JOURNAL GEOLOGICAL SOCIETY OF INDIA
Vol.70, September 2007, pp.411-426

Along-strike Escarpment Heterogeneity of the Western Ghats: A Synthesis of Drainage and Topography Using Digital Morphometric Tools

DAVID HARBOR[1] and YANNI GUNNELL[2]
[1]Department of Geology, Washington and Lee University, Lexington, VA 24450, USA
[2]Department of Geography, CNRS UMR 8591, Université de Paris 7, 2 Place Jussieu, 75251 Paris, France
Email: gunnell@paris7.jussieu.fr

Abstract: We present the first synthetic and systematic attempt to fingerprint topographic attributes of the Western Ghats passive margin escarpment using newly available SRTM digital elevation data. Spanning 12 degrees of latitude, the escarpment is shown to exhibit contiguous segments where scarp sinuosity and relief, but also drainage basin attributes such as stream orientation, spacing of scarp, coastline and continental divide, basin shape, basin hypsometry and stream longitudinal profile covary in ways that suggest differences in the process of retreat of the Western Ghats as a continuous yet heterogeneous landform. The methodology presented here could serve as an improvable template applicable to other escarpments around the world for comparative purposes. It can be potentially standardized as a tool designed to construct inferences about the variability of scarp retreat processes under a range of conditions tied to drainage and geological structure. For the Western Ghats, we suggest that site-specific feedbacks between climate, drainage and geologic structure are key to understanding scarp dynamics and the manner in which the evolution of drainage boundaries across strike affect morphology and evolution along strike.

Keywords: Escarpment, Drainage, Topography, Western Ghats.

INTRODUCTION

We are accustomed to portraying escarpments along strike-perpendicular swaths that capture maximum topographic heterogeneity and make them compatible with rifting scenarios. The Western Ghats Escarpment (WGE) forms the edge of the Deccan Plateau and is a remarkably linear feature extending uninterrupted over nearly 12° of latitude. Here we focus on the lateral variability of topography, i.e. along strike, from north of Mumbai to the Palghat Gap (Fig. 1), in an attempt to understand the variability of scarp recession processes that underpin the respective sinuosities of the topographic escarpment and the continental divide — and hence the variability in width of the coastal plain. The approach here relies exclusively on digital topography data recently made available by the Shuttle Radar Topography Mission (SRTM, 2004). This data format allows us, for the first time in this region, to deal with the Western Ghats as a topographic continuum in which natural variability can be appreciated free of the usual impediments imposed by map scale or map boundaries. The synthetic information we derive from drainage, structural and topographic attributes along and across strike bring out a new quantitative vision of the escarpment, which can be interpreted accordingly through a set of existing hypotheses concerning modes of scarp retreat. Our emphasis in this paper is less on previously unknown facts and features concerning the Western Ghats at the local scale, than on the use of new quantitative tools as a way of describing relief and as a source of inspiration for ongoing and future work aimed at understanding escarpment form and process.

POTENTIAL CONTROLS ON ESCARPMENT MORPHOLOGY

The Western Ghats is a wall of relief broken only at the Palghat Gap near 10ºN latitude. In this low-relief pass, the drainage divide has moved inland and the lack of resistance in the underlying shear zone (e.g., Chetty, 1996) results in a low-relief drainage basin divide. The high-relief linear escarpment continues south through Kerala (not addressed here). In detail, however, the Western Ghats is not a simple

