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River spacing and drainage network growth in widening mountain ranges

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ABSTRACT

Drainage networks in linear mountain ranges always display a particular geometrical organisation whereby the spacing between the major drainage basins is on average equal to half the mountain width (distance from the mountain front to the main drainage divide), independent of climate and tectonics. This relationship is valid for mountains having different widths and is thus usually thought to be maintained by drainage reorganisation during mountain belt widening. However, such large-scale systematic drainage reorganisation has never been evidenced. In this paper, we suggest an alternative explanation, namely that the observed drainage basin relationships are an inherent property of dendritic river networks and that these relationships are established on the undissected, lowland margins outside mountain ranges and are progressively incorporated and quenched into uplifted topography during range widening. Thus, we suggest that the large-scale geometry of drainage networks in mountain ranges is mainly antecedent to erosion. We propose a model in which the large-scale drainage geometry is controlled mainly by the geometrical properties of the undissected surfaces (in particular, the ratio of the regional slope to the local slope related to roughness) over which rivers are flowing before uplift, and is therefore independent of climate and tectonics.

INTRODUCTION

A frequent feature of drainage networks in linear sections of mountain ranges is the apparent regular spacing between transverse rivers at the mountain front (Fig. 1). Addressing this observation, and in particular the consistency of this regularity, Hovius (1996) analysed the drainage of 11 different linear mountain belts worldwide. His study showed that the outlets of the major transverse rivers at the front of these topographies are not only regularly spaced but also that their spacing S is on average proportional to the width W of the range (measured from the drainage divide to the front) following the relation $S = W/R$, where the spacing ratio R is in a narrow range of values around a median of 2.1 (Hovius, 1996). An important aspect of this observation is the regularity of spacing ratios between the mountain ranges despite strong differences in climate and rock uplift rates. This seems to constitute a paradox as in many current landscape evolution models, the patterns of drainage network growth, as seen for example in drainage density and channel spacing, depend on both climate (e.g. Tucker & Slingerland, 1997; Tucker & Bras, 1998; Simpson & Schlunegger, 2003) and tectonics (e.g. Tucker & Whipple, 2002).

The question of what causes linear sections of mountain belts around the world to be characterised by a consistent regularity of catchment spacing (Hovius, 1996) has raised the interest of only a few studies (e.g. Hovius, 1996; Talling *et al.*, 1997). In these, recognising that mountain belts widen during their evolution, the observation of a nearly constant spacing ratio R for mountains with different widths has been interpreted as an indication that, as topography grows, a balance must be maintained between the lengthening of the main streams and the widening of drainage basins. This enlargement of the drainage basins is generally thought of as taking place by erosion through processes such as sideward capture of streams and drainage divide collapse (Hovius, 1996; Talling *et al.*, 1997; Jones, 2004). It thus implies a major re-organisation of the drainage network during, or after, the widening of the mountain belt. However, although processes such as sideward capture and divide collapse are occasionally observed in analogue experiments (Parker, 1977; Hasbargen & Paola, 2000) and numerical simulations (Howard, 1994; Simpson & Schlunegger, 2003; Pelletier, 2004), they have not been reported much and evidence for their past occurrence in nature is rare (Howard, 1971a). It can thus be doubted whether they are relevant for the organisation of river systems at large scales (Talling *et al.*, 1997).

The fundamental problem posed by the regularity of drainage spacing ratios in linear sections of mountain belts needs to be further addressed in order to understand how drainage networks develop at the scale of mountain ranges, and because understanding the three-dimensional (3-D) pattern of drainage networks in orogens is relevant to the prediction of (1) landscape response to climate or tectonic changes, (2) the magnitude of sediment efflux as

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a function of relief and (3) the distribution of sediment sources to basins at the mountain front and the consequent 3-D architecture of sedimentary deposits.

In this paper, we propose a new conceptual approach to this problem. We distinguish in particular two sub-questions that outline the organisation of our work: (1) how does the drainage network grow in a widening linear mountain belt, and (2) why is there a nearly constant linear relationship between the width of the topography and the spacing of the main transverse drains? We first try to answer and discuss these two questions separately and then bring some implications for the general organisation of drainage networks.

DRAINAGE NETWORK GROWTH IN A WIDENING OROGEN

Investigating and understanding how river networks develop is made difficult by (1) the impossibility of observing drainage network formation at large scales because it takes place over millions of years and (2) by the fact that we lose track of past drainage networks due to their intrinsic erosive nature. Thus, drainage network development has mainly been investigated either in small-scale outcrops such as badlands (Schumm, 1956), where it occurs rapidly enough to be directly observed, or in analogue (Mosley, 1972; Schumm & Khan, 1972; Parker, 1977; Hasbargen & Paola, 2000; Bonnet & Crave, 2003; Pelletier, 2003) and numerical experiments (Stark, 1991; Willgoose *et al.*, 1991; Howard, 1994; Tucker & Bras, 1998; Simpson & Schlunegger, 2003). However, there is a major difference between the boundary conditions used in current models of drainage network growth, whether conceptual or numerical, and the settings in which large-scale river networks such as seen in mountain ranges have developed: typical modelling approaches treat network propagation into uplifted, nearly smooth surfaces with fixed linear 'fault' boundaries or periodic edges, whereas real orogens widen laterally with time and progressively absorb former foreland zones. Therefore, the boundary and initial conditions used in these models do not accurately represent the conditions under which drainage networks grow at large scales.

