Tectonic uplift, threshold hillslopes and denudation rates in a developing mountain range

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ABSTRACT

Studies across a broad range of drainage basins have established a positive correlation between mean slope gradient and denudation rates. It has been suggested, however, that this relationship breaks down for catchments where slopes are at their threshold angle of stability since, in such cases, denudation is controlled by the rate of tectonic uplift through the rate of channel incision and frequency of slope failure. This mechanism is evaluated for the San Bernardino Mountains, California, a nascent range that incorporates both threshold hillslopes and remnants of pre-uplift topography. Concentrations of in situ–produced cosmogenic ^{10}Be in alluvial sediments are used to quantify catchment-wide denudation rates and show a broadly linear relationship with mean slope gradient up to ~30°. Above this value denudation rates vary substantially for similar mean slope gradients. We propose that this decoupling in the slope gradient – denudation rate relationship marks the emergence of threshold topography and coincides with the transition from transport-limited to detachment-limited denudation. The survival in the San Bernardino Mountains of surfaces formed prior to uplift provides constraints on the topographic evolution of the range, in particular the transition from slope-gradient dependent rates of denudation to a regime where denudation rates are controlled by rates of tectonic uplift. This type of transition may represent a general model for the denudational response to orogenic uplift and topographic evolution during the early stages of mountain building.

Keywords: cosmogenic nuclides, denudation, erosion rates, erosion control, orogenesis, San Bernardino Mountains.

INTRODUCTION

Knowledge of the factors that control rates of denudation and the associated development of topography is fundamental to an understanding of several key components of the earth system. These include mass transfer from continents to oceans, interactions between tectonics, climate and topography, and the mediation of global climate by long-term changes in CO_2 drawdown through silicate weathering. A number of broad-scale surveys of denudation rates across a range of topographic settings and climatic and tectonic environments have identified relief (as a proxy for mean basin slope) as a dominant control (Ahnert, 1970; Milliman and Syvitski, 1992; Summerfield and Hulton, 1994; Harrison, 2000). However, more detailed work focusing on active orogens has suggested that above a threshold slope gradient denudation rates vary substantially between catchments with similar (threshold) mean slope gradients (Burbank et al., 1996). The explanation proposed for this is that once valley-side slopes are steepened to their threshold angle for landsliding by active basal channel downcutting any further increase in the rate of channel incision is accommodated by an increased frequency of slope failure rather than by slope steepening. Consequently, as rates of tectonic uplift vary, the rate of channel incision and valley-side slope failure, and hence the rate of basin wide denudation, will change in response, even though there is no associated change in mean slope gradient.

Although this idea has gained some empirical support (Montgomery and Brandon, 2002), there is a lack of detailed studies of variations in denudation rates as the critical slope threshold value is crossed. This is perhaps surprising given the broad implications of the development of threshold slopes for modeling the interactions between tectonics and surface processes in mountain belt evolution (Montgomery, 2001; Willett et al., 2001).

Here we use catchment-averaged concentrations of in situ–produced cosmogenic ^{10}Be to quantify denudation rates for basins in the San Bernardino Mountains, southern California in order to evaluate their relationship to mean basin slope, and to establish whether a transition to slope-independent denudation rates is observed. We employ this approach as inventories of cosmogenic ^{10}Be in alluvial sediments provide estimates of denudation rates typically integrated over several thousand years. Our results are therefore more likely to be representative of geologically meaningful rates than decadal-scale estimates from modern river load data. Nonetheless, this integrating period is sufficiently brief that we can confidently employ measurements of present-day topography to characterize mean basin slope gradient over the relevant time period. The San Bernardino Mountains were selected as they represent a young orogen with a well-constrained tectonic history and clear morphological evidence of the transition from an uplifted block with remnants of subdued, pre-uplift topography to an expanding zone of deeply incised valleys characterized by frequent slope failure.