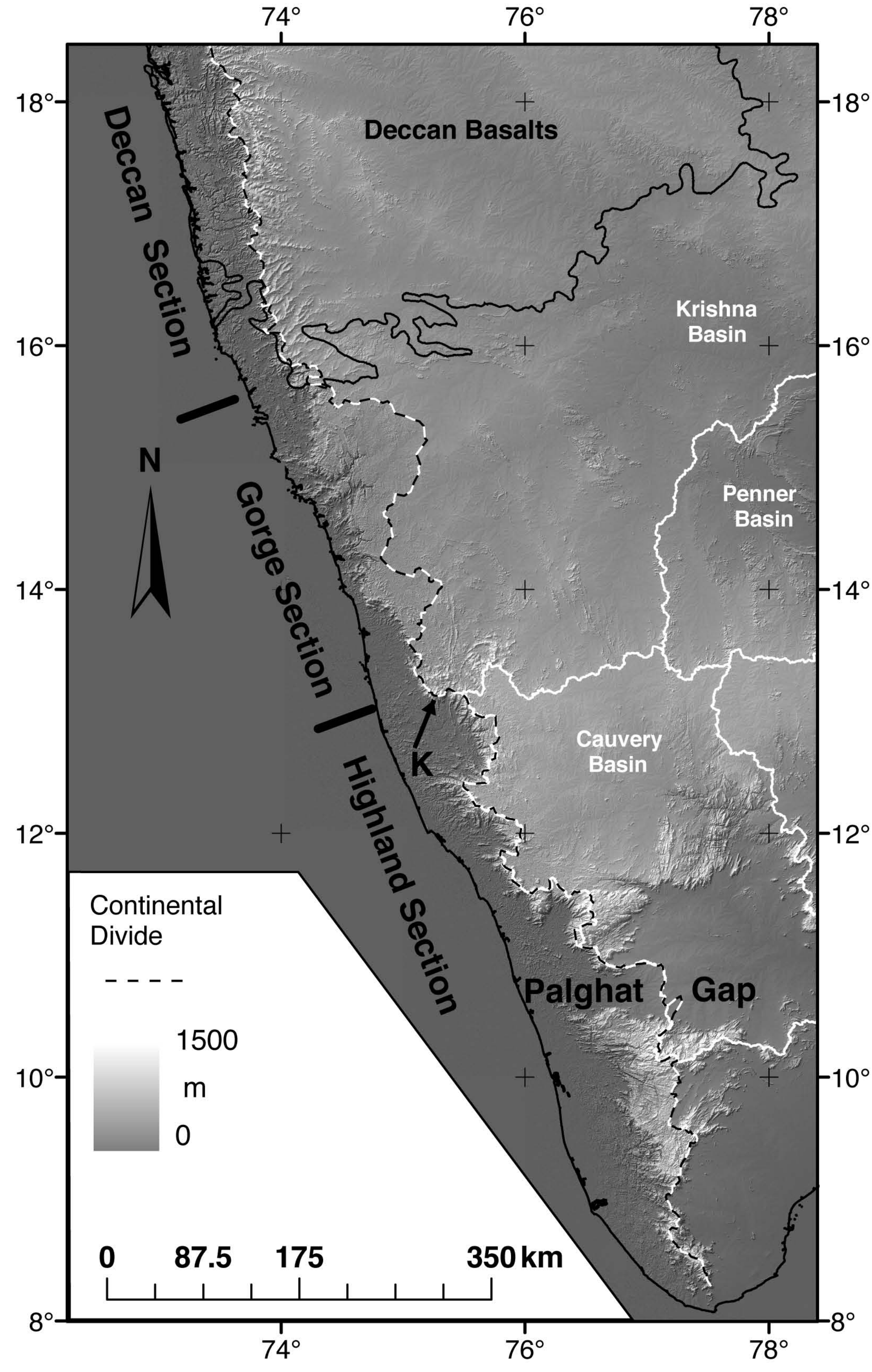

Fig.1. Location of the Western Ghats sections described in the text. Also included are the Palghat Gap, and the Kerala ghats, which are a continuation of the same phenomenon but are not considered in this study. Elevation data are derived from the Shuttle Radar Topography Mission (SRTM) first release data (Jet Propulsion Laboratory, 2002; data available at http://seamless.usgs.gov) gridded at 3 arc seconds of latitude and longitude. The geological contact is derived from data in Wandry and Law (1998). K - Kudremukh "headland" mentioned in text.

escarpment, but exhibits variability in the relief, sinuosity, and degree of entrenchment by scarp-piercing streams. The potentially important and well-known controls on escarpment retreat in South India are lithology, structural weaknesses like faults and fractures, and structural features, mainly folds in the supracrustal rocks of the Dharwar Craton (Gunnell and Radhakrishna, 2001). Three sections broadly characterize the Western Ghats north of the Palghat Gap. The Deccan section is characterized by relatively flat-lying Mesozoic flood basalts that have been cut away by retreat in the most linear segment of the escarpment (Widdowson, 1997). The flood basalts of the Deccan Plateau onlap a Mesozoic erosional surface cut on igneous and metamorphic rocks of the Dharwar Craton. In this segment, rivers have penetrated the relatively weak metamorphic rocks and extended gorges far into the plateau. In the south, the WGE again becomes more linear where it is retreating against highly resistant and high-relief rocks in the granulite terrain of southernmost India. This highland section is underlain by resistant Proterozoic rocks, including the charnockite that produces the high relief of the Nilgiri Hills.

METHOD

We refine the characterisation of existing WGE morphology (e.g. Gunnell and Radhakrishna, 2001, and contributions therein) based on a sequence of analyses that capture the main morphometric signatures of this remarkable landform. The approach differs from standard morphometry in that we do not produce numerical indices but, instead, graphical representations of variables that remain spatially explicit and can be scaled and superimposed for comparative purposes. The analyses are based on digital estimates of topography from radar interferometry measurements taken during a Shuttle flight in 2000. The absolute accuracy for 90% of points is targeted for 16 m vertical and 20 m horizontal, but the relative accuracy in the vertical is targeted for less than 10 m (Jet Propulsion Laboratory, 2002). This level of precision is adequate for morphological study at the basin scale. Experience with DEM data in other parts of India suggest that the relative vertical precision is much less than 10 m. Digital data were downloaded from the SRTM server and seamed together using 3DEM (a shareware program available on the web). These data are obtained in a geographic format based on the WGS 1984 datum. If distances are calculated, either the data must be projected or calculation of distance must be done using great circles. Many Geographical Information System (GIS) routines require that the location data must be projected into a grid with regular metre or foot spacing (ArcGIS, for example). Projecting data results in systematic grid errors where grid cell size and location differences between the projected and geographic grids results in doubled and skipped cell locations. These systematic errors make the calculation of slope, aspect, hillshading and drainage network less effective. The analyses for this project are based on the original 3 arc-second data in unprojected geographic space. SRTM data (release 1) contain a significant number of voids where clouds and terrain blocking prevented the collection of radar data. These voids are filled using a program that fills voids by interpolation. Newer releases of SRTM have fewer voids. In southern India, void filling is usually necessary only in valley bottoms and does not result in significant uncertainty in the representation of the landscape. Most plotting showing the terrain is enhanced by the merging of a hillshading image with the elevation. Both are black to white gradients.

Derivative data for analysis were largely computed using RiverTools software. The routines in the software calculate areas, slopes and lengths using latitude and longitude; it does not have to be projected, which is true for many GIS programs, including ArcGIS. Drainage basins are derived solely from the topography using drainage analyses based on elevation and the determined flow direction. Like most watershed creation routines, the RiverTools flow algorithm relies on “pit-filling”, where all local pits (no outflow) are filled until the drainage can be traced entirely across the surface. This results in significant “stepping” in the profiles of rivers and streams where errant high cells “dam” the flow upstream, resulting in an artificially flat profile above the error. Except in areas of extremely low relief, the flow path is reliable, as is the overall profile shape, but in detail there can be many local errors. From the artificially recreated drainage network, channel profiles, watershed hypsometry, and basin characteristics can be quickly determined. For this study, determinations of basin hypsometry, river profiles and basin boundaries, plus calculations of slope, drainage area, and flow length were computed in RiverTools. Streams were defined as beginning where the drainage area is greater than 1 square kilometer. This arbitrary function likely overestimates the number of actual first-order river channels in the rain shadow east of the Ghats, but under-represents the number of water-filled channels in the WGE itself.

The digital representation of topography also facilitates the analysis of linear features and the topographic characteristics within restricted areas relative to other features. The sinuosity of the escarpment was developed using a single contour line, extracted from a derived contour set. The 450 m contour line was selected because it corresponds to the upper end of the scarp midsection, and because it is continuous from Mumbai to Kanyakumari. Other 450 m contours surround masses separate from the escarpment; these were not sampled. In this study, areas within a “buffer” of the escarpment or the continental divide were analyzed for relief. A buffer is drawn around a linear element using a straight-line distance. The continental divide, which was extracted from the basin boundaries derived from RiverTools, and the 450 m contour were both buffered. The range of the area inside these buffers was computed along the length of the escarpment. A larger buffer (25 km) was also constructed around the continental divide for the analysis of stream orientation. The orientation of a line between the beginning and end of each stream segment that was equal to or larger than 4th order was determined in ArcGIS using attribute calculations derived from EasyCalculate (available on the web). The orientation was matched to the midpoint latitude for analysis by spatial correlation to other WGE features.