Let us consider a simple conceptual scenario: the widening of a simple linear mountain range in a compressional setting. Two extreme cases can be envisaged, either (1) there is a foreland alluvial plain that separates the range front from the sea, or (2) the foreland is submarine and the sea is at the range front. In both cases, when the mountain front propagates and the range widens, new surfaces that were previously outside the erosion zone, and therefore called here 'yet undissected surfaces', become exposed to erosion. At this point, the rivers coming from the mountains upstream flow towards the sea on these yet undissected surfaces where they become unconfined (by opposition to their confinement in valleys inside the mountains), free to move laterally and merge in the downslope direction. During this stage, the rivers coalesce as they flow towards the sea, giving rise to a dendritic drainage geometry within which the rivers become naturally more widely spaced away from the high relief. Eventually, as uplift continues, the rivers become too entrenched to move further laterally and the dendritic geometry becomes quenched in the erosional topography (Fig. 2).

How long this stage lasts and how long it takes for the network to acquire its eventual geometry is difficult to constrain. We anticipate that it could occur very 'rapidly' as, for example, when related to new exposure of a surface by earthquakes, or quite slowly and possibly in a less straightforward way than imagined here in the case of a more gradual base-level lowering or of a more complex history of uplift and subsidence in the foreland (e.g. internally drained foreland basins).

A natural example illustrating the idea of a quenched river network in which rivers have merged downwards and cut into the former foreland zones can be seen in the western margin of the Central Andes (Chile, Fig. 3). There,

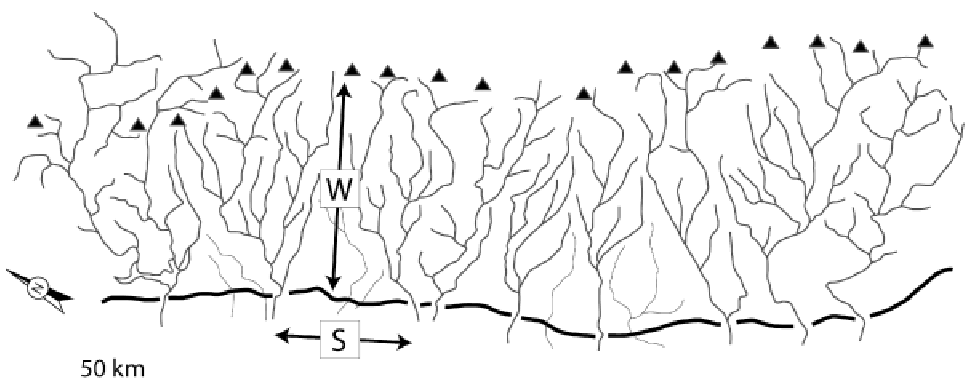

Fig. 1. Sample drainage network in the linear section of a mountain belt, Sierra Nevada, California, showing regularly spaced rivers at the mountain front (modified from Hovius, 1996). The width W of the mountain is measured from the drainage divide (black triangles) to the mountain front (bold line), and the spacing S between rivers is measured at the mountain front for major rivers draining the entire orogen. The spacing ratio R is the ratio between W and S.

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West-flowing rivers from high relief fed an alluvial and lacustrine forearc basin at the range front during Oligo-Miocene times, and have subsequently cut into these forearc deposits from Late Miocene on (Garcia & Hérail, 2005). Today, due to the arid/hyper-arid climate of the area, the former forearc surfaces have been preserved largely undissected between the main entrenched rivers (Fig. 3).

Several observations are in agreement with the ideas suggested above. First, in mountain belts (e.g. Pyrenees, European Alps) where alluvial bodies deposited in the now uplifted foreland are preserved, it has been shown in some instances (Trümpy, 1980; Jones, 2004) that the position of the rivers that were feeding these systems has not changed notably over significant time periods (10^7 years). This indicates that the large modern rivers deeply incised into now uplifted forelands could have once been alluvial systems wandering across the foreland plains.

Second, in many active collision zones (e.g. Himalaya, central Apennines, Bolivian Andes), the large-scale drainage network is made up of rivers that originate behind the highest peaks and flow transversely through the orogen across the main structural trend. The simplest explanation for this observation is that these rivers are antecedent to deformation (Oberlander, 1985) and extended progressively downward as the mountain range widened, rather than cutting backward across the range.

Finally, Mesozoic and Cenozoic pre-deformation series often cover considerable areas inside mountain ranges, and previous foreland series (up to the youngest ages) can be usually well studied in the external zones of most orogens. This precludes the operation of a constantly reorganising drainage network because in this case the migrating valleys would constantly sweep out the upmost terrains and prevent the observation of relatively young terrains inside orogens.

In summary, what we propose here as a solution to the first question addressed in the present paper, i.e. how does the drainage network grow in a widening linear mountain belt, is based on the following premises. For a drainage network to grow at a large scale in a mountain range, it has to invade previously undissected areas, which, in simple settings, are primarily found outside uplifted topography (i.e. outside the already dissected erosion zone) and progressively made available to network invasion by the lateral tectonic growth of topography. As the mountains widen, they progressively absorb undissected foreland surfaces on which the rivers are relatively unconfined and thus acquire their dendritic organisation by downward coalescence. Therefore, we propose that river networks in widening linear mountain ranges grow mainly in a 'downward' or 'mouthward' manner, from sources to the sea, as opposed to a 'headward'-type growth of river networks (Fig. 4), which is perhaps more typical of small-scale drainage network growth (e.g. as seen in physical experiments or at hillslope scale) or specific tectonic conditions (e.g. plateau uplift). Although it seems natural that networks develop in a mouthward manner in a widening topography, this type of network growth was never considered before as a fundamental process responsible for dendritic drainage patterns in widening mountain belts.

