THE IMPACT OF STRUCTURAL ADJUSTMENT ON RIVER NETWORKS

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Bute Landscape on Pachmarhi Mesa

Abstract
Branching river networks are one of the well-known and recognized features of Earth's landscapes and have also been discovered in the Solar System [1, 2] but the mechanisms that create these patterns and control their spatial scales are rarely understood. Theories based on probability[3,5] or optimality[3,6,8] have proven useful[9], but not explained how river networks develop over time through erosion and sediment transportation. Here I show that branching at the uppermost reaches of river networks is rooted in two coupled instabilities. First, valleys widen at the expense of their smaller neighbours, and second, side slopes of the widening valleys become susceptible to channel incision. Each instability occurs at a critical ratio of the characteristic timescales for soil transport and channel incision. Measurements from two field sites demonstrate that our theory correctly predicts the size of the smallest valleys with tributaries. I also show that the dominant control on the scale of landscape dissection in these sites is the strength of channel incision, which correlates with aridity and rock weakness, rather than the strength of soil transport. These results imply that the fine-scale structure of branching river networks is an organized signature of erosional mechanics, not a consequence of random topology.

Keyword : Branching river Plateau gorges. Mesa, ridgelines Peclet number, tributary basins,

Observers have long recognized that branching river networks, in which tributaries merge in the downstream direction, are a fundamental outcome of erosion by flowing water. Early field observations led to conceptual models in which hierarchical drainage networks result from progressive integration of initially separate drainages through divide migration and stream capture [10,11]. More than a century of study of erosional mechanics has culminated in numerical models that produce landscapes dissected by branching river net-works [12, 14] and lend some support to the early conceptual models, but a physically based theory that explains the form of tributary networks has proven elusive.[15]

The main reason for this shortcoming is that there is no clear consensus about what such a theory should be suitable to predict. Early efforts to identify unique geometric characteristics of natural river networks[11,16,17] failed when the proposed scaling laws were subsequently shown to apply to all hierarchical networks, riverine or other-wise. This fuelled a broader class of studies based on principles other than erosional mechanics, including probabilistic models of topologically random networks [3,5] and optimality arguments based on energy dissipation or entropy.[3,6,8] Such studies have provided new insights into the structure of natural river networks,[9] but cannot directly relate river network form to the erosional mechanisms that shape the topography: I know what the skeleton of a landscape looks like, but not how it grows.

Despite progress in characterizing the geometry of drainage system and modeling landscape evolution, it remains unclear how the form of drainage system records the dominant factors that shape landscapes, such as bedrock properties, tectonic deformation, climate and life. Here I use a simplified model to show that branching tributary networks form through two coupled instabilities, and propose that the scale of the smallest valleys with tributaries is a signature of this process. I then present field measurements from two sites with drainage networks that differ considerably in scale, and show that both are consistent with our theory. This comparison reveals how the spatial structure of river networks records fundamental geological and environmental factors such as rock type and rainfall.

To recognize specified scales in tributary networks, I evaluated the valley networks in two landscapes with similar erosion processes but different scales of fluvial dissection (Fig. 1).

The Pachmarhi Plateau is extensively covered by the plinthite-ferricrete that occurs as the cap-rock and outcrops around the edge of the Pachmarhi Plateau. Excellent exposures can be observed, on the forest trail down the Pachmarhi Scarp on the way to Binora, on the trails leading up to Dhupgarh Peak and on trails from Kajri to Pachmarhi town.

