NUMERICAL MODEL OF PACHMARHIS
INORDER TO INFER SCENARIO FOR THE EVOLUTION OF DRAINAGE SYSTEM

Dr. N.L. Dongre, IPS, Ph.D., DLitt

Multistoried units of Pachmarhis displaying trough cross bedding exposed in the Dhupgarh Mountain.

Abstract: It is studied that the reorganisation of drainage patterns in response to the tectonically driven emergence of Pachmarhis (Satpura) along the flank of Northern Pachmarhis Mountains as described by the author in his previous work on Parchmarhis of Central India. It is compared that the results of a numerical model of landscape evolution (CASCADE) in which stream incision is linearly related to local slope, discharge (hence catchment size), and sediment load, to present-day drainage patterns in Pachmarhis in order to infer possible scenarios for the evolution of the stream network. It is concluded that the observed drainage patterns along the North Pachmarhis are most likely to have resulted from the lateral propagation of South Pachmarhis

Mountains . The conclusion is also supported by simple mathematical derivations which imply that the periodic patterns observed in the modern fluvial network—the regular spacing of wind gaps and stream valleys—may have been created by a constant tectonic driving force. A dimensionless number is found the best to decipher stream evolution as a function of tectonic uplift, erosion, and slope. It is also explained, how the shape of a landform may be used to constrain the sequence of events that have occurred to its design.

Keywords: - drainage patterns; modelling; Pachmarhis; Satpura.

INTRODUCTION

The Pachmarhis region of Satpura is an area of active continental shortening. In the previous study of the area, described a series of mountain systems and the associated drainage patterns. By predicting the effect of tectonic activity on drainage patterns, and comparing these with observed patterns, have attempted to constrain the dynamics of fold growth and propagation and, ultimately, the tectonic history of the region.(Fig:1)

Of particular interest is the evolution of Pachmarhis Mountains (Fig. 2). It is interpreted, the Mountains developed by northward propagation along the pre-existing, larger Mountains . Observing the asymmetrical catchment areas of streams flowing through Pachmarhis Mountains , It is inferred that an originally evenly spaced stream system has been perturbed by the encroachment of Pachmarhi Mountains .

Originally parallel streams that were deflected by Pachmarhi mountain's growth joined neighbouring streams to form larger catchment areas; streams that had increased catchment areas were not deflected (Fig. 2). Crookshank.H (1936) suggested that the periodicity of climate cycles or earthquake recurrence rates may be responsible for the selection of which streams are deflected.

In this study, It is divided, interpreted and tested by using a landscape evolution model to simulate the North Pachmarhi and Pachmarhis Mountains system. The aim is to reproduce the present-day drainage patterns by using a linear, plane view model with uniform climate and rock lithology, and constant monotonous tectonic uplift. It is also developed a simple one-dimensional model of the diversion of a stream by the emerging Pachmarhis Mountains and use it to derive a series of dimensionless numbers, which relate length scales and slopes measured from the landscape, to the dynamics of the landscape and drainage system evolution.(Dongre.N.L.2013)

The purpose is to test the hypothesis presented by Jackson et al. (1996) regarding the development of drainage patterns along the Mountains' flanks. In this paper it is demonstrated that periodic patterns in drainage system geometry may not require a cyclic driving force or periodical lithological contrasts to develop.

SURFACE PROCESSES MODEL

It is attempted to reproduce the drainage patterns of Northern Pachmarhi by using a surface processes model named CASCADE (Braun and Sambmountain 1997). In CASCADE, surface topography is discretized along a series of nodes, $h(x_{i,}y_i) = h_{i,,}$ and is assumed to evolve in response to two processes: long-range fluvial transport and local Mountain slope processes. A detailed description of CASCADE can be found in Braun and Sambmountain (1997); it is limited here to a brief listing of its various components.

$$\frac{\partial h_i}{\partial t} = \frac{Q_i - Q_i^E}{L^{E,D}} \qquad (1)$$

where Q_i is the sediment load transported from upstream, and $L^{E,D}$ is a length-scale for erosionand deposition.

The carrying capacity in turn is proportional to local slope, S_i, and discharge per unit channel width, q_i; is a constant.

$$Q_i^E = K_r q_i S_i \qquad (2)$$

where K_R is a constant loosely referred to as the "erodibility'" of the substratum. Discharge is proportional to mean precipitation, v, and the surface area of the catchment area draining through the stream segment, A_c,i.

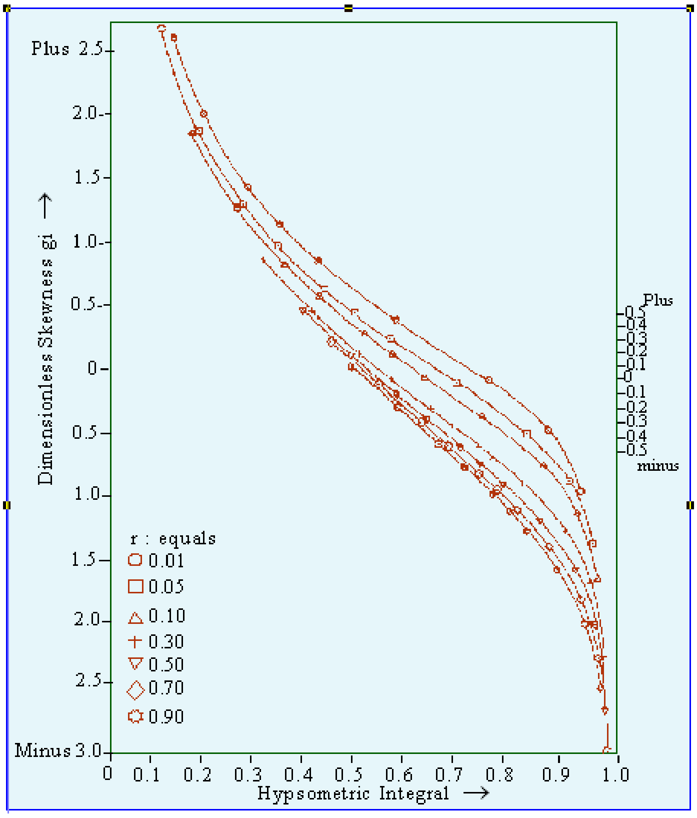


Figure. 1 Relationships between altitude skewness and hypsometric is integral for Pachmarhis Mountains and North Pachmarhis model hypsometric curves. Though non-linear, the relationship between skewness and hypsometric integral is perfectly regular within altitude frequency distributions. The Pachmarhis are characterised by r, a sinuosity parameter. The lower the value of r, the more sinuous is the hypsometric curve, i.e. the higher is the peak frequency of altitude for a given hypsometric curve. For low values of r, zero skewness corresponds to hypsometric integrals greater than 0.5. (Dongre.N.L.1999)

Where $Q_i < Q_i^E$, erosion takes place at a rate given by the disequilibrium between carrying capacity and sediment load $\frac{Q_i - Q_i^E}{L^E}$ Where $Q_i > Q_i^E$, Where $Q_i < Q_i^E$ deposition takes place at a rate given by $\frac{Q_i - Q_i^E}{L^D}$. L^E is assumed to have a much greater value than L^D,that is, erosion is limited by the "credibility" of the surface whilst deposition is solely limited by sediment supply. In practice, L^D is set to the local channel length (i.e.,the length comprised between two adjacent nodes).