RELATIONSHIP BETWEEN RIVER SPACING AND MOUNTAIN WIDTH

In a simplified geometrical representation of a dendritic drainage network (Fig. 5) made up of rectangular catchments, it is the junction angle α (in plan view) between rivers that controls the spacing between them. The relation between the spacing of streams S and the distance to the divide, i.e. the mountain width W, is:

$$R = \frac{W}{S} = \frac{1}{\tan \alpha}. \quad (1)$$

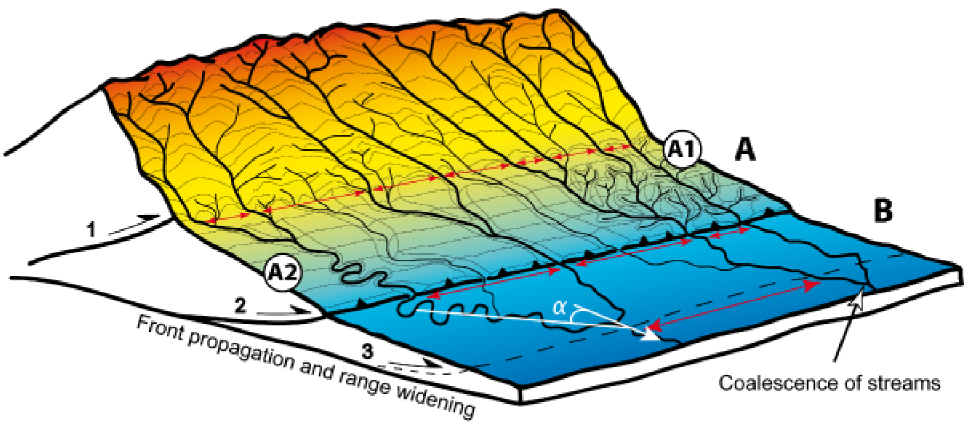

Fig. 2. Conceptual sketch of drainage network development in widening topography. The rivers coming from the existing hinterland wander and coalesce on the lowland plains outside the range, increasing their spacing downstream (red arrows) at a rate that depends on the angle α (orientation in plan view) with which streams flow with respect to the regional slope (white arrow). The resulting dendritic network becomes progressively 'quenched' in the landscape as the range front propagates (steps 1, 2 and 3) and the foreland is uplifted. Surface B is 'yet undissected', whereas surface A has just been recently incised by the network. Depending on climate, a secondary network invades (A1) or not (A2) the surfaces between newly incised streams.

Similarly, in a natural dendritic drainage network that would develop in a linear mountain belt according to the model outlined above, it is the mean angle with which rivers flow on yet undissected surfaces before they become quenched in the erosional landscape that determines the eventual dependency of river spacing on mountain width.

Exactly how rivers develop and choose their path on a rough surface are complex topics that are beyond the scope of this article. However, as a preliminary approach, we suggest that, intuitively, there are two relevant first-order controls on the path chosen by water on a simple rough inclined surface: (1) the local roughness of the surface, and (2) its regional slope. Indeed, observations in experiments or outcrops show that steep smooth surfaces usually develop near-parallel drainage patterns (small deviation from the regional slope), whereas relatively flat rough surfaces present more branched river networks (i.e. stronger deviation; Parker, 1977; Schumm, 1977; Simpson & Schlunegger, 2003).

To investigate how the roughness and regional slope influence the flow geometry, we have performed a series of numerical experiments of water flow over simple surfaces having a constant regional slope and a randomly distributed roughness (Fig. 6) described by a characteristic amplitude A_r and wavelength λ_r. In these experiments, we tested the role of the 'relative roughness' Φ of the surface, described as the ratio between the local slope S_r due to surface roughness ($S_r = 2A_r/\lambda_r$) and the regional slope S_R of the surface, on the average angle of water flow with respect to the orientation of the regional slope. We then compared numerical results with analytical predictions. Indeed, it can be shown that, on a surface with a relative roughness Φ, the topographic contour lines possess a characteristic azimuth whose normal makes an angle α with respect to