FIELD SETTING

The San Bernardino Mountains form part of the Transverse Ranges of southern California (Fig. 1A). Composed predominantly of granitic rocks (quartz monzonite and gneiss), the mountains extend ~100 km from east to west and ~80 km north to south. Most of the range exceeds 1000 m and the maximum elevation is 3506 m. Structurally the San Bernardino Mountains comprise a number of distinct fault-bounded blocks that become smaller and more complex toward the San Andreas fault zone that bounds the range to the south. The northern two-thirds of the range consists of the Big Bear block which is flanked by north and south facing escarpments: these correspond, respectively, to the Northern

Frontal thrust system bounding the Mojave basin to the north, and the Santa Ana thrust to the south. The southern third of the range comprises a series of east-west trending ridges of high, rugged topography separated by major faults located in the intervening valleys. Uplift of the Big Bear block has been due principally to motion along the Northern Frontal thrust system, whereas the apparently more rapid uplift of the smaller blocks in the south has resulted from vertical motions associated with the accommodation of transpression within the San Andreas fault zone (Spotila and Sieh, 2000).

Although steep valley-slope gradients and sharp drainage divides characterize the southern blocks, the Big Bear block has a plateau form with the northern and southern escarpments flanking a core of generally subdued topography dissected locally around its periphery by deeply incised valleys. Much of this low relief landscape is mantled by deeply weathered granite, locally overlain by basalts and Miocene sediments. This weathered horizon is considered to have originally been contiguous with a similar granitic weathering mantle found in the lower-lying Mojave Desert to the north and is thought to have formed under a more humid climate in the Miocene prior to uplift of the San Bernardino Mountains (Oberlander, 1972; Sadler and Reeder, 1983, Meisling and Weldon, 1989).

METHODS AND RESULTS

Mean denudation rates were determined, using standard analytical procedures, from concentrations of in situ–produced ^{10}Be in quartz in alluvial sediments (Bierman and Steig, 1996; Granger et al., 1996) for 20 small (<10 km^2) catchments in the Big Bear and Yucaipa Ridge blocks of the San Bernardino Mountains (Figs. 1B and 1C)[1]. To avoid the potential effects of ice cover on cosmogenic nuclide production rates, and of glacial activity on denudation rates, sampling was confined to catchments lacking any evidence of Quaternary glaciation (Owen et al., 2003). The influence of lithological variations both on the uniformity of quartz distribution and on denudation rates was minimised by limiting sampling to catchments with ‘granitic’ lithologies (predominantly quartz-monzonite and gneiss). Where they constitute a significant component of overall denudation, deep-seated bedrock landsliding events can potentially violate the assumption that basin-wide cosmogenic nuclide concentrations have achieved secular equilibrium, and thereby bias denudation rate estimates (Niemi et al., 2005). However, in the southern sector of the San Bernardino Mountains the fractured nature of the near-surface bedrock appears to minimize the occurrence of deep-seated landslides and favours shallow failure (Spotila et al., 2001). In other parts of our field area we avoided sampling basins displaying evidence of recent deep-seated landsliding. Insufficient alluvial mixing may also bias cosmogenic nuclide concentrations in stream sediments in steep terrain, but the careful sampling we adopted minimised the likelihood of this occurring (Binnie et al., 2006). Mean slope gradients were calculated for each sampled basin using the 10 m-grid U.S. National Elevation Data set digital elevation model (DEM)[1].

We used field observations to select catchments representative of the main types of denudational environments in the San Bernardino Mountains[1]. These catchments range from those dominated by detachment (weathering)-limited processes (characterized by steep hillslopes and evidence of active shallow-landsliding) to those where transport-limited processes predominate (characterized by a lack of active landsliding with generally more subdued topography and remnants of deeply weathered granite). We also sampled intermediate catchments which contain elements of both landscape types.

Denudation rates range from a mean of 1700 mm ka^{-1} for the detachment-limited catchments (mean slope gradient 36°) to 87 mm ka^{-1} for catchments characterized by transport-limited processes (mean slope gradient is 13°). The intermediate catchments lie between these values with a mean denudation rate of 454 mm ka^{-1} and mean slope gradient of 26° (Table 1). Plotting catchment mean slope gradient against denudation rate for each catchment reveals a broadly linear trend up to a mean basin slope gradient of ~30°. Above ~30° there is a wide scatter in the data with no relationship evident between denudation rate and mean basin slope gradient (Fig. 2). All the transport-limited, and the majority of the intermediate, catchments lie on the linear trend, whereas all of the detachment-limited catchments occur in the zone of wide data scatter.