Cross-sections of the WGE topography were taken in swaths to determine averaged responses to the geological conditions. The swaths are constructed using a centerline profile and parallel profiles moving out in both directions. The distance between each profile varies depending on the variability of the topography, but is usually 15 times the grid spacing (approximately 1.5 km). The sampling continues until a predetermined width is reached, usually 15 or 25 km. The grid cells crossed by each profile within the swath are plotted, forming a density plot of elevation ranges inside the swath. The calculations were carried out using Matlab with grid and profile location data exported from ArcGIS.

RESULTS: ESCARPMENT MORPHOLOGY

Escarpment Retreat and Sinuosity

The lateral distance of the escarpment and drainage divide relative to the coastline (Fig. 2) shows considerable variability over the length of the Western Ghats. The modern shoreline is not a marker of the former position of the escarpment, but it serves as a first-order proxy for retreat. Distance of the escarpment from the modern coastline decreases relatively consistently from 19ºN to 14.5ºN, which is also consistent with or similar to the decreasing relief of the escarpment (Fig. 2A). The distance between the escarpment edge and the drainage divide, however, shows the dramatic jump that results from gorges cutting into the plateau. This difference means that the drainage divide has moved inward from the major relief, which is the potential energy source for the further advancement of the drainage divide. South of 14.5ºN, the distance of the escarpment retreat from the coast is more erratic and is matched by a much more variable relief along the drainage divide and scarp.

One consequence of the variability in the degree and process of scarp retreat is the shape of the escarpment. In the north, the WGE at continental scale view (i.e. low resolution) is almost linear (Fig. 1) but at a more detailed view (Fig. 3), any particular level in the escarpment follows a sinuous path around each eroding headwater, and the sinuosity value is greater than 5 (Fig. 2B). In the Dharwar Craton section the escarpment, again at the continental scale appears to be more sinuous as it cuts back into deep canyons and embayments that characterize both the other margins in deep valleys of this section. One might conclude here that a more sinuous escarpment exposes a greater area to erosional retreat by wearing back at the same time that stream incision by waterfall or knickpoint retreat makes inroads into the plateau. However, the sinuosity determined over many tens of kilometers does not change appreciably because the pinnate sinuosity of the northern section almost equals values for the more macro-scale sinuous section near the gorges. In the south, for instance between Agumbe and Kudremukh, there are truly linear escarpment sections where the divide and escarpment are currently up against linear resistant rock elements between deeper embayments.

Stream Orientation

The main driving mechanism of escarpment retreat is stream erosion of the continental margin. Stream erosion conditions hillslope erosion at the line of greatest relief. At maximum relief and gradient, hillslope processes, including landsliding, will keep the face of the escarpment connected to these backwearing streams. Changes in the character of stream erosion reflect the interaction between surface process and geologic substrate. Where there is relatively homogeneous bedrock — which is the case chosen for most coupled surface-process and tectonic numerical models in the literature — or where bedrock is layered but relatively flat-lying, headward stream retreat results in a linear escarpment at low resolution (i.e. the continental to regional scale). The linearity stems from the lack of erosional advantage given to any one stream. However, where there are abundant fractures, joints or faults, or where rocks of differing resistance to erosion are juxtaposed, erosion by some streams is favored over others. This anisotropy becomes particularly