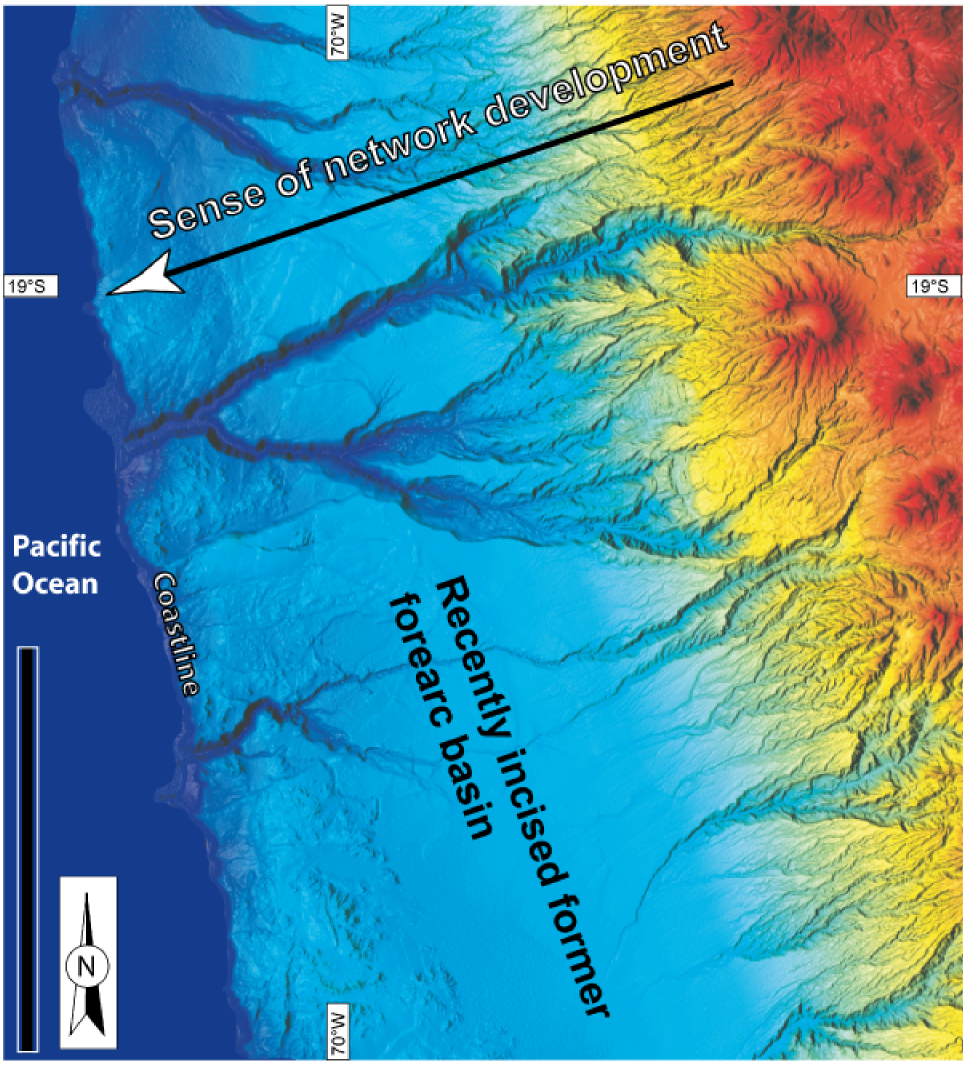

Fig. 3. Shaded topography (SRTM data) of the western margin of the Central Andes. The scale bar in black represents 50 km. Peak elevations to the East (in red) are around 4500 m and the sea is in blue to the West. The streams to the West were first feeding the forearc basin, which was then uplifted and incised. As this occurred, the streams coalesced downstream and their spacing increased. Because of the arid climate in the lowland plain, the surfaces between those recently incised streams have been left undissected. Note the two streams in the middle that first separate away from each other before joining close to the coastline. Note also that some streams in the lower part of the DEM did not reach the coastline.

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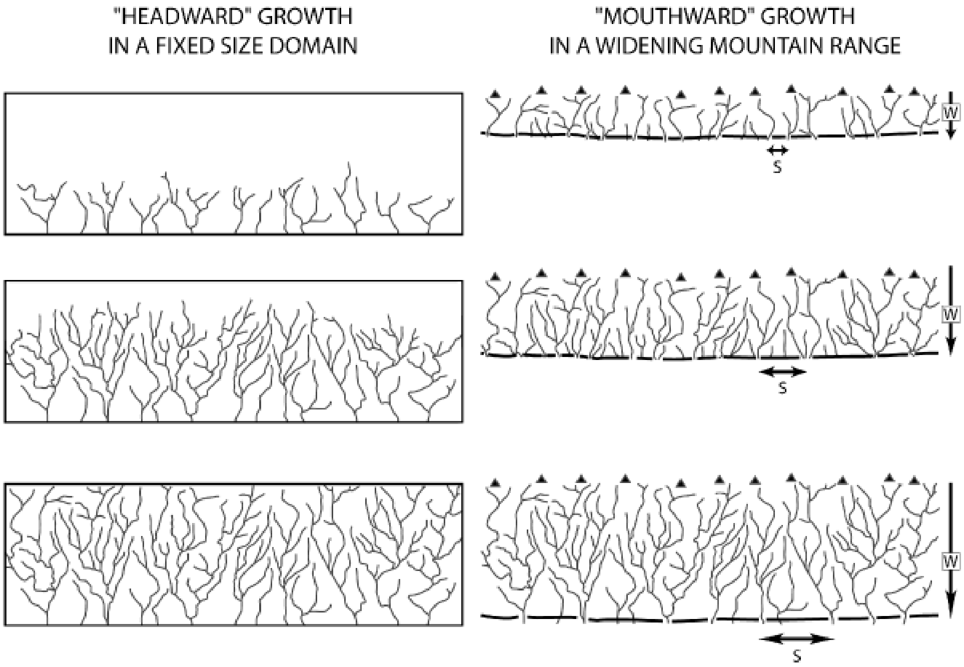

Fig. 4. Schematic representation of two models of drainage network development with time (time is from top to bottom): the 'headward' and the 'mouthward' growth models. Both models lead to the same drainage network. In the headward growth model, the network progressively invades by river headward bifurcation an undissected surface with fixed dimensions. In the mouthward growth model, the network progressively extends by river coalescence as the surface widens with time, such as in a widening orogen. In the mouthward model, the river spacing naturally increases away from the drainage divide (black triangles) as the mountain width W increases and the rivers progressively coalesce downstream.

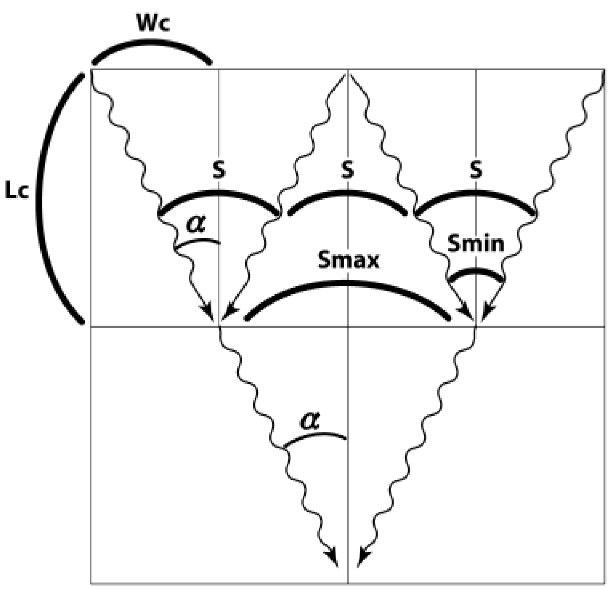

Fig. 5. Simple plan view representation of a dendritic drainage network. The regional slope is from top to bottom. Streams are considered to flow with a mean angle α with respect to the orientation of the regional slope, thus designating rectangular catchments. Stream spacing is comprised between a maximum $S_{\max}$ (depending on the initial spacing) and a minimum $S_{\min}$ (approaching 0). Within this range, the regular spacing S between the streams corresponds to the width of the considered catchment and is directly linked to the angle α. Substituting catchment length L_c and width W_c to mountain width W and river spacing S, respectively (Hovius, 1996), gives the following expression for the spacing ratio R: $R = W/S = L_c/W_c = 1/\tan\alpha$.

the orientation of the regional slope (Fig. 6). This angle is given approximately by the following relation:

$$\alpha = \tan^{-1}\frac{S_r}{S_R} = \tan^{-1}\Phi. \qquad (2)$$

Assuming that water flows perpendicular to contour lines, the angle α also corresponds to the characteristic azimuth of water flow with respect to the orientation of the regional slope (Fig. 6).