DISCUSSION AND CONCLUSIONS

The concept of threshold hillslopes was originally associated with the response of specific slope segments in soil-mantled landscapes to changes in the mechanical properties of the regolith as a result of progressive weathering (Carson and Petley, 1970). The idea has subsequently been applied at a larger scale to hillslopes in mountain ranges where there is little or regolith present. In this case threshold slopes are considered to be established and maintained by bedrock landsliding, and their gradients determined by bedrock strength at the mountain scale (Schmidt and Montgomery, 1995). This situation occurs where mass is removed at the base of slopes by channel processes at least as rapidly as it is supplied; channel incision thereby maintains valley-side slopes at a threshold gradient that is a function of large-scale bedrock strength. In such cases the rate of denudation will be determined not by hillslope gradient but by the frequency and magnitude of landsliding which is controlled by the rate of channel incision.

The small southern crustal blocks of the San Bernardino Mountains, such as the Yucaipa Ridge block, exhibit a hillslope gradient distribution which is indicative of threshold topography (Spotila et al., 2001). The width of this block (~5 km at its broadest extent) is constrained by the major high angle strands of the San Andreas Fault along which it has risen. Thermochronological data indicate that this block has undergone 3–6 km of denudation over approximately the last 1.5 Ma (Spotila et al., 2001) and this is consistent with the rapid rates of denudation recorded here (>1000 mm ka^{-1}). The narrow form and consistently high rates of denudation of this block mean that it would have quickly achieved, and continues to maintain, threshold hillslopes dominated by landsliding. Our data suggest that this occurs as slopes reach ~30°, a similar value to that recorded by Burbank et al. (1996) for the NW Himalayas and comparable to the results of Montgomery and Brandon (2002) for the Olympic Mountains, Washington. Interestingly, there is at present no major channel incising at the base of the southern flank of the Yucaipa Ridge block, suggesting that the base level fall arising from the relative vertical movement across the strand of San Andreas Fault bounding the ridge to the south is sufficient to maintain threshold slopes.

Spotila et al. (2002) have previously compared variations in slope gradient across the present-day topography of the Transverse Ranges with spatial variations in long-term denudation rates averaged over 10^6-year time scales based on low-temperature thermochronology and depths of incision of the weathered granitic horizon. They demonstrated a positive correlation between slope gradient and mean denudation rate, but speculated that the deviation that they observed of the Yucaipa Ridge block from the general trend might be due to the inability of its slopes to steepen further in response to rapid tectonic uplift. Our higher resolution data that provide denudation rates averaged over a time scale related directly to the presently observed topography support this speculation and clearly reveal the threshold slope transition (Fig. 2).

There is a relatively large degree of variation in the mean hillslope gradients of those basins on the Yucaipa Ridge block considered to be at threshold (basins 1, 2, 3, 4 and 5, Table 1). In the Nepalese Himalayas Gabet et al. (2004) found an inverse relationship between mean threshold hillslope angles and a variation in mean annual precipitation from ~1800 to 4000 mm. However, the range of mean annual precipitation on the threshold slopes of the southern San Bernardino Mountains is considerably smaller (~900–700 mm) (Minnich, 1989) and the degree of scatter in threshold hillslope angles that we observe is more likely due to a variation around a mean threshold value that is inherent to the small scale of the basins sampled.

Stratigraphic evidence indicates that the formation of the San Bernardino Mountains began only 2–3 Ma ago (May and Repenning, 1982; Meisling and Weldon 1989), and variations in denudation rates across the range suggest that channel networks are continuing to adjust to base level falls caused by tectonic uplift. The preservation of remnants of a pre-uplift landscape in the subdued topography of the Big Bear and San Gorgonio blocks, and the low rates of denudation in this terrain, demonstrate that base level falls associated with the uplift of these blocks have yet to be fully propagated throughout their drainage systems. By contrast, in the small southern blocks where the terrain is rugged, and on the steep flanks of the larger blocks to the north, there is no evidence of pre-uplift topography. The four transport-limited catchments sampled on the plateau of the Big Bear block (basins 17, 18, 19 and 20, Fig. 1C) retain extensive remnants of the deeply weathered horizon that formed prior to uplift and this suggests that these catchments have not yet undergone significant denudation as a result of the tectonic uplift. The topography of the Big Bear block plateau and the Yucaipa Ridge block can thus be taken as representative of, respectively, the initial and final states of the sequence of hillslope steepening caused by the base level fall associated with rapid tectonic uplift. The intermediate catchments record the transition between these states that is occurring over time in the San Bernardino Mountains as base level falls are propagated through the range. The topographic response to the initiation of orogenesis can thus be described by the left to right trajectory of the points plotted in Figure 2.