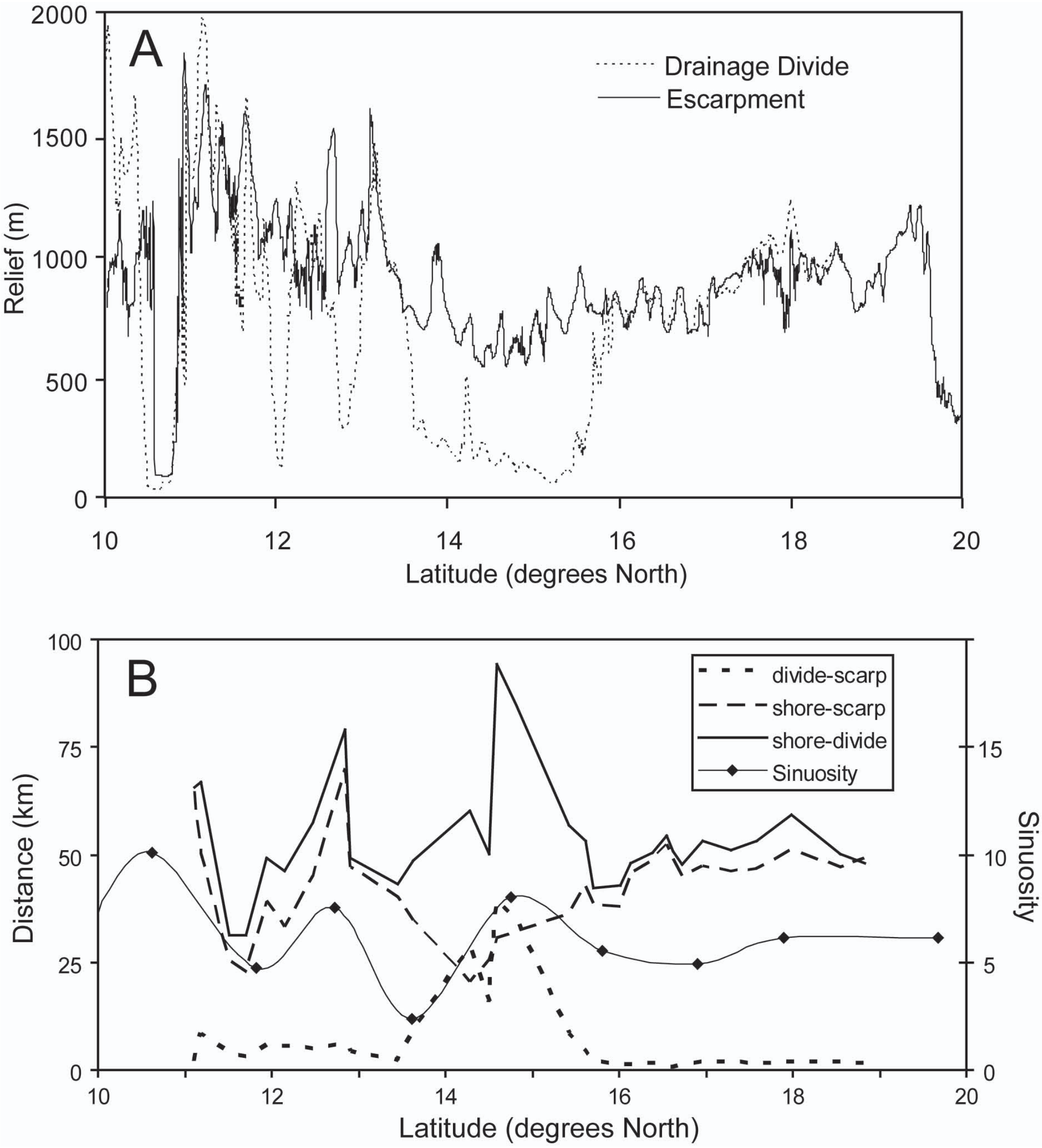

Fig.2. Characteristics of the Western Ghats Escarpment and drainage divide. A: relief of the escarpment and drainage divide. The escarpment relief is the range of elevations within a 2500 m band on each side of the 450 m contour, and the relief of the Ghats Continental Divide is calculated on a similarly sized buffer. B: distance of the continental divide and escarpment from the current shoreline averaged for each of the Ghats drainage basins that share a portion of the continental divide. The WGE was simulated using the 450 m contour line. Sinuosity of the escarpment (right axis) was calculated over large sections of the Ghats Escarpment using the distance along the 450 m contour divided by straight line distance.

important where the orientation of preferred streams is aligned parallel to the moving escarpment front (Fig.5). In the section of the Deccan Plateau shown in Fig.4, the alignment of the headwater stream from the Krishna Basin will permit the sudden capture of a 910 km^2 drainage basin. This effectively allows the escarpment to “jump” from the western side of the drainage basin to the eastern side. In the comparatively nonresistant rocks of the Deccan Plateau, this stream will quickly carve a gorge and eliminate the relief between the new and former escarpment positions. In the Dharwar Craton section of the WGE, the distance between the divide and escarpment reaches a maximum (Fig. 2). Here, drainage basins greater than 4000 km^2 exist between the western edge of the escarpment and the continental divide (Fig. 6). The drainage in these basins is directed by major and minor geological structures, and significant portions of the drainage net initially flow away from the escarpment to the east.

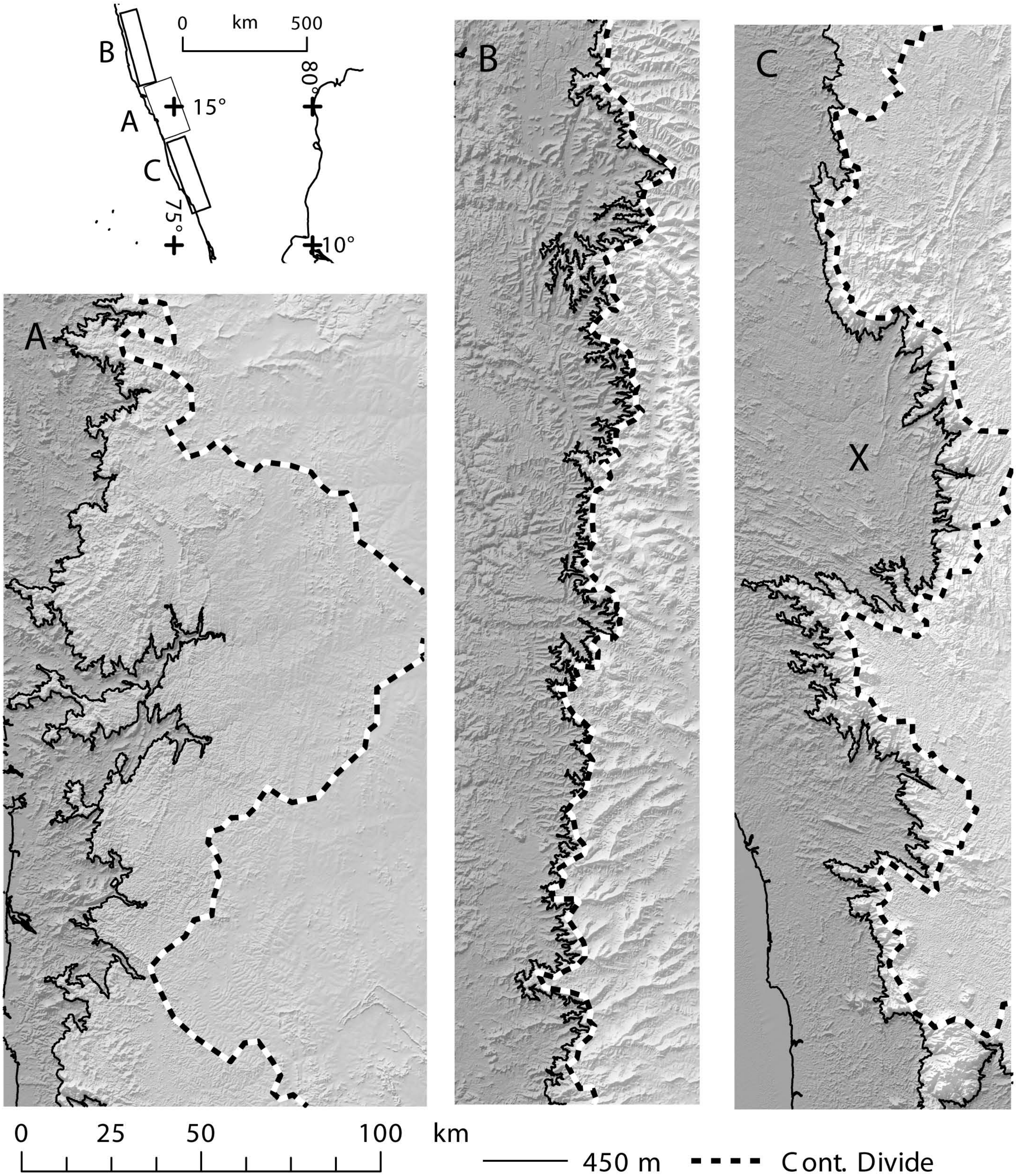

Fig.3. Sinuosity of the Western Ghats Escarpment. Uplands are in light grey, coastal lowlands in darker grey. The numerical change of sinuosity along the length of the WGE (Fig. 2B) does not capture the changes in the character of the scarp, i.e. its gorge-type or divide-type character. The 450 m contour line, which is in the upper-middle part of the escarpment is used as a proxy for the position of the erosional wave. A fine-scale sinuosity in the northern segment (B) is replaced by deeper gorges and embayments in the middle section (A). The southern section (C) is highly varied. See text for comment on embayment X.