Analytical predictions of mean flow orientation calculated with Eqn. (2) compare well with numerical simulations of water flow over synthetic surfaces with $0 < \Phi < 1$ (Fig. 7). Note that the orientation of water flow cannot be described by the simple relation of Eqn. (2) when $\Phi > 1$. This is because in this case the local slope becomes greater than the regional slope, and thus the geometry of the local roughness dominates entirely the orientation of water flow (as discussed below in more detail).

Comparing Eqns (1) and (2) gives $R = 1/\Phi$, so a direct comparison can be made between the spacing ratios observed in linear mountain belts and the relative roughness of the undissected surfaces on which the drainage in these mountains may have organised, if they developed according to the model we propose. Most individual spacing ratios in Hovius' data (i.e. spacing ratios calculated locally, for each pair of catchment, by dividing the local mountain width with the local spacing, instead of spacing ratios calculated using average mountain widths and spacings; see Hovius, 1996) are grossly comprised in a range between 1 and 5, around a mean of 2.7 (standard deviation of

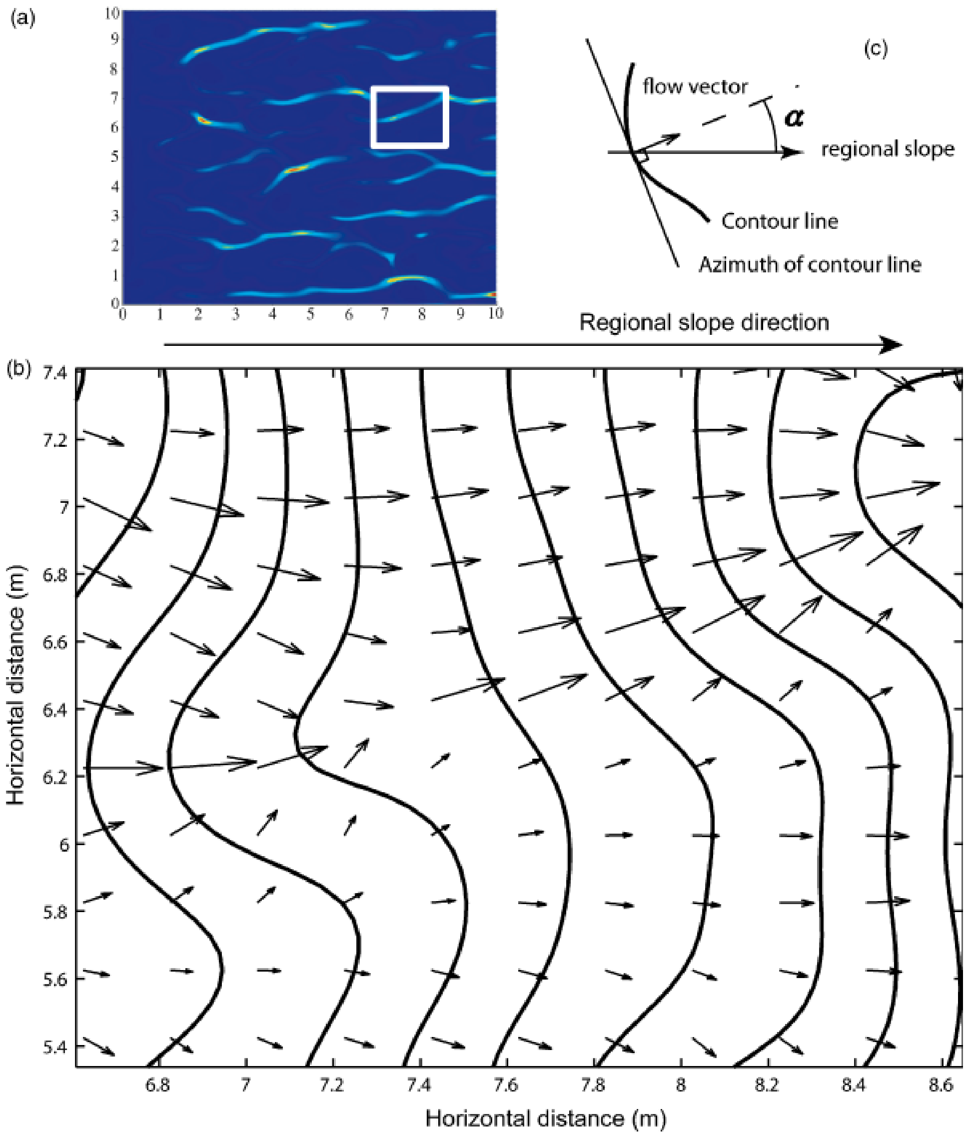

Fig. 6. Numerical simulation of water flow over a tilted plane with random perturbations. The numerical model is based on the resolution of the shallow water equations (Simpson & Castelltort, 2006). (a) The surface (in plan view) is a 10×10 m inclined plane with slope from left to right. The colours represent water depth (red = maximum depth, blue = minimum depth) highlighting the formation of discrete channels that flow with a mean angle to the regional slope and coalesce downstream. (b) Detail of the experiment (white rectangle on (a)) showing the contour lines and the flow vectors. The water flow is largely perpendicular to contour lines. (c) Sketch illustrating the relations between the angle with which water flows with respect to the regional slope and the azimuth of contour lines due to local roughness (see text).