Our findings show that in a predominantly granitic terrain experiencing persistent base level lowering the relationship between basin-wide denudation rate and mean slope is decoupled when a gradient of ~30° is reached, and that this decoupling is coincident with a transition from transport to detachment-limited processes. This is consistent with the emerging idea that denudation rates in zones of 'threshold' topography in actively uplifting mountain belts are controlled by rates of channel incision related to uplift rate rather than slope gradient. Here we have illustrated the evolving relationship between hillslope gradient and denudation rate, and hence topographic evolution towards threshold conditions, during the early stages of mountain building. Such an analysis provides empirical constraints for numerical modeling of the response of the denudational system to active tectonic uplift.

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FIGURE CAPTIONS

Figure 1. A: The San Bernardino Mountains, showing positions of crustal blocks and major faults. Inset shows location of the mountains with respect to western USA. BBB, Big Bear block; SGB, San Gorgonio block; YRB, Yucaipa Ridge block; WCB, Wilson Creek block; NFTS, North Frontal thrust system; SAT, Santa Ana thrust fault; MCF, Mill Creek strand of the San Andreas Fault; SAF-SBS, San Andreas Fault-San Bernardino strand. B: The basins for which denudation rates are derived on the Yucaipa Ridge block, sample numbers correspond to Table 1. C: The basins for which denudation rates are derived on the Big Bear block, sample numbers correspond to Table 1. The extent of the weathered granitic

surface, indicative of minimal denudation since the initiation of orogenesis, is adapted from Spotila and Sieh (2000).

Figure 2. A plot of average basin hillslope gradients versus basin-wide denudation rates derived from cosmogenic ^{10}Be analysis in the San Bernardino Mountains reveals a broadly linear relationship that decouples as average hillslope gradients tend towards ~30°. Above ~30° hillslope gradient does not relate to denudation rate. The decoupling coincides with the transition from transport-limited to detachment-limited hillslope regimes. The left to right trajectory of the plot describes the response of hillslopes to rapid tectonic uplift, and hence, the evolution of hillslopes during orogenesis as they tend towards threshold conditions.

[1]GSA Data Repository item 2007xxx, cosmogenic nuclide analytical methods, data, production rates, and denudation rates, is available online at www.geosociety.org/pubs/ft2007.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

TABLE 1. CHARACTERISTICS OF SAMPLED BASINS

Basin number*	Denudation rate ($mm.ka^{-1}$)†	Average catchment hillslope gradient (°)	Catchment area (km^2)	Hillslope regime	Average denudation rate (ē) and hillslope gradient (Θ)
Yucaipa Ridge					
1	2200 ± 500	30.7	1.13	Detachment-limited	n = 5 ē = 1700 $mm.ka^{-1}$ Θ = 36°
2	2700 ± 500	35.4	0.59	Detachment-limited	
3	1300 ± 200	37.0	2.37	Detachment-limited	
4	1200 ± 200	38.0	0.87	Detachment-limited	
5	1100 ± 200	37.2	0.34	Detachment-limited	
6	230 ± 30	25.3	0.84	Intermediate	n = 11 ē = 454 $mm.ka^{-1}$ Θ = 26°
Southern Escarpment					
7	1200 ± 200	32.2	2.63	Intermediate	
8	660 ± 80	28.1	3.49	Intermediate	
9	520 ± 60	26.5	2.87	Intermediate	

10	170 ± 20	30.9	3.09	Intermediate	
11	1600 ± 300	32.3	4.08	Intermediate	
12	230 ± 20	27.5	1.56	Intermediate	
13	280 ± 30	28.4	1.5	Intermediate	
Northern Escarpment					
14	100 ± 10	19.5	1.21	Intermediate	
15	89 ± 10	18.4	1.71	Intermediate	
Big Bear Plateau					
16	150 ± 20	21.6	2.34	Intermediate	
17	97 ± 9	14.4	7.67	Transport-limited	$n = 4$
18	71 ± 7	9.7	8.38	Transport-limited	$\bar{e} = 87$ mm.ka^{-1}
19[§]	129 ± 15	16.8	6.09	Transport-limited	$\Theta = 13°$
20	52 ± 5	9.2	7.56	Transport-limited	

Note: Details of how table values were derived can be found in the data repository.