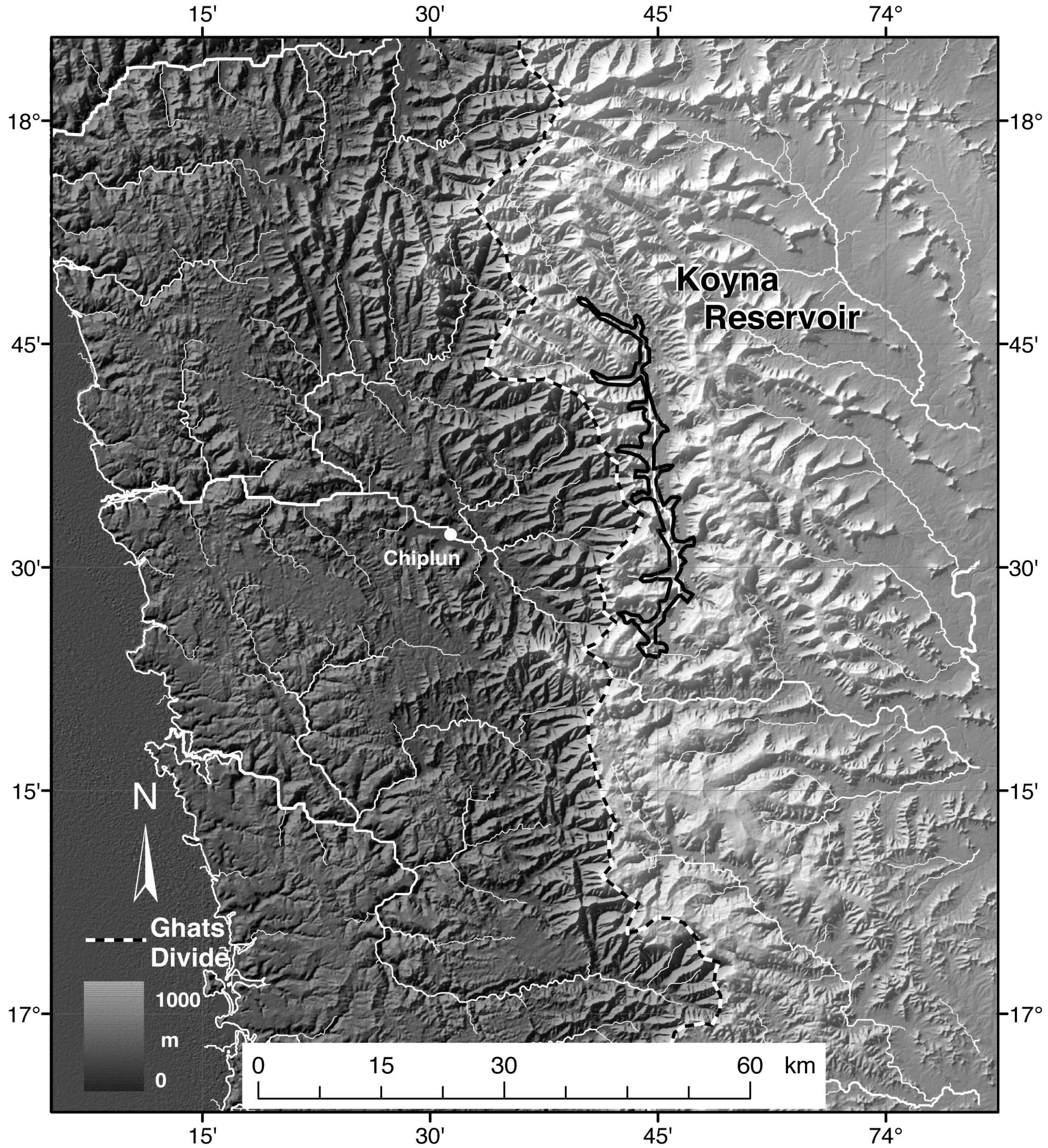

Fig.4. Example of potential for stream capture in the Maharashtra Western Ghats. In the Deccan section, most of the drainage on both sides of the continental divide is aligned perpendicular to the crest of the Ghats Escarpment. However, in the Krishna River headwater basin that includes the Koyna Reservoir, a north-south stream (the Koyna River) oriented parallel to the divide is poised to be diverted over the edge.

The landscapes shown in Figs. 4 and 6 suggest that the true engine of scarp retreat by drainage capture is a prevalence of stream segments, especially those with significant area, that are sub-parallel to the escarpment. The tendency for streams to align parallel to the escarpment varies in the three sections of the Western Ghats (Fig. 5). In the Deccan section north of about 16ºN, most of the streams have orientations that are mostly perpendicular to the escarpment, which trends N15ºW. In the section near 18ºN, the orientations are more varied than to the north or south. In this region, the scarp is more embayed and has retreated farther inland (Figs. 1, 3). South of 16ºN, in the gorge section, stream orientations shift away from E–W and trend more toward N–S. South of the gorge