2.1, Fig. 8a). According to Eqns (1) and (2), respectively, the flow angles α are comprised between 10° ($R = 5$) and 45° ($R = 1$), and the corresponding relative roughnesses (Fig. 8b) range between 0.17 ($R = 5$; $\alpha = 10^\circ$) and 1 ($R = 1$; $\alpha = 45^\circ$). Note that in the whole data set, individual spacing ratios range from 0.4 to 19.3 (Hovius, 1996).

As an answer to the second question addressed in the present paper, i.e. why is there a nearly constant linear relationship between the width of the topography and the spacing of the main transverse drains in linear mountain belts, we suggest that it is because, in these settings, the drainage networks acquire their organisation on surfaces having relatively similar geometrical properties in terms of roughness and regional slope, i.e. relative roughnesses mostly comprised in a finite restricted range of values ($0.17 < \Phi < 1$). These surfaces may have similar roughnesses mainly because (1) they are undissected at the time of drainage network organisation and were most frequently previously sedimentary surfaces whether marine or continental, and (2) linear mountain belts are relatively simple structural settings in which it can be expected that the yet undissected surfaces are relatively undeformed at the time of drainage organisation (as discussed more below). These surfaces may have similar regional slopes at the time of drainage organisation because they immediately receive rivers coming from the mountains existing upstream when they become exposed, and thus they are unlikely to acquire a strong slope (due to tectonics) before incision takes place.

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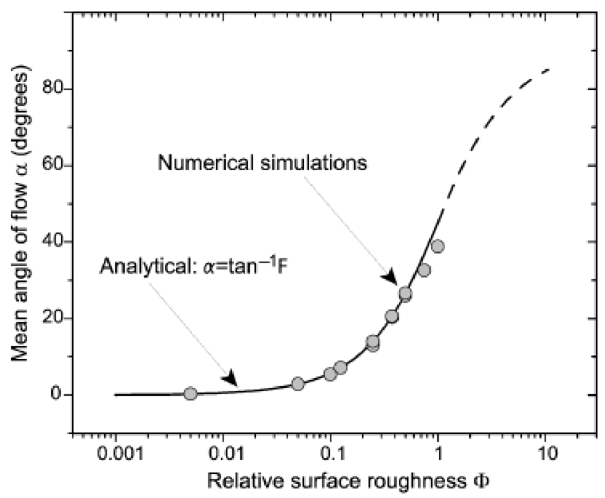

Fig. 7. Influence of relative surface roughness Φ (ratio between local slope, due to local roughness, and the regional slope) on the orientation of water flow (angle of flow α (in plan view) with respect to the regional slope) over random topography. Analytical predictions (solid curve) are confirmed by numerical simulations (shaded circles) using the shallow-water equations to compute water flow over randomly perturbed, non-erodible, surfaces.

As a corollary, it follows that catchments with spacing ratios outside of the 'frequent' range indicate specific conditions of either roughness and/or slope. Firstly, spacing ratios lower than 1 will be mainly found where local roughness overcomes the regional slope and streams deviate strongly from it ($\alpha > 45°$). This may be the case when local tectonic structures in the foreland create, before erosion, sufficient topography (with respect to the regional slope) to control stream orientation before the drainage network becomes entrenched. Such a scenario could occur when the mountain widens, absorbing a low-slope, overfilled alluvial foreland basins such as in the Himalayas, which clearly have the highest proportion of 'wide' ($R < 1$) catchments (range *F*, Fig. 9). There, some catchments have $R < 1$ because their main streams were deflected by tectonic structures at the mountain front (Hovius, 1996; Gupta, 1997). It is also common to observe rivers defeated by growing anticlines as evidenced, for example, by wind gaps (Burbank *et al.*, 1996). The Tian Shan and Kirgizskiy ranges (ranges H and G, Fig. 9) show spacing ratios distributed towards relatively lower spacing ratios and with maximum lower than 5. As for the Himalayas, but in a less pronounced way, 'wide' catchments in both of these ranges could result from drainage organisation on anomalously low-slope alluvial surfaces.

Secondly, spacing ratios higher than 5 will be found where the regional slope strongly overcomes the local roughness and the catchments are thus anomalously elongated (directed down the regional slope). One possibility is that mountain range widening exposes surfaces with a relatively strong slope. This could apply to catchments draining directly to a marine underfilled foreland, thus showing less possibility to merge downward on wide alluvial surfaces and resulting in more elongated networks.

