D). Following a step-function change in net erosional efficiency, K^*, the erosion rate, $E_{p,r}$, total erosional efflux, F_E, and rock uplift rate, $U_{p,r}$, each exhibit an impulsive initial response and then relax exponentially (Fig. 4E and F). The impulsive initial response involves a 1 : 1 change in erosion rate and total erosional efflux and a nearly 1 : 1 change in rock uplift rate with the change in erosional efficiency. The strong response in rock uplift rate is a consequence of isostatic compensation of erosional unloading (here assumed to be instantaneous on the timescale of orogen response — an order 10 ka viscous lag time can be assumed negligible), which diminishes with time as the system approaches a new steady-state condition (Fig. 4F). The numerical simulations of Stolar et al. [35] are generally consistent with our model, but lack this impulsive rock uplift response to climate change because their model imposes a horizontal basal boundary and thus excludes any isostatic response (in this case the rock uplift history looks much like that in Fig. 4C).

An interesting implication of our finding is that rock uplift rate is far more sensitive to climatic perturbation during transients than determined for the steady-state case [23–25] — roughly analogous to the observation, at much smaller space and time scales, that hillslope sediment flux is far more sensitive to climate change than to differences in steady climate conditions [60,61]. Whereas a net change in rock uplift rate persists as the wedge shrinks or grows, erosional efflux returns to its original steady-state condition balancing the total accretionary flux (Fig. 4E and F). Only during the transient adjustment is climate change expected to drive a change in overall sediment delivery rates. In addition, where a climate change involves a change in the C_p/C_r ratio, λ is permanently changed, influencing F_{Ep} and F_{Er} accordingly, and also total F_A in cases where some material is recycled back into the pro-wedge ($\xi > 0$). The area under the $F_E(t)$ curve (Fig. 4E), corrected for the fraction of material not recycled into the wedge $(1 - \xi\lambda)$, is the predicted total excess sediment delivered to basins from active orogens in response to climate change [21].

The orogen response timescale derived here is only weakly dependent on the value of the wedge area exponent, p (Eqs. (10) and (12)), and therefore only weakly dependent on the initial and final cross-sectional areas, the accretionary flux, and both the magnitude and sign of either climatic or tectonic perturbations. As shown earlier, for orogenic wedges with the same initial cross-sectional area, and subjected to the same perturbation in K^* or F_A, $T_{1/e}$ is found to vary by less than a factor of two within the range $0.7 \le p \le 1.2$ (Fig. 3). Whipple and Meade [24] considered the extent to which different erosion process mechanics and deviations from self-similar wedge growth (as might occur because of rheologic variations) may be expressed as deviations in the orogen-scale erosion rule exponents a and b (and therefore p). The weak dependence of orogen response time on the exponent p suggests that it is not strongly sensitive to either erosion process mechanics or wedge rheology, although the magnitude of the net change in wedge size and rock uplift rate is moderately sensitive to both [24].

Acknowledgements

This work was funded by the NSF Continental Dynamics Program through Grant EAR-003571 to Whipple and a Daly Postdoctoral Fellowship grant to Meade. Careful reviews by George Hilley, Peter Molnar, and two anonymous reviews of an earlier draft significantly improved the manuscript.

References

[1] F.A. Dahlen, J. Suppe, Mechanics, growth, and erosion of mountain belts, in: S.P.J. Clark, B.C. Burchfiel, J. Suppe (Eds.),