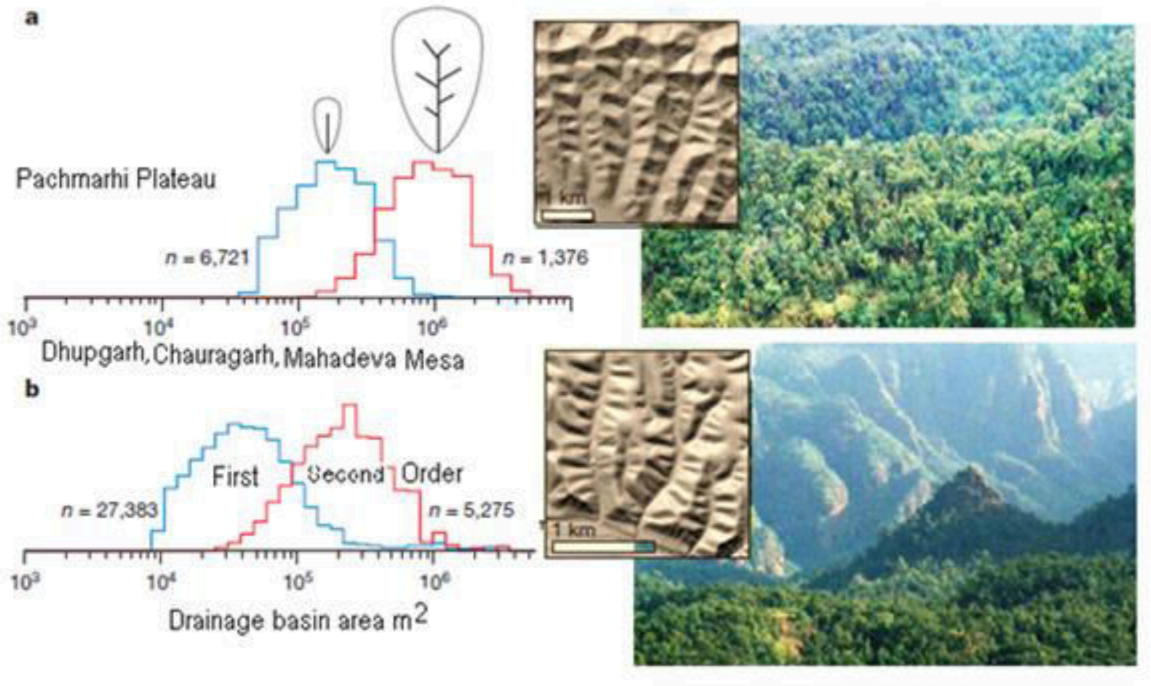

Figure.1 Properties of the study sites. **a,** The Pachmarhi Plateau, **b,** Dhupgarh, Mahadeva, Chauragarh California. Left, area distributions of first- and second-order drainage basins, with inset sketches showing examples of first- and second-order basins. Coloured lines are histograms with counts weighted by drainage basin area to compensate for the greater abundance of smaller basins. Insets at centre, shaded relief maps of small portions of the study sites generated from laser altimetry, with vegetation filtered out. Right, photographs showing views from the tops of ridgelines, with first-order valleys in the near distance.

Most of the ferricrete was in situ, except when approaching the waxing-slope segment leading to a stream indenting the Plateau where detrital fragments occasionally dominated the debris slope segment. Excavations into the valley wall yields a moist, soft, deep tan coloured, mottled clay that soon becomes hard on exposure to the atmosphere. This layer thins out towards the summit of the plateau. . Pachmarhi plateaus is dissected by a deeply cut streams. The relief is great and that distinguished them from plains. The region is higher than the surrounding country and bordered by scarps. The valleys in a plateaus are deep gorges. That is, they conform with the usual conception of a canyon and have steep or vertical walls, with bare rock exposures. The presences of vertical cliffs in the plateaustructure. The steep valleys in the Plateau exhibit cliffs hundreds of feet in height where the streams have cut through massive sandstone.