The value of L^E cannot be easily derived from experiments or direct morphometric observations, it corresponds to the distance required for a stream to erode, deposit a fraction *e* of the disequilibrium between the local stream carrying capacity and sediment load. In CASCADE, it may be used to differentiate between different rock qualities (or resistance to fluvial incision).

CASCADE also represents Mountain slope erosion processes through a simple linear diffusion equation:

$$\frac{\partial h_i}{\partial t} = K_D \nabla^2 h_i \qquad (3)$$

where K_D is a constant.

The constant K_D and the constant K_R are adjustable parameters. Although their values can be derived from a detailed analysis of field observations (i.e., geomorphometric parameters combined with geochronological data), this is beyond the scope of the present study. Here K_D and K_R are treated as free parameters.

Although CASCADE is able to consider orographic effects on rainfall, these need not be taken into account for the Pachmarhi region which experiences uniform rainfall patterns from the east.

Unlike most surface processes models (Willgoose et al. 1991a, b, c; Kooi and Beaumont 1994), CASCADE allows for a non-rectangular spatial discretisation of the landscape. This flexibility is essential to avoid apparent symmetries which may arise from the interaction between unidimensional features—such as an advancing mountain—and a rectangular numerical mesh, and may lead to discretization dependent drainage pattern reorganisation (Braun and Sambmountain 1997). It is well known, for instance, that the preferred directions imposed by a rectangular discretization cannot properly sample slopes along a radially symmetrical landform which leads to the development of unacceptable drainage patterns (Chase 1992; Braun and Sambmountain 1997).

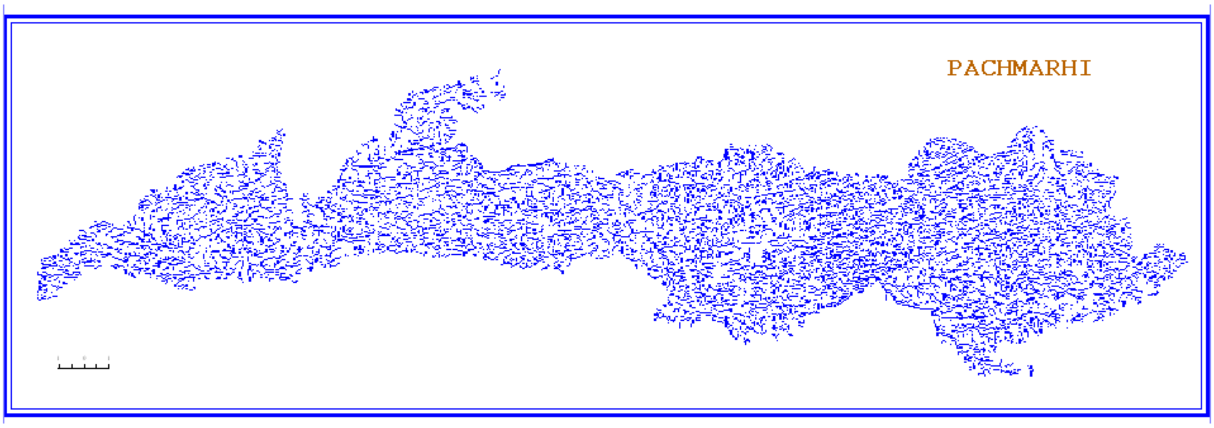


Figure. 2 Drainage pattern on the Pachmarhi showing the wind gaps (dry valley) also.

PROBLEM SETTING AND PARAMETER VALUES

Surface lithology in the Pachmarhi is dominated by the Basaltic sand stone rocks and for the modelling purpose, can therefore be regarded as uniform; also, there is little evidence of surface faulting as most of the tectonically driven deformation is accommodated by folding. It is therefore appropriate to use spatially uniform values for the various geomorphic parameters such as the length scale L^E and the coefficient K_R.

As this study focuses on drainage pattern reorganization by competition between tectonic uplift and fluvial incision, it is assumed that Mountain slope (diffusion) processes are negligible and K_D is zero.

The parameter values used are: $K_R = 7.10^{-3}; v = 1\ \mathrm{m/yr};\ L^E = 100\ \mathrm{km}; K_D = 0\ \mathrm{m}^2/\mathrm{yr}$.

As stated earlier, it is considered that the scenario in which the Pachmarhi grows and propagates northwards along the flank of the larger, pre-existing, north-south-striking Mountains .

In the model, the initial set up consists of a large mountain that is assumed to extend infinitely in the y −direction and the x −geometry of which may be described as:

$$h_i(x) = \begin{cases} 400 + 100\left(\frac{x}{3}\right) & \text{if } x < 3; \\ 500 - 400\left(\frac{x-3}{2}\right) & \text{if } 3 \le x < 5; \\ 100 - 20\left(\frac{x-5}{1}\right) & \text{if } 5 \le x < 6; \\ 80 - 20\left(\frac{x-6}{1}\right) & \text{if } 6 \le x < 7; \\ 60 - 60\left(\frac{x-7}{3}\right) & \text{if } x \ge 7 \end{cases}$$

where the height of the ith node (h_i) is expressed in metres, and distance (x) is expressed in kilometres. This geometry is shown in Fig. 3. The computation domain is limited to [0-10] km in both the x −and y −directions.

The emergence and propagation of Pachmarhis Mountains is introduced in the model as an imposed, time-dependent, uplift function whose geometry is described by the following relationships:

$$dh_i(y) = \begin{cases} dh_i(x) \text{ if } t > 1500 \times y; \\ 0 \quad \text{ohterwise} \end{cases}$$

$$dh_i(x) = \begin{cases} 0 & \text{if } x < 5; \\ 0 - 10^{-4}\left(\frac{x-5}{1}\right) & \text{if } 5 \le x < 6; \\ 10^{-4} - 10^{-4}\left(\frac{x-6}{1}\right) & \text{if } 6 \le x < 7; \\ 0 & \text{if } x \ge 7 \end{cases}$$

Where the ith node's uplift rate $(dh_i)$is expressed in metres per year, distance *(x,y)* is expressed in kilometers, and time(t) is expressed in years.

The geometry of the region in which uplift can occur is also shown in Fig. 3. This particular geometry and assumed uplift/propagation rates result in a horizontal towards North Pachmarhis velocity of 6.7 mm/yr, and a constant uplift velocity of 0.1 mm/yr at the centre of the propagating Mountains, decaying linearly towards zero along its flanks.

The above parameter values approximate the size and shape of North Pachmarhi and Pachmarhi Mountains . The resulting ratio of the small mountain vertical uplift rate to horizontal propagation rate is similar to Jackson et al.'s (1996).

The boundary conditions for the left and right (west and east) boundaries of the model are open; this means that water and any sediment load that may be transported by the stream network towards these boundaries are lost to the system.