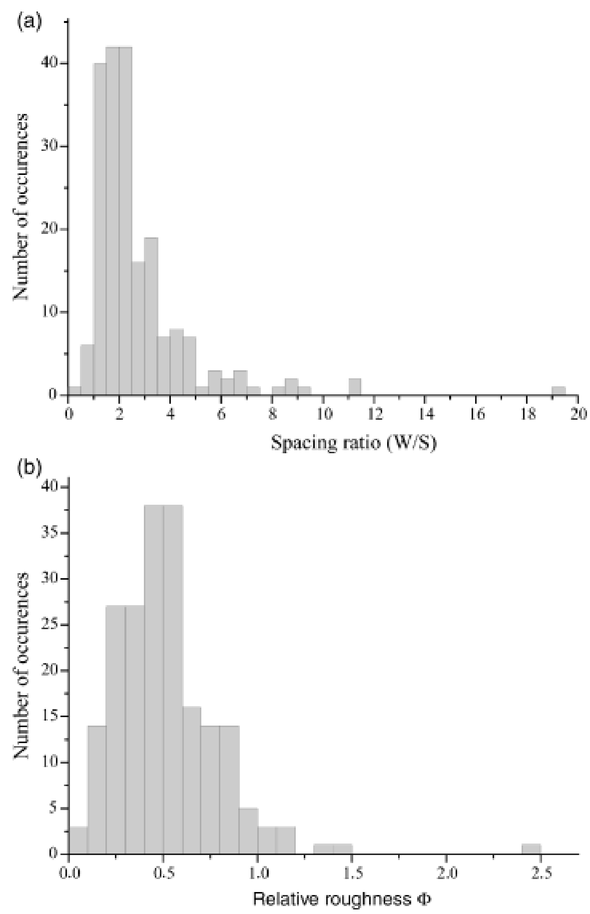

Fig. 8. Histograms of spacing ratios in 11 linear mountain belts (a, data from Hovius, 1996) and associated relative roughnesses (b, this study). The spacing ratios are mostly comprised in a narrow range of values between 1 and 5 (mean of 2.7 and standard deviation of 2.1), which correspond to a narrow range of relative roughnesses between 0.17 and 1 (mean of 0.51 and standard deviation of 0.28).

Natural examples of this case could be the Finisterre, Maoke, Barisan and Central Ranges (ranges B, C, D, E in Fig. 9), which all have at least two catchments with $R > 5$. The Apennines and Peruvian Andes (ranges I and K, Fig. 9) which do not show extensive alluvial foreland plains, also have quite elongated networks.

Although we have not validated these predictions because each range and each individual catchment in a given range may have a particular history, they show that further work remains to be carried out on the interpretation of drainage network geometry in terms of tectonics and climate.

IMPLICATIONS FOR THE GENERAL ORGANISATION OF DRAINAGE NETWORKS

Assuming rectangular drainage basins and replacing the width of topography (W) with basin length (L_b) and the product of width and spacing (WS) with the basin drainage

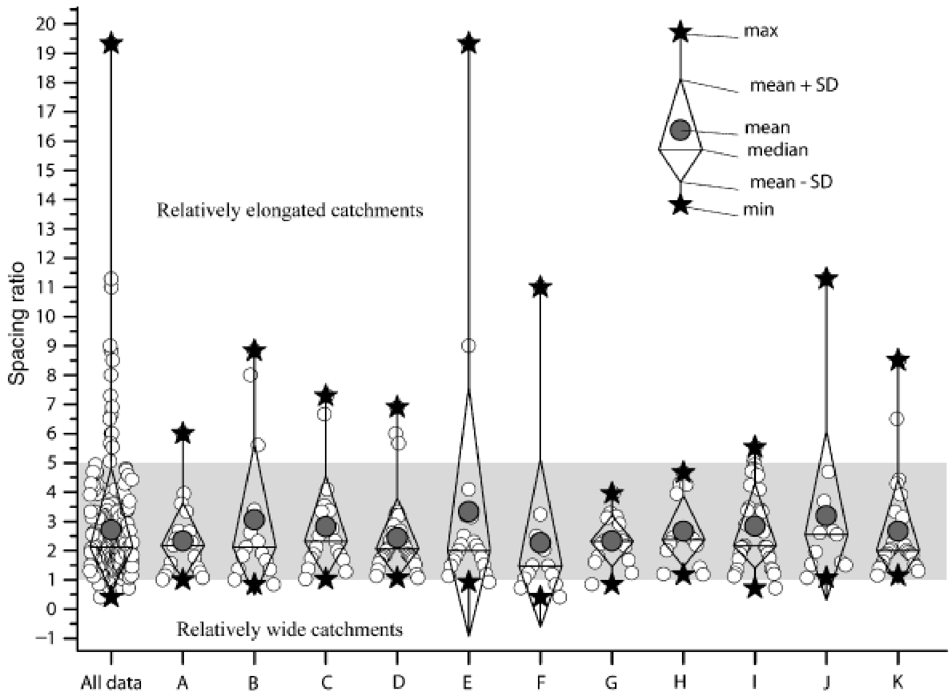

Fig. 9. Distribution of spacing ratio data for all mountain ranges (all data) and for each mountain range. Data from Hovius (1996). The grey area represents spacing ratios comprised between 1 and 5. Above this area is the domain of relatively elongated catchments and below are the relatively wide catchments. (A) Southern Alps, New Zealand, (B) Finisterre Range, Papua New Guinea, (C) Maoke Range, Irian Jaya, (D) Barisan Range, Sumatra, (E) Central Range, Taiwan, (F) Himalaya, India/Nepal, (G) Tian Shan, China, (H) Kirgizskiy Khrebet, Kirgiztan, (I) Apennines, Italy, (J) Sierra Nevada, California, (K) Andes, Peru.

area (A_b), Hovius (1996) showed that the linear relationship between the mountain width and spacing of main streams is equivalent to Hack's law (Hack, 1957) in which the length L_b of a basin scales with its drainage area A_b follows a relation of the form $L_b = cA_b^b$ (Montgomery & Dietrich, 1992) (Fig. 10).

Because Hack's law holds for a vast range of basin sizes (Montgomery & Dietrich, 1992; Rodriguez-Iturbe & Rinaldo, 1997; Dodds & Rothman, 1999), the dependency of river spacing on the distance to the drainage divide must hold not only at the mountain front but also within the mountain itself and in adjacent lowlands (when present). This can be confirmed by analysing width to spacing data in Hovius' ranges at arbitrary distances from the drainage divide (Fig. 10). The equivalency of Hack's law and the *W/S* relationship is important because it indicates that the mechanisms responsible for the development of drainage networks in linear mountain belts are likely to be the same as those for drainage networks in general (Hovius, 1996). Indeed, except for pristine topography such as a mountain belt emerging from the sea, every surface newly submitted to erosion is usually adjacent to pre-existing topography, and thus receives, in addition to rainfall on the surface, an input of water in the form of streams entering at its upstream boundary. Thus, although every drainage network must ultimately begin with channel initiation (as studied e.g. by Smith & Bretherton, 1972; Loewenherz, 1991, 1994; Izumi & Parker, 1995, 2000), we suggest that the dendritic geometry of drainage networks is controlled largely by the downstream coalescence of existing channels on undissected surfaces as a result of the natural aggregative behaviour of downhill fluid flow (Schorghofer & Rothman, 2002).