Dhupgarh –Mahadeva-Chauragarh Mesa with restricted peaks which have been referred to as butte e.g. Chauragarh. The above geomorphological features are controlled primarily by bedding and subordinately by jointing and faulting etc. At places where truncation of spurs has not been complete, relics of former spurs project from valley floors as field of rounded and sometimes grotesquely shaped rock knobs, among which there may be scoured-out rock-basin. Some of these peaks reflect the earlier joint controlled geometry of landform initial geometry discernible:

These orientation peculiarities of highlands are expression of two prominent sets of joints tending N.S. and E.W. which are conspicuous in this area The Mesa in Pachmarhi landscape are the isolated table lands, capped with a protective covering, which is essentially horizontally bedded and associated with the plateau. Features similar in character with more limited summits are usually called butte. Commonly in the area, mesa and butte are rimed by scarp, formed by resistant cap rock. Mainly they are formed by the Sandstone, but at very few places it is capped with lawa flows.Mesa and butte show smooth texture light greyish to blue and light red colour due to variation in vegetation cover. It shows escarpment at places.

I mapped the valley network over a large area of each landscape (Methods). I then applied the Horton-Strahler stream ordering scheme[11,16] to identify first-order drainage basins (those with no tributaries) and second-order drainage basins (those with at least one first-order tributary) (Fig.1). The upstream areas drained by basins of a given order are log-normally distributed around a well-defined modal value (Fig.1). Moreover, I find that the modal drainage areas of first-and second-order basins in the Pachmarhi Plateau and Dhupgarh Mahadeva Chauragarh Mesa differ considerably. The smallest basins with tributaries are typically four times larger in the Pachmarhi Plateau, despite the similar appearance of the landscape (Fig. 1). I seek an explanation for this fundamental scale difference.

Valleys surrounded by smooth ridges emerge in soil-mantled landscapes from a competition between river incision, which amplifies topographic perturbations, and soil creep, which damps perturbations. The extent of valley incision can also be limited by a threshold for runoff production or surface erosion[22], but I make the simplification that soil creep is the dominant effect, an assumption supported by previous analyses[21,23]. The smoothing effect of soil creep can be characterized with a diffusion time, $t_{\mathrm{diff}} = L^2/D$, where L a horizontal length is scale and D is the soil transport coefficient(in $\mathrm{m}^2\ \mathrm{yr}^{-1}$). Channel incision can be characterized by an advection time that describes the rate at which changes in elevation propagate through the drainage network, $t_{\mathrm{adv}} = L^{1-2m}/K,$ where m is a constant and K is a channel incision rate coefficient (in $\mathrm{m}^{1-2m}\mathrm{yr}^{-1}$) The ratio $t_{\mathrm{diff}}/t_{\mathrm{adv}}$which describes the strength of channel incision relative to soil creep at a chosen scale $L,$ is analogous to a Peclet number, $\mathrm{Pe} = KL^{1+2m}/D$ (refs21,23).

The branching valley networks will develop at a finer scale in landscapes where channel incision is strongly related to soil creep. To examin this idea, I used a landscape evolution model (Methods) to simulate the development of a ridgeline bounded by two incising channels for many different values of Pe. Each simulation formed drainage basins extending from the bounding channels up towards the drainage divide. The length scale L was chosen to be the half-width of the ridgeline, which roughly equals the length of the largest basins (Fig. 2a, inset). (Throughout this study, L is taken to be the length of a drainage basin, or the length of a slope on which a drainage basin may develop.) From the final, equilibrium topography in each experiment, I measured the drainage areas of the basins. A plot of normalized drainage area versus Pe for all the simulations (Fig. 2a) reveals a transition at 250 < Pe<300. For Pe<250, drainage basins have a uniform size. For Pe >300, the distribution of basin size is bimodal, with each basin either extending all the way from a lowering boundary to the central drainage divide, or extending only part way to the divide and occupying a small space between larger basins. Nearly all of the larger basins for Pe>300 developed tributaries.