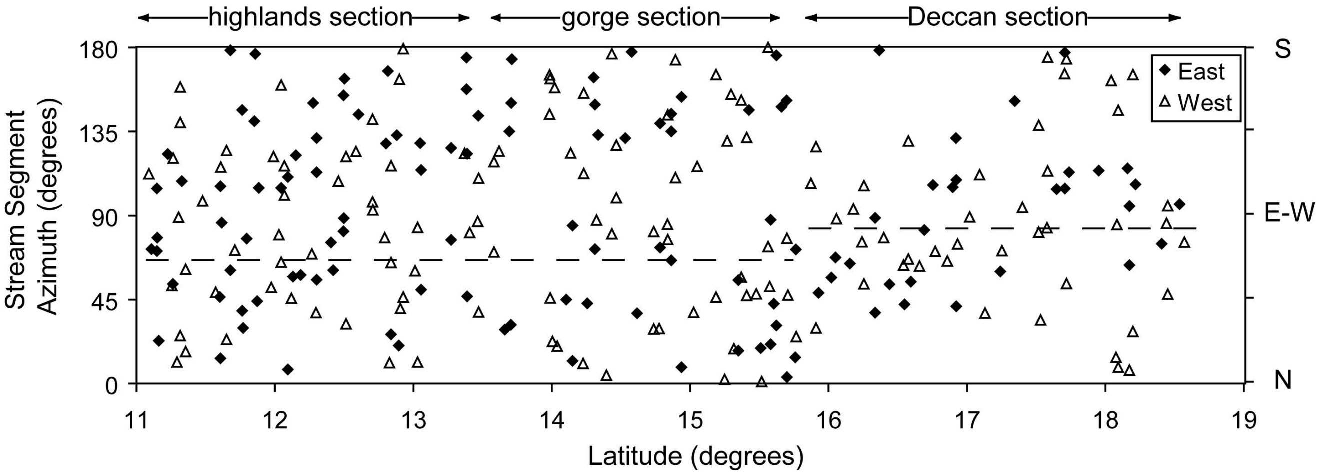

Fig.5. Orientation of 4th order streams and larger within a 25 km buffer of the drainage divide. The orientations were collapsed into 0–180º to overlap the east- and west-flowing streams, thus a west-flowing stream with a bearing of 210º plots the same as an east-flowing stream with a bearing of 30°. For this analysis, 1st order streams were defined at a drainage area threshold of 1 km^2. The dashed lines represent the orientation of streams perpendicular to the divide, which bends slightly more toward the east south of 16ºN. Due to the natural slope of the escarpment and the position of the oceanic base level, most drainage basins are roughly perpendicular to the escarpment and straddle it. However, all other parameters being equal, the higher the frequency of strike-parallel streams (guided by geologic structure), the greater the potential for stream capture and eastward scarp jump.

section, the streams are aligned neither away from the escarpment nor along it. It is the streams east of the divide that provide the potential for capture (Fig. 5), but streams west of the divide likely preserve the orientation of the streams captured, where this process occurs, and whose incision helps shape the WGE today. In the upper reaches of the west-flowing streams of the gorge sections, the current stream network is almost certainly aligned to the same structures that permitted drainage reversal.

East of the divide in the gorge section, streams are not simply draining to the northeast off the WGE flank as they are in the Deccan section. Here in the rocks of the Dharwar Craton, streams are more favourably aligned for capture as the WGE retreats across prominent structural elements (Fig. 6). This fabric, which is visible in the relief, is built from the differential weathering and erosion of the underlying fold belts in Archean rocks, including greenstone, and the metamorphic fabric. In particular, the headwaters of the Kalinadi River exhibit flow aligned to major fabrics as well as reversed drainage. North of the gorge, streams flow east away from the WGE before turning back to the gorge.

River and Basin Characteristics

The profiles of rivers and characteristics of drainage basins change remarkably along the length of the WGE. The streams north of 16ºN have a strongly concave profile (Streams #1 and #2, Fig. 7A) that plots for the most part as a straight line on a log-distance vs. elevation plot (Fig. 7B). A straight line implies a simple, logarithmically smooth profile (Goldrick and Bishop, 1995). However, two changes of slope in the log plots suggest that there are three separate sections of streams that drain the linear Ghats Escarpment in the Deccan section. The upper portions from less than 100 m up to 1.5 to 5 km downstream constrain the steep streams on bedrock that fall down the upper reaches of the escarpment. The middle reach extends 20–50 km downstream to just 10–20 m above sea level. This reach is more gently concave, which likely signals the transition from detachment-limited to transport- limited conditions. The coastal section runs at very low slope to the sea, and likely is influenced by Holocene sea level rise having formed rias in that region. One profile from the southern granulite section (#5) shows a less concave, less deeply incised profile, although the overall shape is similar to those in the Deccan section. Starting at the southern feather edge of the Deccan basalts and continuing into the Dharwar Craton section, the continental drainage divide moves eastward away from the escarpment edge. Most major rivers have significant proportions of their headwaters above and landward of the escarpment edge. Some, like the Kalinadi River (#4) south of Goa, have carved a long deep gorge that extends 50–60 km into the upland plateau. The headwaters sections less than 1–5 km from the divide are