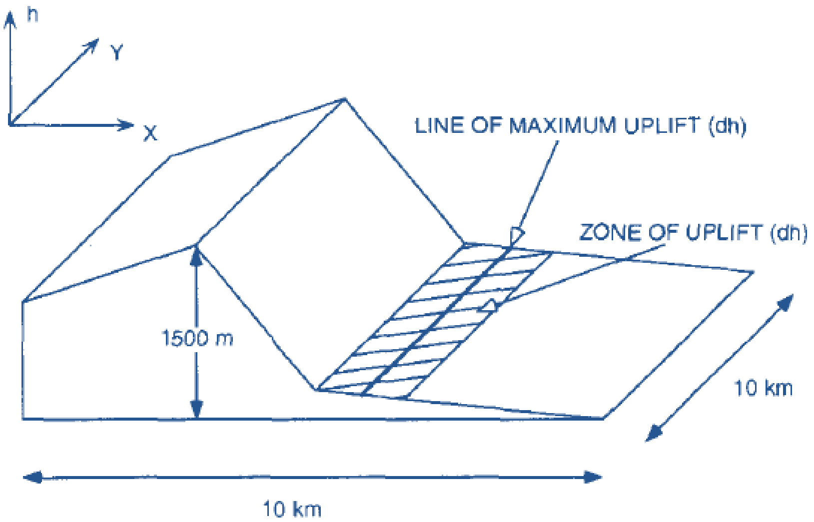


Figure. 3 Initial numerical model setup. The 1350 m mountain peak shown corresponds to the top of Pachmarhis. The hatched region represents the area affected by uplift. The line of maximum uplift corresponds to the future central axis of Pachmarhi Mountains

The top and bottom (south and north) boundaries are closed; this means that water and hence sediment is not permitted to exit through these boundaries. This forces the stream network to artificially "bounce back" and find an alternative escape route.

The small scale of the region studied here precludes contributions from lithospheric flexure to local drainage reorganisation, and is therefore neglected.

MODEL RESULTS

Figures 4A-F shows the evolution of the model through time. Black lines represent streams whilst the white lines enclose individual catchments. The panels (Fig. 4B-F) show the results at 500 000 yr intervals, beginning from the initial conditions (Fig. 4A).

The left half of the panel represents North Pachmarhi. Along the left boundary of the model, a steep slope is progressively dissected by a series of short streams; this part of the model is of no interest here and should not be compared to any feature of the North Pachmarhi system. The right-hand side of the model represents the side of Pachmarhi along which Pachmarhis Mountains are propagating. There, an array of nearly parallel streams have developed on the flank of the large mountain (North Pachmarhi) before the arrival of the smaller mountain (Pachmarhi Mountains). These streams are characterized by elongated, near-rectangular catchments (Fig. 4A).

The propagating mountain advances from bottom to top (south to north) along the middle of the model. After 1 m.y. (Fig. 4C), the bottom-most streams are diverted, and catchments along the flank of the larger mountain have been merged. As the small mountain growth progresses, more streams are interrupted (Fig. 4D, E, F) and, locally, transitory lakes form (Fig. 4D). Wind gaps (i.e., dry valleys) form where streams were originally flowing (Fig. 4F).

As streams are diverted, their catchments along the flank of the large mountain join to feed the streams that have not been diverted. The resulting large catchments tend to be asymmetric, with their exit points across the propagating mountain which are always located along the northern end of the catchment. Inside the catchment, a large stream flows in the direction of the propagating mountain.

The results shown in Fig. 6A-C correspond to numerical model runs in which the parameter $K_R$has been (A) reduced to 4.7×10^{-6}, (B) increased to 11.6×10^{-6}, and (C) to14×10^{-6}, respectively. The streams that are not diverted by the emergence of the small Mountains of Northern Pachmarhi are those which have seen their catchment surface area increase at the expense of the adjacent diverted streams. This means that as the parameter K_R is decreased, the number of streams interrupted by the emergence of the small mountain must increase. Indeed, for a stream to make it through the small emerging mountain, its $T_P$value must be smaller than 1; if the erodibility is decreased, a stream must attain a larger catchment surface area by capturing more diverted streams before it has enough incision power to make it through the emerging mountain. Conversely, if K_R is increased, the density of diverted streams (and hence wind gaps) will be smaller. This is what is observed in Fig. 6B and C.The relationship between erodibility and the density of diverted segments is in fact linear. This is because the increase in catchment surface area is linearly proportional to the number of diverted streams.

The stream and catchment geometry predicted by the model, as well as the presence of wind gaps along the top of the propagating mountain, are similar to landforms characterizing the flank of North Pachmarhi along which Pachmarhis Mountains has been assumed to propagate (see Fig. 2). This provides support for the propagating mountain hypothesis put forward by Jackson et al. (1996). However, contrary to Jackson et al.'s (1996) conclusion, the model results also clearly show that periodic landforms can be created under conditions of uniform uplift rate and constant rainfall.

LINEAR STREAM DIVERSION ANALYSIS

The numerical model results reflects that a model in which river incision is linearly related to local slope and upstream catchment size through discharge can account for the peculiar stream and wind gap geometries observed along the eastern flank of North Pachmarhi . It is proposed now to simplify the model by focusing on a single stream originally flowing down the flank of North Pachmarhi and undergoing progressive differential uplift as Pachmarhis Mountains propagates northward.

It is defined that the original slope of the side of the larger mountain (i.e., before the emergence of the smaller mountain) to be S_0. As the smaller mountain propagates, it affects the slope of the larger mountain. Locally, this results in a reduction in slope, which ultimately may lead to stream diversion. The evolution of stream slope along North Pachmarhi is thus determined by two competing processes: tectonic uplift and stream incision.

In the following analysis, the time-dependent slope S of a stream initially flowing along the flank of North Pachmarhi is calculated at the point of maximum tectonic uplift; that is, at the centre of the newly emerging mountain. Under the assumptions that both the width of the emerging mountain, *2L*, and the rate of uplift is constant, the rate of tectonic slope change, S^T, may be expressed as