I explain this transition in landscape form in terms of a stability diagram (Fig. 2a). At Pe<250, an array of parallel, uniformly sized basins is a stable configuration: additional numerical experiments confirmed that if any one basin in such a configuration is perturbed by increasing its drainage area, the topographic divides separating the enlarged basin from its neighbours will migrate back towards the

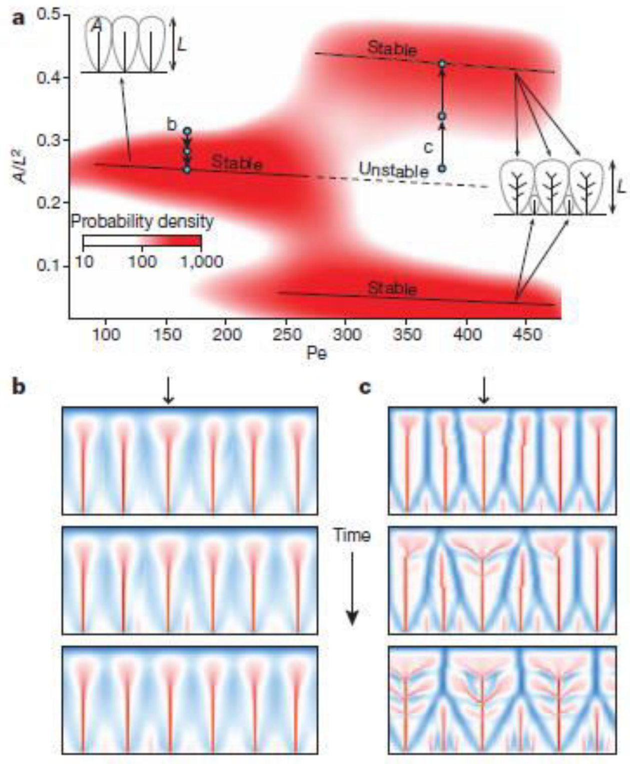

Figure. 2 Branching instability in valley networks. a, Stability diagram for first- and second-order drainage basins as a function of Peclet number, Pe. Insets illustrate the definitions of ridgeline half-width, *L*, and basin area, A. Background colour (see key) indicates probability density distribution of drainage basins generated in numerical experiments, which partly reflects variable initial conditions . Paths with blue points and arrows trace the evolution of the numerical experiments in **b** and **c,** which illustrate the response of an array of parallel valleys to a perturbation in which one valley (marked with an arrow) is enlarged slightly. Colours in **b** and **c** denote drainage area, with blues corresponding to ridgelines and reds to valleys.

Center of the enlarged basin is such that it shrinks back to the size of its neighbours (Fig. 2b). At Pe > 300, an array of parallel, equally sized basins is unstable: enlarging the drainage area of any one basin causes the topographic divides to continue to migrate away from the centre of the enlarged basin, such that it widens at the expense of its neigh bours (Fig. 2c). This instability propagates through the landscape until all drainage basins have either grown or shrunk to reach one of the two stable sizes. Supplementary Fig. 3 shows several drainage basins in Dhupgarh Mahadeva Chauragarh Mesa that may have experienced this instability. This transformation of the drainage network is comparable to an effect observed in laboratory analogue experiments [24], and may explain the uniform aspect ratios of basins that drain to linear boundaries[25],

The explanation for the critical value of Pe concerns the feedbacks that operate when a basin is enlarged. The increase in drainage area increases channel discharge, and therefore channel incision rate. Faster incision further deepens the basin, driving the surrounding ridgelines towards neighboring basins and enlarging the drainage area—a positive feedback. Competing against this is a negative feedback in which deeper valleys with a sharper "V" shape are filled in faster by diffusive soil creep. For Pe>~300, the positive feedback is stronger.

This instability exhibits the enlargement of some of the basins, but it does not explain why the enlarged basins develop tributaries on their side slopes (Fig. 2c). To determine why the tributaries grow, I performed a second experiment in which I subjected an inclined, planar surface with a prescribed Peclet number (intended to mimic the side slopes of a drainage basin) to a series of small-amplitude perturbations with a range of wavelengths, and measured the growth or decay rate of the perturbations (Fig. 3). The length scale L used to calculate Pe was chosen to be the horizontal length of this sloping surface, which is the length of the incipient valleys. For Pe<~60, perturbations of all wavelengths decay, and no tributary valleys form. At Pe $< \approx 60$, wavelengths of roughly one-third of the slope length become unstable, and grow into incipient tributary valleys. The range of unstable wavelengths widens as Pe increases above this critical value. A similar wavelength selection has been inferred in analytical studies of incipient channelization under sheet flow [26,27].