* See Figures 1B and 1C for locations and extents of basins sampled.

[†] Uncertainty is 1σ

[§] Although the stream draining basin 19 was sampled where it leaves the mountains along the northern escarpment the majority of the basin area lies on the Big Bear block plateau.

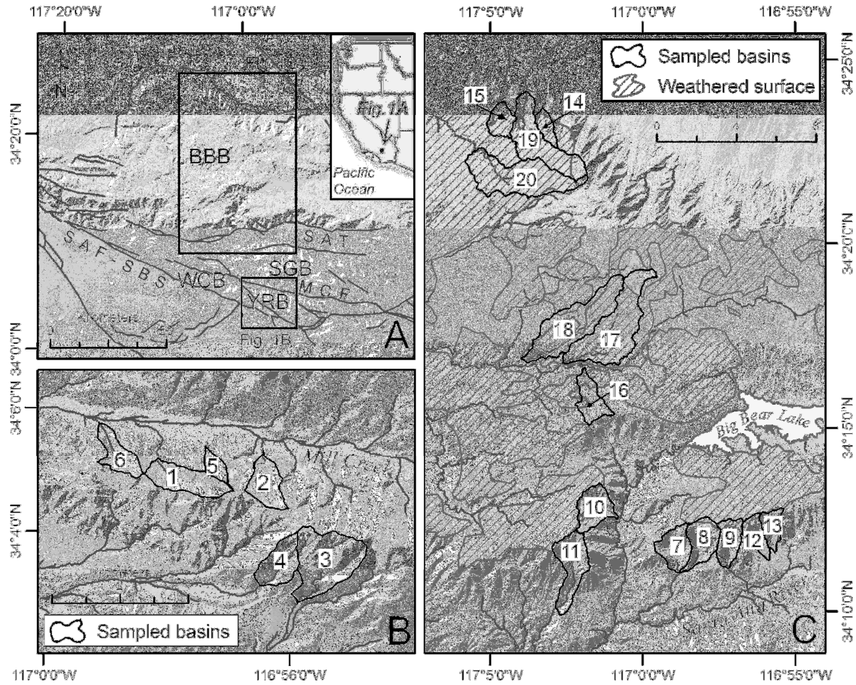
117°20'0"W
117°0'0"W
117°5'0"W
117°0'0"W
116°55'0"W
34°20'0"N
34°0'0"N
BBB
S.A.T.
S.A.F.-S.B.S.
WCB
SGB
M.C.F.
YRB
Fig. 1B
Fig. 1A
Pacific Ocean
A
34°6'0"N
34°4'0"N
Sampled basins
B
117°0'0"W
116°56'0"W
Mill Creek
Weathered surface
Big Bear Lake
C
34°25'0"N
34°20'0"N
34°15'0"N
34°10'0"N
1
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Figure 1

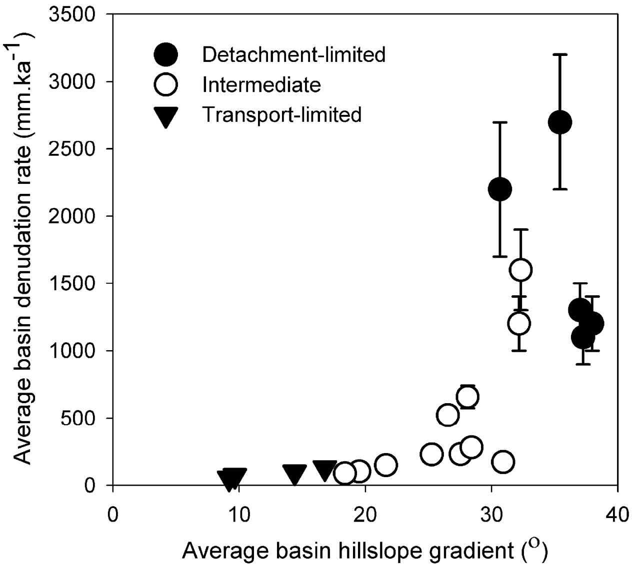
Detachment-limited
Intermediate
Transport-limited
Average basin denudation rate (mm.ka-1)
Average basin hillslope gradient (o)
3500
3000
2500
2000
1500
1000
500
0
10
20
30
40

Figure 2