$$\dot{S}^T = \frac{1}{L}\frac{\partial h_0}{\partial t}\Big|_T \quad (4)$$

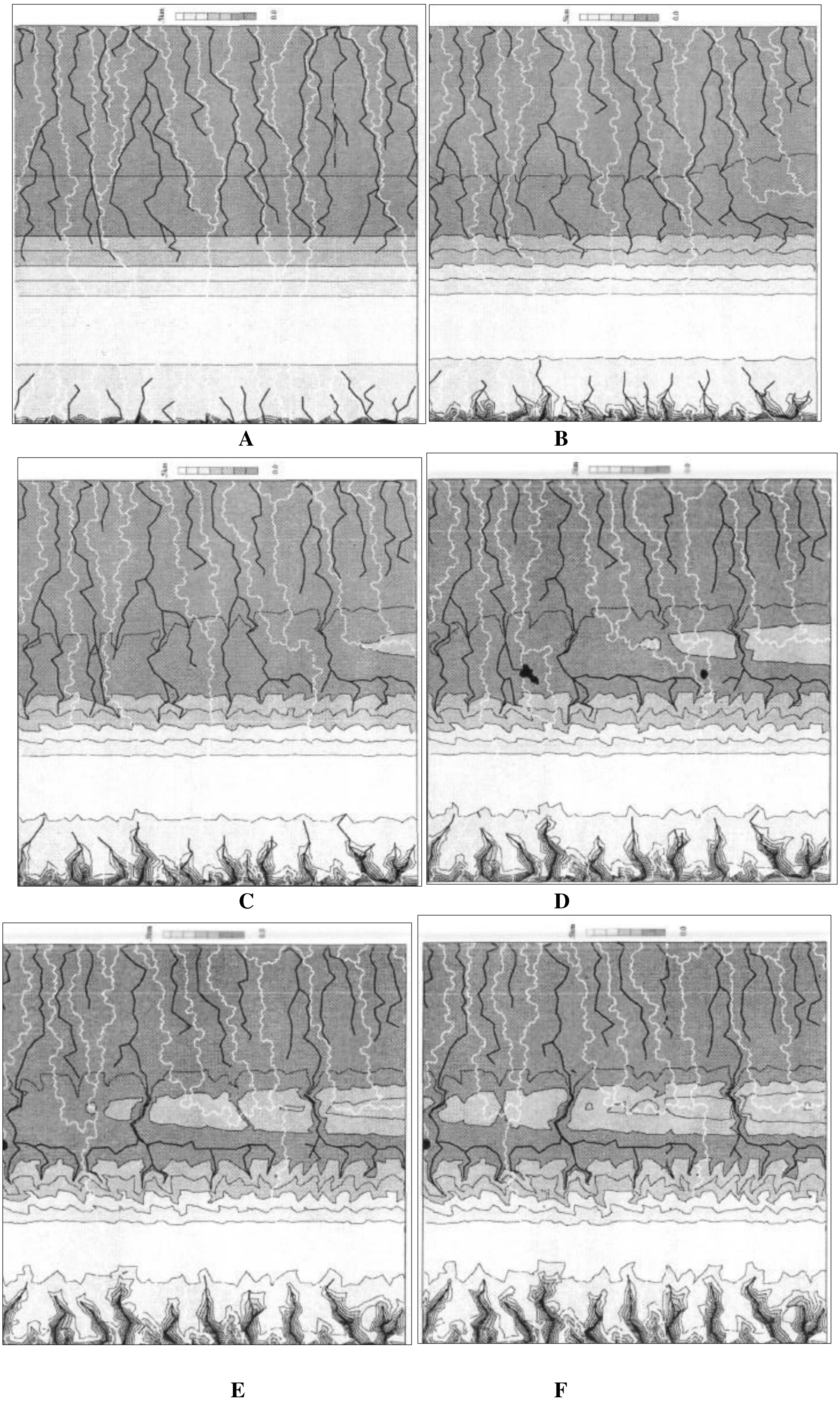


Figure. 4 Model results at 500000 yr intervals, starting at time *t* = 0 m.y. (4A) and concluding at *t* = 2.5 m.y. (4F). Height variation is shown with grey shades and thin contour lines. Dark lines represent rivers, and white lines represent catchment boundaries. Black areas represent elevated topography. (Toposheets: 55, J, 6.)

where h_0 is the height of the centre of the small mountain and $\left.\frac{\partial h_0}{\partial t}\right|_T$ is the tectonic uplift rate. It is assumed that the rate of stream incision, $\left.\frac{\partial h_0}{\partial t}\right|_R$ 'be parameterised in the following manner:

$$\left.\frac{\partial h_0}{\partial t}\right|_R = \frac{A_c}{LW}\frac{L}{L^E}K_R v^S \tag{5}$$

Where A_c the surface area of the catchment draining into the stream is segment and W is the width of the stream valley; in short, the erosive power of a stream is linearly proportional to discharge but inversely proportional to the area it is to erode. This is identical to the river incision model used in CASCADE under the assumption that rivers are always far from their carrying capacity.

It is assumed that deposition of sediment does not play an important role in the slope evolution. This is supported by the numerical model results and the observation that the region between the two Mountains consists of pedement remnants, and is not overlain with large amounts of Tertiary deposits.

This relation may be simplified to:

$$S^R = \frac{1}{L}\left.\frac{\partial h_0}{\partial t}\right|_R = r\frac{S}{\tau} \tag{6}$$

where s^R is the rate of slope change in response to stream incision, r is the ratio of the catchment surface area to the effective cross-sectional area of the stream segment:

$$r\frac{A_c}{LW} \tag{7}$$

and τ is the time-scale for stream incision:

$$\tau = \frac{L^E}{K_R v} \tag{8}$$

τ represents the time in which a stream's slope increases by a factor e by river incision.

The equation governing the evolution of the slope of the stream segment initially flowing down the large mountain but now perturbed by the emergence of the small mountain is derived by combining (4) and (6):

$$\dot{S} = \dot{S^R} - \dot{S}^T = \frac{rS}{\tau} - \dot{S}^T \tag{9}$$

With $S(t = 0) = S_0$, the solution for S is:

$$\mathrm{S} = \left[\mathrm{S}_0 - \frac{\dot{\mathrm{S}}^{\mathrm{T}}\tau}{\mathrm{r}}\right]\mathrm{e}^{\frac{\mathrm{tr}}{\mathrm{r}}} + \frac{\dot{\mathrm{S}}^{\mathrm{T}}\tau}{\mathrm{r}}. \tag{10}$$

From this solution, two behaviours may be expected:

(a)$\dot{S}^T > \frac{S_0 r}{r}$ and the stream segment is interrupted by the emergence of the small mountain;

(b) $\dot{S}^T > \frac{S_0 r}{r}$ and the stream segment is not interrupted by the emergence of the small mountain.

Stream segment evolution may then be predicted from the value of a dimensionless number:

$$T_P = \frac{\dot{S}^{\tau}\tau}{S_0 r} \tag{11}$$

For values of $T_P > 1$, tectonic uplift overcomes stream incision and the small mountain interrupts the flow of the stream segment. If $T_P < 1$, it does not.

NUMERICAL TEST OF LINEAR ANALYSIS

The validity of equation (11) in a more complex two-dimensional situation can be tested by altering the input parameters of the numerical model (CASCADE). The results shown in Fig. 5 correspond to a situation for which both the Uplift rate, $\frac{\partial h_0}{\partial t}$, and the river incision parameter, K_R, have been lowered by a factor of 2 in comparison to those in Fig. 4F.

These two changes should counteract one another as any given stream's T_P number should remain unaffected. This is clearly the case as the number of streams traversing the mountain in Fig. 5 is unchanged from the situation shown in Fig. 4F.

This clearly demonstrates that equation (8) is robust under input changes to the model. The specific values for L^E and K_R do not effect the output as long as τ remains unchanged.