To relate this instability to tributary valleys like those in Fig. 2c, I calculate Peclet numbers for the side slopes of drainage basins with and without tributaries in the numerical model solutions, using the horizontal lengths of the basin side slopes as L (Fig. 3 inset). This comparison confirms that the difference between valleys with and without tributaries is whether Pe for their side slopes is greater than or less than the critical value of —60. For example, the side slopes of the first-order basins in Fig. 2b have Pe = 12, whereas those of the second-order basins in Fig. 2c have Pe = 75. Thus, the basin-widening instability shown in Fig. 2 is accompanied by the formation of tributary valleys because the lengthening side slopes exceed the critical Pe for growth of incipient valleys.

Together, these two instabilities provide an explanation for the characteristic branching pattern of fine-scale tributary networks. In addition, our theory makes a testable prediction: second-order drainage basins should have Peclet numbers that exceed the critical value of —300 (Fig. 2a), regardless of the absolute spatial scale of the landscape. To test this prediction, I calculated Pe for drainage basins in the Pachmarhi Plateau and Dhupgarh Mahadeva Chauragarh Mesa. This requires measurements of $K/D, m$ and drainage basin length, L, each of which can be estimated from topographic data. K/D and m have been estimated[21] for representative sites in each landscape from an independent analysis of the topography . Combining these values with our measurements of L , I compiled frequency distributions of Pe (Fig. 4). Unlike the drainage area distributions in Fig. 1, which differ betweeen sites by a factor of four, the Pe distributions are quite similar. The critical range of 250< Pe< 300 (Fig. 2) falls between the modal values for first- and second-order basins in both landscapes, consistent with the prediction that most second-order basins should exceed this range, whereas most first-order basins should not. The match is slightly better for the Pachmarhi Plateau, whereas the gap between the modes occurs at approximately 300 < Pe< 350 for Dhupgarh Mahadeva Chauragarh Mesa, but this difference is small compared with the scale discrepancy in Fig. 1. In addition, most first-order basins in both landscapes exceed the critical value of Pe<60 for the development of incipient valleys (Figs 3 and 4). Thus, drainage networks in both the Pachmarhi Plateau and Dhupgarh Mahadeva Chauragarh Mesa are consistent with our proposed mechanism for tributary network development, despite their difference in spatial scale.

This result implies that the ratio of coefficients describing the long-term rates of channel incision and soil creep, K/D, can be estimated from a drainage basin's stream order and size. Because m is typically ~0.5 , $Pe \approx KL^2/D$ as a rule of thumb. Thus, K/D, where Pe_n is the modal Peclet number for a basin of order n (from Fig. 4, for example, Pe< 600). With this approach, it may be possible to use remote imagery to help calibrate long-term erosion laws, a result with promise for both terrestrial and planetary landscapes. The specific expressions presented here only apply to low-order, steady-state drainage basins shaped by regolith creep and ephemeral channel incision. Nonetheless, the principle that stream order and basin size provide a proxy for long-term process rates may also apply to higher-order drainage basins and landscapes shaped by different hill slope and channel erosion mechanisms. I show in the Supplementary Information that the branching mechanism documented in Figs 2 and 3 occurs even with different erosion and transport laws, provided that channel incision depends on drainage area and regolith transport depends on slope.