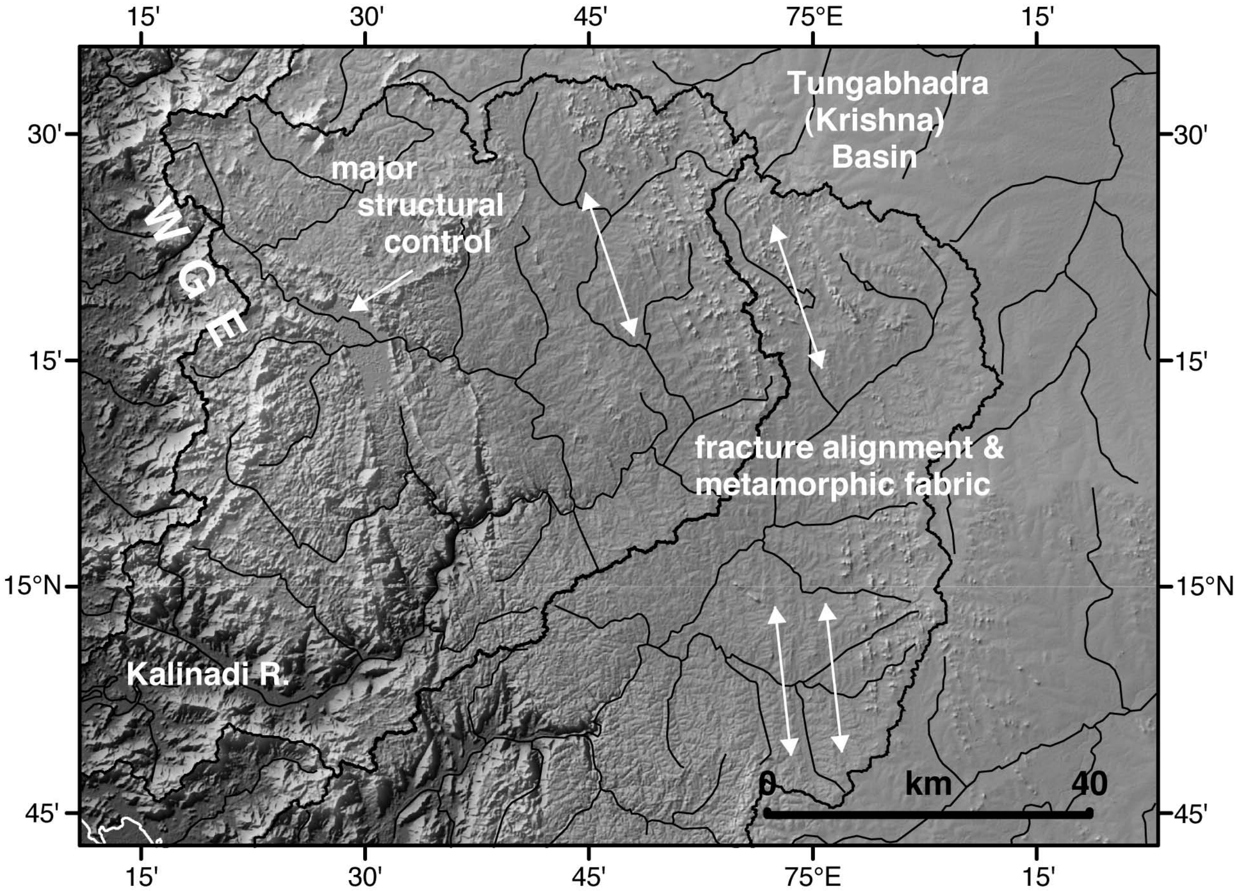

Fig.6. Drainage alignment to structure in the Dharwar Craton. Major and minor structural features influence the drainage orientation and path. Note the "elbow of capture" north of the Kalinadi River gorge.

variable in morphology, but can be quite low in slope. Above the prominent profile knickpoints we observe concave profiles that are dramatically less steep and less concave (lower slope angle on the log profiles) than the scarp-face drainage. Many of these profiles originating on the upland have similar shapes in the section just above the knickpoint on the log-distance plots regardless of latitude or lithology (Fig. 7B). In this similarity lies the suggestion that rivers are graded to erosional processes above the knickpoint that are substantially different from those acting along the gorge. However, because of the similarity of profile shape (slope on the log plot), they are not substantially different from the sections of streams just above base level at the coast (dashed lines, Fig. 7B).

The process of capture dramatically changes the erosional processes acting on the escarpment. Rather linear walls characterize most of the WGE in the Deccan section. This shape follows from the progressive backwearing of the escarpment face by low-order streams in which no single basin gains much advantage. This particular style of headward advance is easily observed in numerical models of retreat where hillslope erosion by landsliding at critical slope is tied to incision of escarpment face streams (e.g., Tucker and Slingerland, 1994). The pattern is common to models and geologic settings with no heterogeneity. In the gorge section, the rocks have more variable lithologic resistance (greenstone, quartzite, gneiss and schist) and one cannot easily find what might be described as an escarpment. Rather, like the 450 m contour, the erosional wave is highly sinuous with deep gorges and long, high-relief ridgelines that extend almost to the sea.

Elongation of drainage basins in the terrain carved out of older rocks south of the Deccan basalts promotes a more varied response to the topographic asymmetry of the rift escarpment. The shape of the incised area reveals evidence of the relative rates of gorge extension and overall escarpment retreat (Fig. 8). When a river, such as the Sharavati River near Jog Falls, captures a significant section of the upland (Radhakrishna, 1964), the pace of gorge deepening and extension quickly outpaces the rate of wall