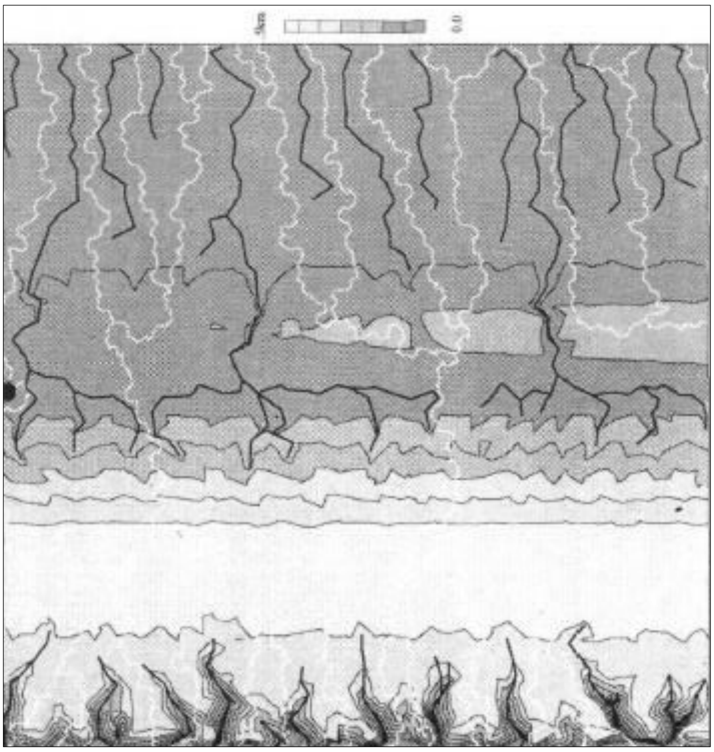


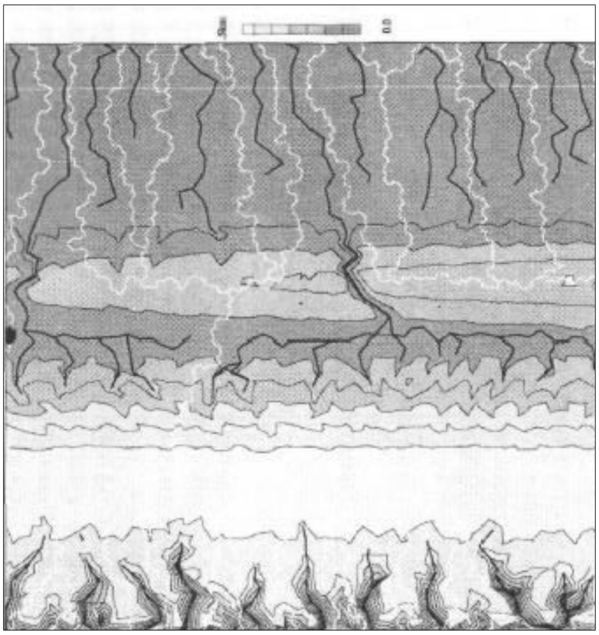
Figure. 5 Model results with altered parameters, shown at time t = 2.5 m.y. (see text for parameter values).

The results shown in Fig. 6A-C correspond to numerical model runs in which the parameter $K_R$has been (A) reduced to 4.7×10^{-6}, (B) increased to11.6×10^{-6}, and (C) to 14×10^{-6}, respectively.

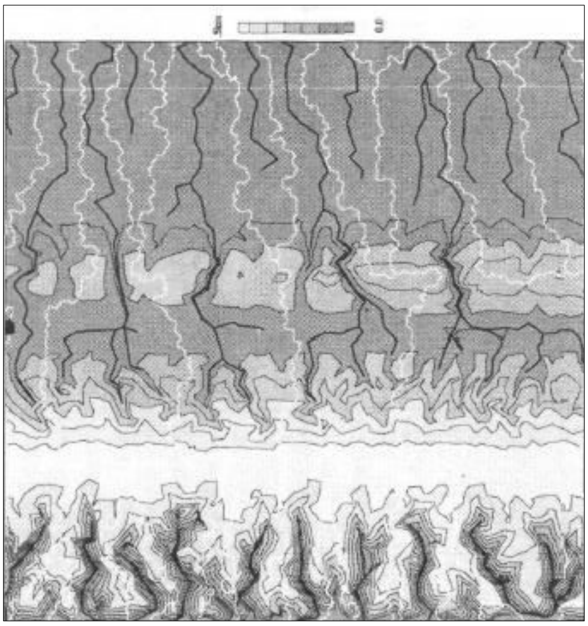
The streams that are not diverted by the emergence of the small Mountains of Northern Pachmarhi are those which have seen their catchment surface area increase at the expense of the adjacent diverted streams. This means that as the parameter K_R is decreased, the number of streams interrupted by the emergence of the small mountain must increase. Indeed, for a stream to make it through the small emerging mountain, its T_P value must be smaller than 1; if the erodibility is decreased, a stream must attain a larger catchment surface area by capturing more diverted streams before it has enough incision power to make it through the emerging mountain. Conversely, if K_R is increased, the density of diverted streams (and hence wind gaps) will be smaller. This is what is observed in Fig. 6 B and C.The relationship between erodibility and the density of diverted segments is in fact linear. This is because the increase in catchment surface area is linearly proportional to the number of diverted streams.

CONSEQUENCES FOR MODEL PARAMETER VALUES

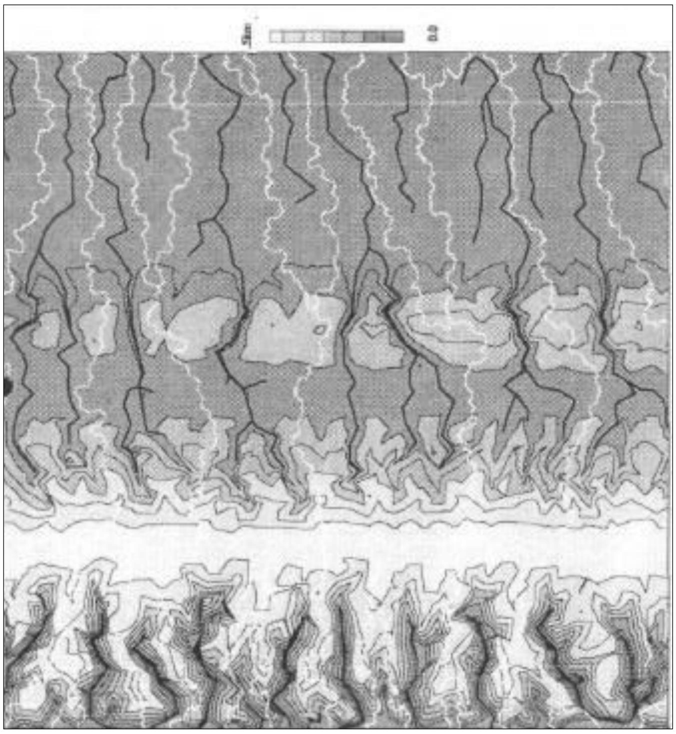
It is demonstrated that the interaction between drainage patterns and a tectonically active mountain system can be used to constrain the value of a dimensionless parameter (called here T_P) which, in turn, can be regarded as the ratio of two time scales: τ, the time scale for stream incision and $t_R (= 1/\dot{S}^T)$the time scale for tectonic uplift. The other factors entering the expression for T_P can be directly measured from the shape of the landscape.



A



B



C

Figure. 6 Model results with altered parameters after 2.5 m.y. evolution. In 6A, K_R = 4.7x 10^{-6}. In 6B, K_R = 11.6 x lO^{-6}. In 6 C, K_R = 14 x 10^{-6}; these values are to be compared to the value used in the model run shown in Fig. 4 of K_R = 7 x 10^{-6}

Selective diversion of a river network by an emerging mountain therefore provides a unique opportunity to calibrate surface processes models. Indeed, if all streams along North Pachmarhi had been diverted by the emergence of Pachmarhi Mountains , this would provide with a lower limit for T_P (i.e., $T_P > 1$); conversely, if none of the streams had been diverted, the geometry of the drainage pattern would offer us an upper limit for T_P (i.e., $T_P < 1$). Because, on average, only one in every five streams is being diverted by the emergence of Pachmarhi Mountains, it can be stated with confidence that the vale of T_P is very close to unity for the streams that have not been diverted.

For those streams, the total catchment surface area is approximately 10 km ×5 km = 50 km^2; the original slope of North Pachmarhi before the emergence of Pachmarhi mountain is approximately 0.02; the width of a river valley is approximately 50 m; and the width of Pachmarhis Mountains is 3 km. Assuming that T_P = 1 leads to:

$$\tau = \frac{L^E}{K_R v} = \frac{S_0 A_C}{\omega L} t_R \approx 6.7 \times t_R \quad (12)$$

A direct measure of the tectonic uplift rate of the Pachmarhis Mountains would therefore give a direct measure of stream incision rate and consequently would tightly constrain the parameter values in the surface processes model.

STREAM DIVERSION SCENARIOS

It is clear that no absolute timing can be inferred from morphometric observations of the Pachmarhis; in other words, the shape of the Pachmarhi landscape cannot tell us anything about its age or the time and rate at which it formed. It is demonstrated, however, that, under the assumption that river incision is linearly proportional to local slope and discharge, simple measurements performed on a landform (such as distances, heights and slopes) can be used to build inferences about the *relative* timing of events in the evolution of the landform.