To understand how the geological, climatic and biological characteristics of a landscape control the scale of the drainage network, I performed an additional calculation. Dhupgarh Mahadeva Chauragarh Mesa is made of weaker rocks than the Pachmarhi Plateau, receives less rainfall in a more seasonal distribution, and has vegetation dominated by grasses rather than forest; it also has larger *K/D* and therefore a finer-scale drainage network (Fig. 1). I determined *K* and *D* independently to discover whether this larger ratio reflects stronger channel incision, less mobile soil, or both. Combining long-term erosion rates inferred from cosmogenic[10] Be in river sediment (Methods, Supplementary Table 1) with surveys of hillslope topography, I calculated *D* for the Pachmarhi Plateau and Dhupgarh Mahadeva Chauragarh Mesa, and divided *D* by *D/K* to obtain *K* (Methods, Supplementary Table 2). This calculation clearly shows that the main difference between the sites is the strength of channel incision: whereas *D* differs by only 25% (and is actually larger at Dhupgarh Mahadeva Chauragarh Mesa, the opposite of what would be expected if *D* are responsible for the scale difference), the channel incision rate factor for a reference drainage area, $KA_{\mathrm{ref}}^{m\,'}$ is roughly seven times larger at Dhupgarh-Mahadeva-Chauragarh-Mesa. The magnitudes and uniformity of the soil diffusivities measured here are consistent with measurements from other landscapes in Mediterranean to humid climates[29], and probably reflect similar soil mechanical properties and bioturbation intensities. There are two likely and

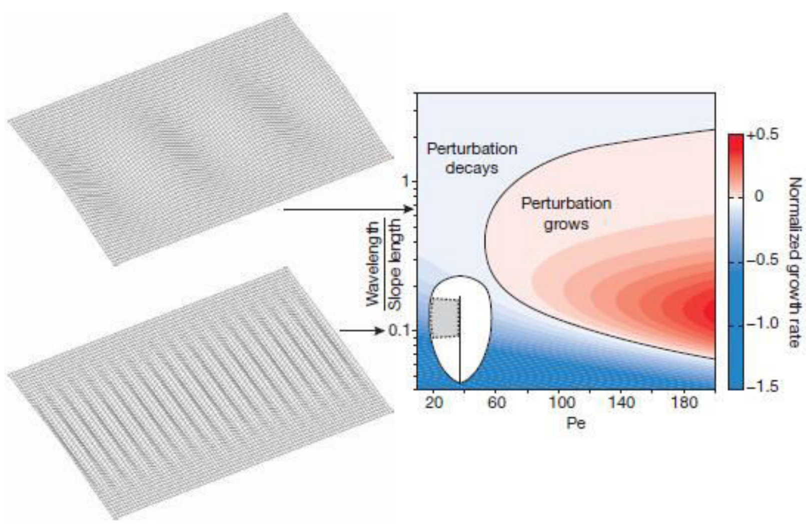

Figure.3 Growth rates of incipient valleys on inclined slopes. Left, wire mesh plots showing vertically exaggerated examples of sinusoidal perturbations on inclined, planar slopes. Right, normalized growth rate (colour coded) of sinusoidal perturbations as a function of Peeclet number, Pe, and aspect ratio (wavelength divided by slope length). Normalized growth rate is proportional to the fractional rate of change of the standard deviation of surface elevation after the background slope has been removed. Contour interval is 0.05, and the black line is the zero contour. Inset, illustration of the hypothetical position of such a slope within a larger drainage basin