Processes in Continental Lithospheric Deformation Geological Society of America Special Paper 218, Geological Society of America, Denver, 1988, pp. 161–178.
[2] P.O. Koons, The topographic evolution of collisional mountain belts: a numerical look at the Southern Alps, New Zealand, Am. J. Sci. 289 (1989) 1041–1069.
[3] C. Beaumont, P. Fullsack, J. Hamilton, Erosional control of active compressional orogens, in: K.R. McClay (Ed.), Thrust Tectonics, Chapman and Hall, New York, 1992, pp. 1–18.
[4] S.D. Willett, Orogeny and orography: the effects of erosion on the structure of mountain belts, J. Geophys. Res. 104 (1999) 28,957–928,981.
[5] C. Beaumont, R.A. Jamieson, M.H. Nguyen, B. Lee, Himalayan tectonics explained by extrusion of a low-viscosity crustal channel coupled to focused surface denudation, Nature 414 (2001) 738–742.
[6] J.G. Masek, B.L. Isacks, T.L. Gubbels, E.J. Fielding, Erosion and tectonics at the margins of continental plateaus, J. Geophys. Res. 99 (1994) 13,941–913,956.
[7] D.R. Montgomery, G. Balco, S.D. Willett, Climate, tectonics, and the morphology of the Andes, Geology (Boulder) 29 (2001) 579–582.
[8] D.W. Burbank, A. Blythe, J. Putkonen, B. Pratt-Sitaula, E. Gabet, M. Oskin, A. Barros, T.P. Ojha, Decoupling of erosion and precipitation in the Himalayas, Nature 426 (2003) 652–655.
[9] S.J. Dadson, N. Hovius, H. Chen, W.B. Dade, M.-L. Hsieh, S.D. Willett, J.-C. Hu, M.-J. Horng, M.-C. Chen, C.P. Stark, D. Lague, J.-C. Lin, Links between erosion, runoff variability and seismicity in the Taiwan orogen, Nature 426 (2003) 648–651.
[10] C.W. Wobus, K. Hodges, K. Whipple, Has focused denudation at the Himalayan topographic front sustained active thrusting near the Main Central Thrust? Geology 31 (2003) 861–864.
[11] S.D. Willett, D.M. Fisher, C.W. Fuller, Y. En-Chao, L. Chia-Yu, Erosion rates and orogenic-wedge kinematics in Taiwan inferred from fission-track thermochronology, Geology 31 (2003) 945–948.
[12] K. Hodges, C.W. Wobus, K. Ruhl, T. Schildgen, K. Whipple, Quaternary deformation, river steepening, and heavy precipitation at the front of the Higher Himalayan ranges, Earth Planet. Sci. Lett. 220 (2004) 379–389.
[13] R.C. Thiede, B. Bookhagen, J.R. Arrowsmith, E.R. Sobel, M.R. Strecker, Climatic control on rapid exhumation along the Southern Himalayan front, Earth Planet. Sci. Lett. 222 (2004) 791–806.
[14] B. Bookhagen, R.C. Thiede, M.R. Strecker, Late Quaternary intensified monsoon phases control landscape evolution in the northwest Himalaya, Geology 33 (2005) 149–152.
[15] P. Molnar, P. England, Late Cenozoic uplift of mountain ranges and global climate change: chicken or egg? Nature 346 (1990) 29–34.
[16] N. Brozovic, D. Burbank, A. Meigs, Climatic limits on landscape development in the Northwestern Himalaya, Science 276 (1997) 571–574.
[17] E.E. Small, R.S. Anderson, Pleistocene relief production in Laramide mountain ranges, western United States, Geology 26 (1998) 123–126.
[18] K. Whipple, E. Kirby, S. Brocklehurst, Geomorphic limits to climatically induced increases in topographic relief, Nature 401 (1999) 39–43.
[19] S. Brocklehurst, K. Whipple, Glacial erosion and relief production in the Eastern Sierra Nevada, California, Geomorphology 42 (2002) 1–24.
[20] P. Molnar, Climate change, flooding in arid environments, and erosion rates, Geology 29 (2001) 1071–1074.