Consider that the time taken for a stream originally at slope S_0 to be diverted by the emergence of the small mountain. It is assumed that S_0 is sufficiently gentle that the stream does not incise into the large mountain flanks before the small mountain's arrival. Stream diversion occurs at time when, despite $t_0$stream incision, the small mountain emergence forces the local slope *S* to vanish (i.e., *S*=0) introducing this into equation (8) yields:

$$0 = (S_0 - S_0^c)e^{\frac{t_u \dot{S}^T}{S_0^c}} + S_0^c \quad (13)$$

Where $S_0^c = \frac{\dot{S}^T r}{r}$. Solving for t_0, it is obtained:

$$t_0 = \frac{S_0^c}{\dot{S}^T} \text{In}\left[\frac{S_0^c}{S_0^c - S_0}\right] \quad (14)$$

Because $t_0(S_0^c)$is a monotonously decreasing function for all values of $S_0^c > S_0$, this result clearly shows that the time taken for a stream to be diverted by the emergence of the small mountain is inversely proportional to S_0^c hence inversely proportional to S^T, but directly proportional to the size of the catchment, A_c, through r.

As stream diversion is dependent on the size of the stream catchment surface area, the process becomes dependent on the number of previously diverted streams of South Pachmarhis.

It is therefore considered, two opposite scenarios: (1) the time required for stream diversion is much smaller than the time required for the propagating mountain to advance from one stream to the next; (2) the time required for stream diversion is much larger than the time required for the propagating mountain to advance from one stream to the next.

First hypothesis

The first hypothesis of the Pachmarhis is exhibited in Fig. 7. At time, the propagating mountain has reached the first stream. At time 2, that is by the time the mountain has reached the second stream, the first stream has been diverted and the catchment surface area (hence discharge) of the second stream has been doubled. This scenario continues at times 3 and 4, until the catchment area of a given stream has reached the critical value corresponding to T_P< 1 and the stream is not diverted. In general, when the *i*th stream begins to feel the presence of the emerging mountain, it has a catchment area *i* times greater than the first one.

Each stream diversion from the Pachmarhis Mountains results in the formation of a wind gap at the top of the propagating mountain. The depth of the wind gaps must increase along the mountain in the direction of propagation as the streams responsible for incising the valleys have increasing catchment areas (hence incising power). Consequently, it is expected, under the first hypothesis, to observe an increase in wind gap depth in the direction of propagation of the small mountain, until a stream's catchment area is sufficiently enhanced that its T_P value is less than one.

Under this scenario, the stream slope equation (eq. 9) for the ith stream becomes:

$$S^{(i)} = \left[S_0 \frac{\dot{s}^T\tau}{r_0 i}\right] e^{\frac{i r_0 i}{\tau}} + \frac{\dot{s}^T\tau}{r_0 i} \qquad (15)$$

Where

$$r_0 = \frac{A_c^{(1)}}{LW} \qquad (16)$$

and $A_c^{(1)}$ is the surface area of the initial river catchments.

It is accepted that the nth stream is not diverted by the mountain. It is a logical assumption to state that, for this stream, the catchment area has exactly the critical value corresponding to $T_P = 1$, such that

$$S_0 \backsimeq \frac{\dot{s}^T\tau}{r_0 n} \qquad (17)$$

Feeding this into the slope evolution equation yields:

$$S^{(i)} = S_0\left(1 - \frac{n}{i}\right) e^{\frac{i r_0 i}{\tau}} + S_0 \frac{n}{i} \qquad (18)$$

From which the time taken to divert the ith stream, $t_0^{(i)}$, may be derived:

$$t_0^{(i)} = \frac{\tau}{r_0 i} \ln\left(\frac{\mathrm{n}}{\mathrm{n}-i}\right) \qquad (19)$$

The resulting wind gap depths, $\Delta h^{(i)}$, can it be calculated as the integrated river incision over the time $t_0^{(i)}$:

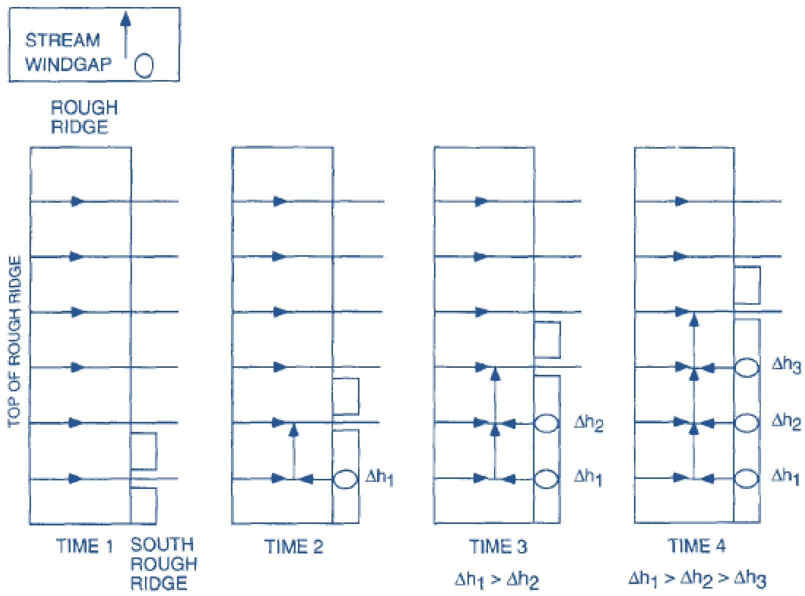


Figure. 7 Diagram of drainage patterns, of a mountain system where river diversion occurs faster than mountain propagation. The figure shows four snapshots of the progression of a small mountain moving along the right -hand side of a larger mountain. The ∇h_n values refer to the depth of the dry valley created by the now defunct nth stream relative to the height of the Pachmarhi Mountains.

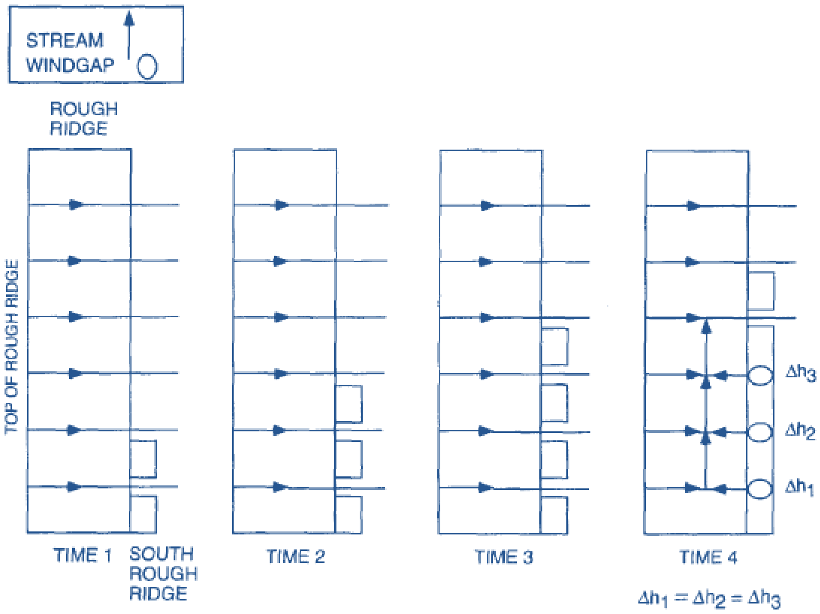


Figure. 8 Diagram similar to the one in Figure. 7 but depicting the drainage patterns of a mountain system where mountain propagation occurs faster than river diversion.

$$\Delta h^{(i)} = L\int_0^{t_0^{(i)}} \dot{S}^R dt = \frac{L_r(i)}{\tau}\int_0^{t_0^{(i)}} s\,dt \qquad (20)$$

hence,

$$\frac{\Delta h^{(i)}}{LS_0} = \frac{r_0 i}{\tau}\int_0^{t_0^{(i)}}\left[\left(1-\frac{n}{i}\right)e^{\frac{ir_0 i}{\tau}}+\frac{n}{i}\right]dt \qquad (21)$$

$$\frac{\Delta h^{(i)}}{LS_0} = -1 + \frac{n}{i}\mathrm{In}\left(\frac{n}{n-i}\right). \qquad (22)$$

This relationship provides with a simple rule for calculating the evolution of the relative wind gap depth as a function of distance along the length of the emerging mountain between two uninterrupted rivers.