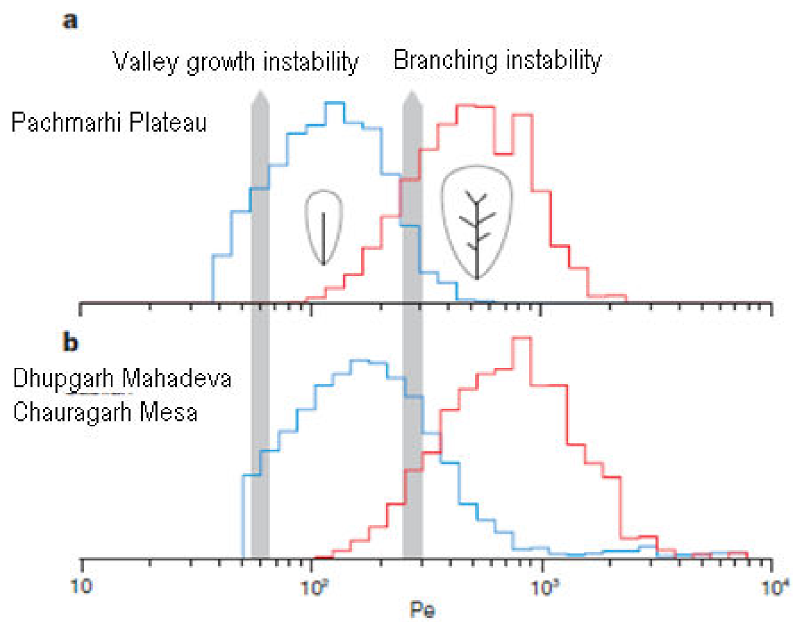

Figure.4 Peclet number distributions of first- and second-order drainage basins in the study sites. a, Pachmarhi Plateau; **b**, Dhupgarh - Mahadeva - Chauragarh - Mesa. Coloured lines are histograms with counts weighted by drainage basin area to compensate for the greater abundance of smaller basins. Inset sketches are examples of first-and second-order basins. Grey bars indicate critical values of Pe for valley growth (Fig. 3) and branching (Fig. 2). Basins analyzed are the same as in Fig. 1.

non-exclusive explanations for the difference in channel incision: first, the rocks at Dhupgarh-Mahadeva- Chauragarh- Mesa- are easier to erode; and second, highly seasonal rainfall and sparser vegetation at Dhupgarh-Mahadeva-Chauragarh-Mesa promote runoff and inhibit infiltration, such that larger surface flows occur at a given drainage area and mean rainfall rate. The broader implication of this result is that the finely branched tips of river networks, which form both the skeleton and the circulatory system of Earth's landscapes, carry a fundamental signature of rock strength, climate and life. A remaining challenge is to further quantify this signature by relating specific materials, mechanisms and conditions to the rate constants used to describe landscape evolution over geologic time

Conclusion

Valleys are areas of anomalously positive contour curvature. I have traced valleys networks over a larger region of Pachmarhi plateau and Dhupgarh- Mahadeva- Chauragarh- Mesa, using a steepest-descent flow routing procedure and a drainage area threshold based on the curvature criterion, and assigned Strahler stream orders to these networks. Drainage basin areas are determined just upstream of the junction with a higher-order link. I approximated drainage basin length as $L \approx \sqrt{3A}$,and calculated the Peclet number as $Pe = (K/D)(3A)^{m+\frac{1}{2}}$ The model solves an equation for the time evolution of an elevation surface due to rock uplift or boundary lowering, channel incision and downslope soil transport. I solved this equation forward in time with a finite difference method on a rectangular grid with periodic x boundaries, lowering y boundaries, and a low-relief, randomly rough initial surface. I varied the Peclet number by varying K/D and performed 1,600 runs with different initial conditions to determine the probability densities in Fig. 2a.

I estimated long-term erosion rates by measuring the concentration of cosmogenic Be in quartz grains in stream sediment and converting these concentrations to surface erosion rates based on rates of Be production and decay. assumed steady state hillslope topography and calculated the soil transport coefficient as $D = -E/\nabla^{2}z_{h,}$ where E is the surface erosion rate determined from cosmogenic Be and $\nabla^{2}z_{h,}$ is the Laplacian of elevation on hilltops, which has been measured from laser altimetry The channel incision coefficient K was calculated by dividing D by previous estimates of D/K ,and the channel incision coefficient for a reference drainage area, KA_{ref}^{m},was calculated with previous estimates of m and $A_{\mathrm{ref}} = 10^{4}m^{2}$.

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