[21] P. Zhang, P. Molnar, W.R. Downs, Increased sedimentation rates and grain sizes 2–4 Myr ago due to the influence of climate change on erosion rates, Nature 410 (2001) 891–897.
[22] G. Tucker, Drainage basin sensitivity to tectonic and climatic forcing: implications of a stochastic model for the role of entrainment and erosion thresholds, Earth Surf. Processes Landf. 29 (2004) 185–205.
[23] G.E. Hilley, M. Strecker, Steady-state erosion of critical coulomb wedges with applications to Taiwan and the Himalaya, J. Geophys. Res. 109 (2004). doi:10.1029/2002JB002284.
[24] K. Whipple, B.J. Meade, Controls on the strength of coupling among climate, erosion, and deformation in two-sided, frictional orogenic wedges at steady state, J. Geophys. Res. 109 (2004). doi:10.1029/2003JF000019.
[25] G.H. Roe, D.R. Stolar, S.D. Willett, Response of a steady-state critical wedge orogen to changes in climate and tectonic forcing, in: S.D. Willett, N. Hovius, M. Brandon, D.M. Fisher (Eds.), Tectonics, Climate, and Landscape Evolution: Geological Society of America Special Paper 398, Penrose Conference Series, Geological Society of America, Boulder, CO, 2006, pp. 227–239.
[26] S.D. Willett, M.T. Brandon, On steady states in mountain belts, Geology (Boulder) 30 (2002) 175–178.
[27] P.O. Koons, The two-sided orogen: collision and erosion from the sand box to the Southern Alps, Geology 18 (1990) 679–682.
[28] D. Lague, A. Crave, P. Davy, Laboratory experiments simulating the geomorphic response to tectonic uplift, J. Geophys. Res.-Solid Earth 108 (2003). doi:10.1029/2002JB001785.
[29] S. Bonnet, A. Crave, Landscape response to climate change: insights from experimental modeling and implications for tectonics versus climatic uplift of topography, Geology 31 (2003) 123–126.
[30] M. Bernet, M. Zattin, J.I. Garver, M.T. Brandon, J.A. Vance, Steady-state exhumation of the European Alps, Geology (Boulder) 29 (2001) 35–38.
[31] F.J. Pazzaglia, M.T. Brandon, A fluvial record of long-term steady-state uplift and erosion across the Cascadia forearc high, western Washington State, Am. J. Sci. 301 (2001) 385–431.
[32] D. Davis, J. Suppe, F.A. Dahlen, Mechanics of fold-and-thrust belts and accretionary wedges, J. Geophys. Res. 88 (1983) 1153–1172.
[33] K.S. Persson, Effective indenters and the development of double-vergent orogens: insights from analogue sand models, in: H.A. Koyi, N.S. Mancktelow (Eds.), Tectonic Modeling: a Volume in Honor of Hans Ramberg Geological Society of America Memoir v. 193, Boulder, CO, 2001, pp. 191–206.
[34] S. Hoth, J. Adam, N. Kukowshi, O. Oncken, Influence of erosion on the kinematics of bivergent orogens: results form scaled sandbox simulations, in: S.D. Willett, N. Hovius, M. Brandon, D. M. Fisher (Eds.), Tectonics, Climate, and Landscape Evolution: Geological Society of America Special Paper 398, Penrose Conference Series, Geological Society of America, Boulder, CO, 2006, pp. 201–225.
[35] D.R. Stolar, S.D. Willett, G.H. Roe, Climatic and tectonic forcing of a critical orogen, in: S.D. Willett, N. Hovius, M. Brandon, D. M. Fisher (Eds.), Tectonics, Climate, and Landscape Evolution: Geological Society of America Special Paper 398, Penrose Conference Series, Geological Society of America, Boulder, CO, 2006, pp. 241–250.