Second hypothesis

According to the second hypothesis, streams are diverted almost simultaneously when the Mountains of the Pachmarhis has reached the *n*th stream defined again as the one that is not diverted. This is illustrated in Fig. 8. At times 1-4, the streams flowing along the flank of the large mountain are progressively influenced by the emerging mountain but are not diverted. This continues until time 4, when the first three streams are simultaneously diverted. In this scenario, the depth of the wind gaps is similar for all streams as the size of the catchments for the streams that caused the wind gaps were the same from time 1 to time 3.

In this scenario, the common wind gap depth is given by:

$$\Delta h = \frac{Lr_0}{r}\int_0^{t_0^{(i)}} S\,dt \qquad (23)$$

where

$$S = S_0(1-n)e^{\frac{ir_0}{\tau}} + S_0 n \qquad (24)$$

and

$$t_0 = \frac{\tau}{r_0}\mathrm{In}\left(\frac{n}{n-1}\right) \qquad (25)$$

which is equivalent to equation (18) where i = 1.

Hence,

$$\frac{\Delta h}{LS_0} = 1 + n \ln\left(\frac{n}{n-1}\right) \qquad (26)$$

Note that both scenarios predict the wind gap depth (or depths) as a function of the original slope, S_0 (or, equivalently, the slope of the flank of Pachmarhi ahead of the advancing Pachmarhi mountain), the width of the advancing mountain, and the number of wind gaps. The wind gap depths are independent of the assumed value for the erosion parameters, the rate of advance and growth of the propagating mountain, or the size of the catchments.

Inferences for the Pachmarhi mountain system

If the propagation of Pachmarhis Mountains follows the first scenario (Fig. 7), and streams are progressively interrupted, it would be expected to see wind gap depths increase along the length of Pachmarhis Mountains between two successive uninterrupted streams. From Fig. 2, one can estimate that, on average, there are four wind gaps for each uninterrupted stream; hence, n = 5.Values for L (= 3 km) and S_0 (=0.02) can easily be extracted from a topographic map of the area. From these values, one can deduce that ∇h (the wind gap depth) should increase progressively from below 10 m to over 60 m between two successive uninterrupted streams along the length of Pachmarhi Mountains.

The second scenario of simultaneous stream diversion leads to a constant wind gap depth of c. 10 m, based on the same parameter values (L = 3 km and S_0 = 0.02).

A plot of wind gap and peak heights versus distance along Pachmarhis Mountains (Fig. 9) extracted from a topographic map does not clearly show a progression in wind gap depth with distance along Pachmarhis Mountains between two successive uninterrupted streams. The wind gap depth appears rather constant at c. 35 m.

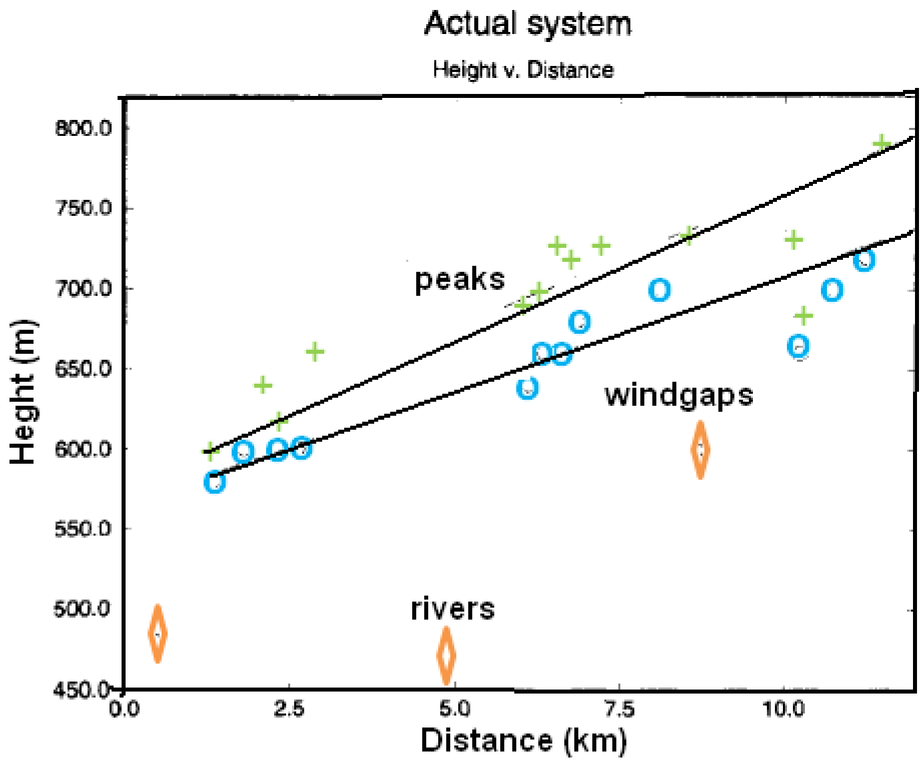


Figure. 9 Plot of peak, wind gap, and river height versus distance along Pachmarhi mountain in the direction of mountain propagation (south to north).

A similar plot generated from the numerical model results displayed in Fig. 4F is shown in Fig. 10 and displays a similar pattern of constant wind gap depth of c. 35 m along the advancing mountain.

Both the natural landscape of the Pachmarhi generated by the numerical model suggest that the second scenario, resulting in a constant wind gap depth, is the appropriate one for the Pachmarhis Mountains-