As for the width to spacing relationship investigated here, the consistency of Hack's law for different drainage networks and at different scales probably results from organisation of streams by their downward coalescence on surfaces having similar geometrical properties mainly because (1) they are yet undissected at the time of channel organisation, and (2) tectonics is unlikely to increase the slope significantly before drainage organisation takes place under 'normal' climatic conditions. Thus, the geometrical properties of drainage networks depend mostly on the geometrical properties of the surfaces on which stream coalescence takes place and the tectonic and climatic conditions at the time of channel organisation but not on the past and present tectonic and climatic conditions in the erosion zone. However, as for Hovius' relationship, Hack's law is a statistical representation of many basins, but each individual basin must display a particular shape (different from Hack's law) that expresses the particular conditions that lead to its formation. In this way, basins having shapes well outside the typical Hack's law most probably express specific tectonic or climatic conditions.

Many existing models produce dendritic river networks that satisfy Hack's law and other geometrical properties of natural drainage basins (Leopold & Langbein, 1962; Howard, 1971b, 1994; Stark, 1991; Willgoose *et al.*, 1991;

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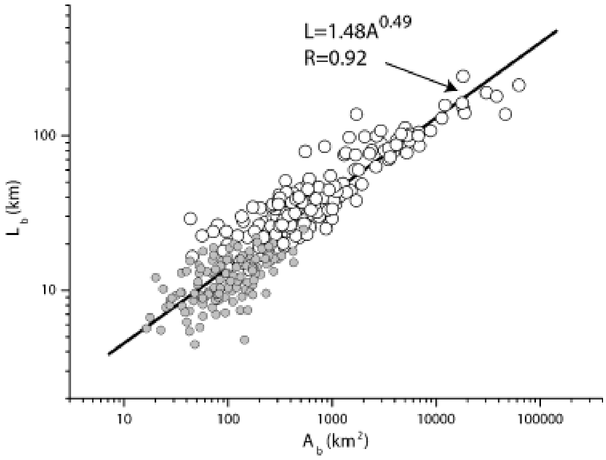

Fig. 10. Plot of basin drainage areas and basin lengths for catchments in Hovius' (1996) linear ranges. Assuming rectangular catchments, the values plotted here are obtained by replacing mountain width W with basin length L_b, and the product width × spacing ($W \times S$) with basin drainage area A_b. The white circles represent width to spacing data measured by Hovius at the mountain front and the grey circles represent measures at arbitrary distances from the drainage divide inside the ranges. The measures at arbitrary distances have the same trend as the ones at the mountain front (134 measures in ranges A, B, C, D and E give a median of 1.4 and a standard deviation of 1.2), which shows that Hovius' relation holds statistically everywhere inside the considered networks. The linear regression obtained on all measures yields a relation $L_b = 1.48A_b^{0.49}$, with coefficient and exponent close to the ones observed for Hack's law when basin length and drainage area are measured (Montgomery & Dietrich, 1992), thus emphasising the equivalency of Hack's law and Hovius' width-to-spacing relationship.

Kirchner, 1993; Rigon *et al.*, 1994; Rinaldo *et al.*, 1995; Rodriguez-Iturbe & Rinaldo, 1997). Among these, our view of river network development is similar to the 'stream convergence' model of Leopold & Langbein (1962), in which streams originating at the upstream edge of a surface progressively join as they follow a random path directed downslope until they reach the downstream edge of the surface. However, our model differs fundamentally from Leopold and Langbein's model and the others cited above in recognising that the surface on which streams flow extends progressively with time instead of having fixed dimensions.

Finally, although we have restricted our discussion to compressional mountain ranges, the model presented here may also apply to other settings showing regular drainage spacings such as linear fault blocks or compressive folds as studied by Talling *et al.* (1997). In these settings, Talling *et al.* (1997) showed that there is a greater variability of catchment spacing ratios. In our view, this could be a result of the fact that widening is relatively limited in these settings, and therefore there is less 'averaging' of the networks properties by progressive organisation on similar undissected surfaces than at the scale of mountain belts. This is consistent with the suggestion by Talling *et al.* (1997) that 'the outlet spacing is largely determined during the early stages of network growth on relatively low slopes', and that 'this dependency on initial conditions may explain the lack of correlation between spacing ratios and parameters measured at the present day (e.g. slope)'. It highlights the need for further investigation of the possible applicability of our model to different settings.

CONCLUSION

We have presented a conceptual model of drainage network growth in widening linear mountain ranges in which the network acquires its organisation by downstream coalescence of rivers on yet undissected surfaces outside mountain ranges and then become progressively incorporated into the erosional landscape as the range widens. The geometry of the surfaces on which drainage networks develop, and in particular their roughness and regional slope, control the mean angle with which the streams flow with respect to the regional slope and thus the rate at which they converge, i.e. the relation between the spacing of catchments and the distance to the divide. As such, the geometry of the networks reflects the geometrical properties of the surfaces on which they have developed and thus the tectonic and climatic conditions prevailing at the time of drainage organisation, but it has no link with the past and present tectonic and climatic conditions in the erosion zone.

The linear relationship between mountain width and catchment spacing in linear ranges probably results from organisation of networks by downward coalescence of streams on surfaces having similar geometrical properties mainly because (1) they are yet undissected at the time of channel organisation, and (2) deformation is unlikely to increase the slope significantly before drainage organisation takes place. As a corollary, drainage networks having geometries outside of the 'normal' as described by Hack's or Hovius' laws could be taken as useful indicators of past specific tectonic and climatic conditions.

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