[36] A.D. Howard, M.A. Seidl, W.E. Dietrich, Modeling fluvial erosion on regional to continental scales, J. Geophys. Res. 99 (1994) 13,971–913,986.
[37] J.J. Flint, Stream gradient as a function of order, magnitude, and discharge, Water Resour. Res. 10 (1974) 969–973.
[38] K. Whipple, Bedrock rivers and the geomorphology of active orogens, Annu. Rev. Earth Planet. Sci. 32 (2004) 151–185.
[39] J.T. Hack, Studies of longitudinal stream profiles in Virginia and Maryland, U.S. Geol. Surv. Prof. Pap. 294-B (1957) 97.
[40] K.X. Whipple, G.E. Tucker, Dynamics of the stream-power river incision model: implications for height limits of mountain ranges, landscape response timescales, and research needs, J. Geophys. Res. 104 (1999) 17661–17674.
[41] K. Whipple, G. Tucker, Implications of sediment-flux dependent river incision models for landscape evolution, J. Geophys. Res. 107 (2002). doi:10.1029/2000JB000044.
[42] J.D. Stock, D.R. Montgomery, Geologic constraints on bedrock river incision using the stream power law, J. Geophys. Res. 104 (1999) 4983–4993.
[43] F.J. Pazzaglia, M.T. Brandon, Macrogeomorphic evolution of the post-Triassic Appalachian mountains determined by deconvolution of the offshore basin sedimentary record, Basin Res. 8 (1996) 255–278.
[44] J.A. Baldwin, K.W. Whipple, G.E. Tucker, Implications of the shear stress river incision model for the timescale of postorogenic decay of topography, J. Geophys. Res. 108 (2003). doi:10.1029/2001JB000550.
[45] J.T. Hack, Rock control and tectonism; their importance in shaping the Appalachian Highlands, U. S. Geol. Surv. Prof. Pap. 1126 (1980) B1–B17.
[46] C.S. Riebe, J.W. Kirchner, D.E. Granger, R.C. Finkel, Erosional equilibrium and disequilibrium in the Sierra Nevada, inferred from cosmogenic 26Al and 10Be in alluvial sediment, Geology (Boulder) 28 (2000) 803–806.
[47] A. Matmon, P.R. Bierman, J. Larsen, S. Southworth, M. Pavich, M. Caffee, Temporally and spatially uniform rates of erosion in the southern Appalachian Great Smoky Mountains, Geology (Boulder) 31 (2003) 155–158.
[48] F. Von Blanckenburg, T. Hewawasam, P.W. Kubik, Cosmogenic nuclide evidence for low weathering and denudation in the wet, tropical highlands of Sri Lanka, J. Geophys. Res. 109 (2004). doi:10.1029/2003JF000049.
[49] H. Kooi, C. Beaumont, Large-scale geomorphology: classical concepts reconciled and integrated with contemporary ideas via a surface process model, J. Geophys. Res. 101 (1996) 3361–3386.
[50] R.L. Hooke, Time constant for equilibration of erosion with tectonic uplift, Geology 31 (2003) 621–624.
[51] G.E. Hilley, M. Strecker, V.A. Ramos, Growth and erosion of fold-and-thrust belts with an application to the Aconcagua Fold and Thrust Belt, Argentina, J. Geophys. Res. 109 (2004). doi:10.1029/2002JB002282.
[52] M.A. Summerfield, N.J. Hulton, Natural controls of fluvial denudation rates in major world drainage basins, J. Geophys. Res. 99 (1994) 13,871–813,883.
[53] P. England, P. Molnar, Surface uplift, uplift of rocks, and exhumation of rocks, Geology 18 (1990) 1173–1177.
[54] J. Suppe, Mechanics of mountain-building and metamorphism in Taiwan, Geol. Soc. Chin. Mem. 4 (1981) 67–89.
[55] J. Suppe, Kinematics of arc-continent collision, flipping of subduction, and back-arc spreading near Taiwan, Geol. Soc. Chin. Mem. 6 (1984) 21–33.
[56] T. Byrne, C. Liu, Preface: introduction to the geology and geophysics of Taiwan, in: T. Byrne, C. Liu (Eds.), Geology and Geophysics of an Arc-continent Collision, Taiwan Geological Society of America Special Paper 358, Boulder, Colorado, 2002, pp. v–viii.
[57] K. Whipple, Fluvial landscape response time: how plausible is steady state denudation? Am. J. Sci. 301 (2001) 313–325.
[58] B.J. Meade, Orogen evolution in response to oscillating climate, Eos Trans. AGU 86 (2005) H33F-03.
[59] P.L. Heller, B.A. Burns, M. Marzo, Stratigraphic solution sets for determining the roles of sediment supply, subsidence, and sea-level on transgressions and regressions, Geology (Boulder) 21 (1993) 747–750.
[60] G.E. Tucker, R.L. Slingerland, Drainage basin response to climate change, Water Resour. Res. 33 (1997) 2031–2047.
[61] C.S. Riebe, J.W. Kirchner, D.E. Granger, R.C. Finkel, Minimal climatic control on erosion rates in the Sierra Nevada, CA, Geology 29 (2001) 447–450.