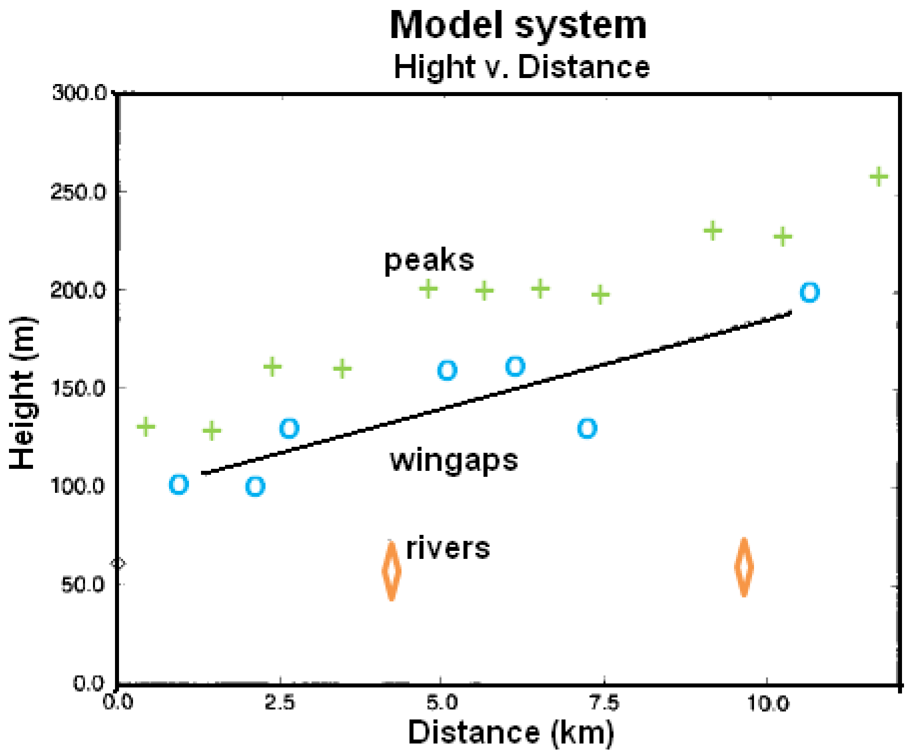


Figure. 10 Plot of peak, wind gap, and river height versus distance along Pachmarhis Mountains taken from the numerical model run shown in Figure. 4.

Pachmarhis Mountains System. That is, within each catchment, all streams were diverted simultaneously at a time that postdates the advance of Pachmarhis Mountains through that catchment.

Both the landscape and the model suggest a value for ∇h of c. 35 m, which is somewhat higher than the value calculated from the linear analysis based on the second hypothesis, but is certainly acceptable in view of the various assumptions on which the linear analysis is based.

RATIO OF TIME SCALES DERIVED FROM MORPHOMETRIC MEASUREMENTS

A more quantitative prediction of which scenario is likely to be applicable to the Pachmarhi mountain system can be made by comparing explicitly the time taken for the mountain to propagate between two successive streams to the time taken for the first stream to be diverted.

The time taken for the mountain to propagate between two streams is

$$\bar{t} = \frac{X}{v_p n} \tag{27}$$

where X is the "prediversion" stream catchment length and the northward propagation velocity of the advancing mountain. v_P is related to u_R the vertical mountain velocity (or uplift velocity), by S^R, the forward slope of the mountain (i.e., the slope in the direction of propagation) by the following relationship:

$$S^R = \frac{u_R}{v_P} = \frac{\dot{S}^T L}{v_P} \tag{28}$$

Direct measurement on a topographic map yields a value of 0.02 for S^R at the tip of Pachmarhis Mountains

The time taken for the first stream to be diverted is given by (eq. 13):

$$t_0 = \frac{S_0^c}{\dot{S}^T} \text{In}\left[\frac{S_0^c}{S_0^c - S_0}\right] \tag{29}$$

In which $S_0^c = nS_0$ as the nth stream is not diverted and is thus characterised by:

$$S_n^c = \frac{\dot{S}^T \tau}{r_0 n} = \frac{S_0^c}{n} = S_0 \tag{30}$$

The ratio of $\bar{t}$ to t_0 can therefore be estimated as:

$$\frac{\bar{t}}{t_0} = \frac{\frac{X}{n v_P}}{\frac{S_0 n}{\dot{S}^r} \text{In}\left[\frac{S_0 n}{S_0 n - S_0}\right]} \tag{31}$$

$$= \frac{S_r X}{n^2 L S_0 \text{ In}\left[\frac{n}{n-1}\right]} \tag{32}$$

Using X = 10 km, L = 3 km, and S_0 = 0.02, the following estimates are obtained:

$$\frac{\bar{t}}{t_0} = 0.91 \text{ for } n = 3$$
$$= 0.72 \text{ for } n = 4$$
$$= 0.59 \text{ for } n = 5$$

In all cases, t_0 is larger than $\bar{t}$,which means that the mountain will reach the second stream before the first is diverted. This supports the earlier conclusion that stream diversion is not concomitant with mountain advance, but is more likely to take place simultaneously for all diverted streams.

CONCLUSIONS

Both the numerical simulation and linear analysis undertaken in this study support the hypothesis that drainage reorganisation took place as a result of Pachmarhis Mountains propagating northward along the flank of North Pachmarhi .

The surface processes model CASCADE successfully recreated the general features of the stream network and landscape under conditions simulating the emergence and northward propagation of Pachmarhi Mountains .

The periodic nature of the wind gap / stream system was recreated under the assumptions of constant uplift rate and uniform rainfall. It istherefore concluded that neither cyclic climatic conditions nor episodic uplift rate are required to create the periodic stream network observed along the flank of North Pachmarhi as suggested by Crookshank. (1936).

The propagating mountain model can also be used to predict the evolution of individual streams; a dimensionless number $T_P$was found that relates the uplift rate to erosion parameters and that determines the condition for stream diversion. T_P can be used to tightly constrain the value of erosion parameters from estimates of tectonic uplift rate.

By examining the distribution of wind gap depths, it is concluded that, in the North Pachmarhi and the Pachmarhi system, stream diversion occurs simultaneously for all streams located between two uninterrupted streams. In other words, all wind gaps located between two uninterrupted streams have "dried out" simultaneously. Dating the timing of wind gap formation (through isotopic dating of lacustrine deposits in the wind gaps, for example) is therefore unlikely to provide useful information about the time evolution of the system.

REFERENCES

- Braun, J. Sambmountain, M., 1997: Modelling landscape evolutior on geological time scales: a new method based on irregular spatial discretization. ***Basin Research 9:*** 27-52.
- Chase, C.G.,I 992: Fluvial landsculpting and the fractal dimensior of topography. ***Geomorphology 5:*** 39-57.
- Crookshank, H. 1936: Grogy of the northern slope of the Satpuras between the morand and the river. Mem geol.surv ind.66(2)77
- Cotton, C. A., 1917: Block Mountains in New Zealand. ***American Journal of Science 44:*** 249-293.
- Dongre, N.L, 1999: Pachmarhis: A geomorphological study research thesis for Ph.D.
- Dongre, N.L, 2013: Tectonic Control of Pachmarhis Drainage System, Google Magazine.
- Jackson, J.; Norris, R.; Youngson, Y. 1996: The structural evolution of active fault and fold systems in central Otago, New Zealand: evidence revealed by drainage patterns. ***Journal of Structural Geology 18 (2/3):*** 217-234.
- Kooi, J.; Beaumont, C. 1994: Escarpment evolution on high-elevation rifted margins: insights derived from a surface processes model that combines diffusion, advection, and reaction. ***Journal of Geophysical Research 99:*** 1219112209.
- Stein, R. Yeats, R. 1989: Hidden earthquakes. ***Scientific American 260:*** 48-57.
- Willgoose, G.; Bras, R. L. Rodriguez-lturbe, I. 1991: A physically based coupled channel network growth and Mountain slope evolution model, 1Theory. ***Water Resources Research 27:*** 1685-1696.
- Willgoose, G. Bras, R. L. Rodriguez-lturbe, I. 1991: A physically based coupled channel network growth and Mountain slope evolution model, 2: Applications. ***Water Resources Research 27:*** 1671-1684.
- Willgoose, G. Bras, R. L. Rodriguez-lturbe, I 1991: Results from a new model of river base evolution. ***Earth Surfaces and Landforms 16:*** 237-254.

Dr. N.L. Dongre
C-14 Jaypee Nagar Rewa 486450
Email:- nl.dongre@jalindia.co.in
dongrenl@gmail.com
Mobile No. 7869918077, 09425152076