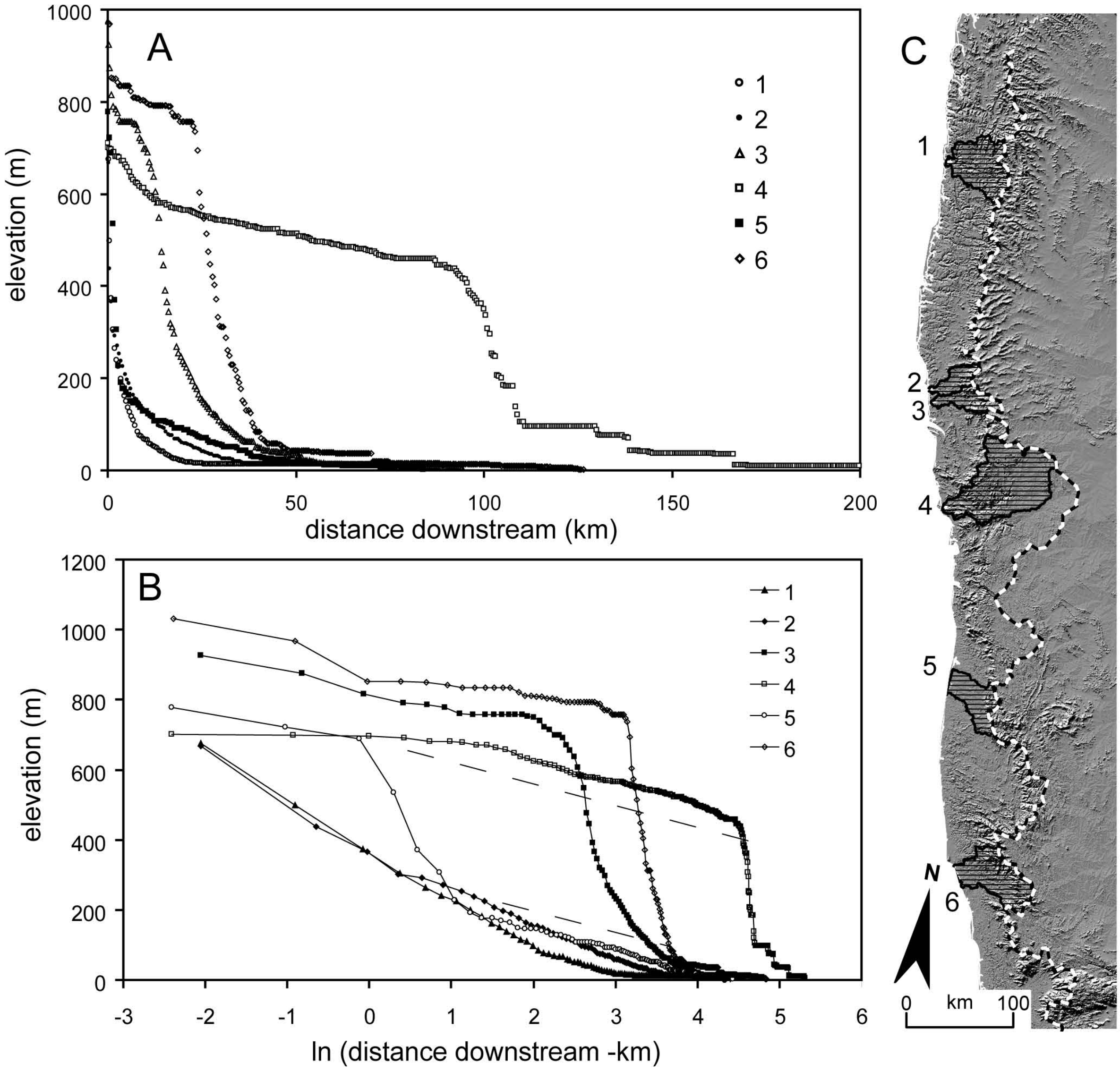

Fig.7. River profiles. Six examples of drainage basins that demonstrate the range of shapes extant on the Western Ghats. River profiles were extracted from SRTM data using the River Tools program, which results in stepped profiles where DEM irregularities occur. The general form of the profile can be trusted, but not the details. Panel A shows the normal profile and Panel B shows the same data plotted on a log-distance vs. elevation basis. In these log profiles, straight lines suggest smoothly concave sections whereas changes of slope indicate increases or decreases in concavity and steepness. The dashed lines denote the similarity of gradient and concavity for the middle reaches of streams on the plateau upstream of knickpoint and the lower profile of the stream in basin 5.

retreat. We can make comparative estimates of rates of gorge extension and wall retreat using the shape of the embayments. The gorges of the Gangavali and Kalinadi are ten times longer than wide. Therefore, migration of the fluvial knickpoint and subsequent canyon production in these examples is an order of magnitude greater than the hillslope and low-order stream erosion of the flanking canyon walls. This process has just begun in the Sharavati River basin because the capture of the upland must be more recent given the major wind gap just near the tip of the gorge (Fig. 8).

These captures focus the discharge from what can be an enormous basin area onto the edge of the large relief of the upper escarpment. Using space-for-time substitution, the gorge of the Sharavati River, now comparatively short and close to the outer edge of the WGE, will elongate

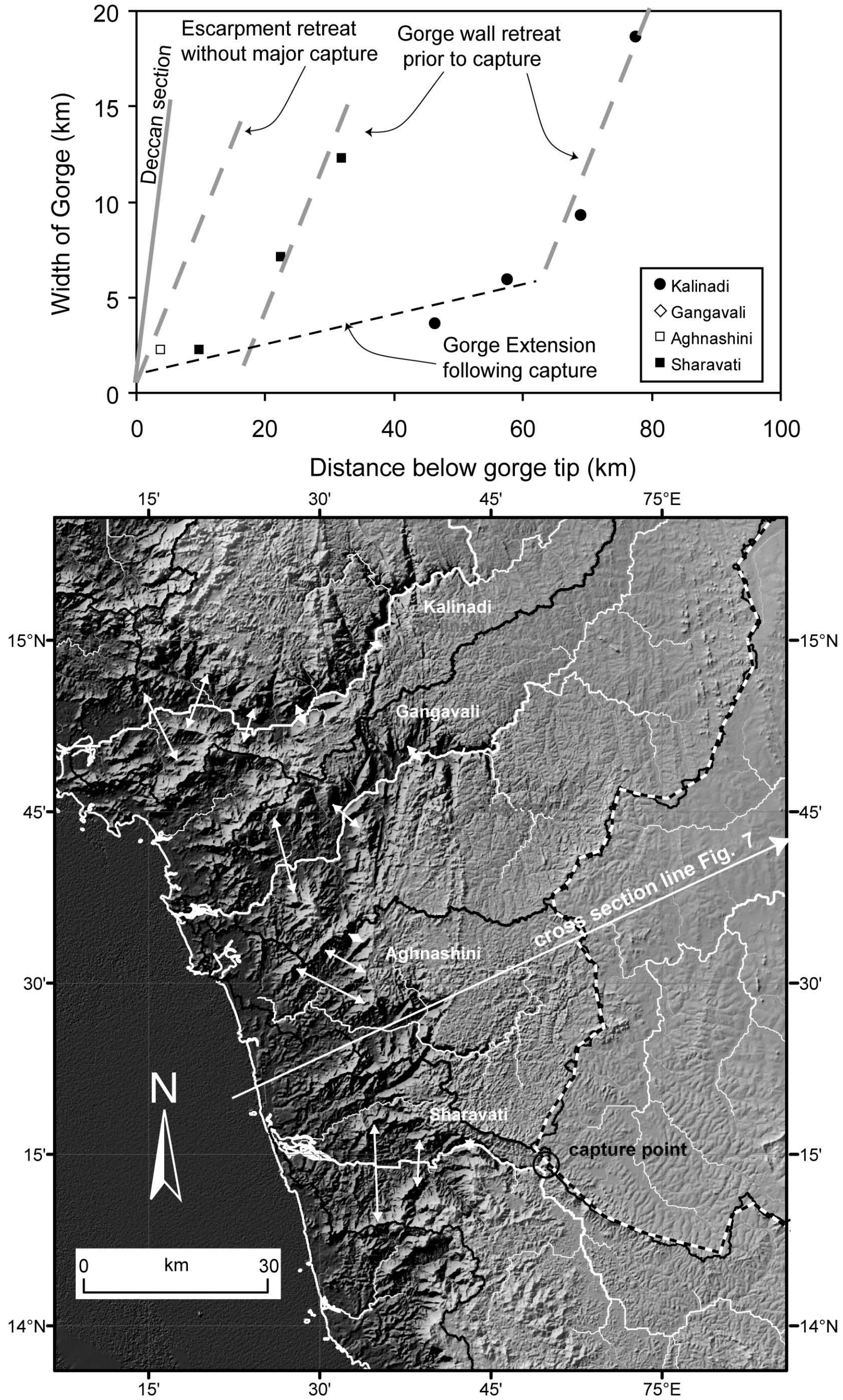

Fig.8. Comparison of gorge extension to escarpment retreat. Using the 450 m contour as a guide to the position of the erosional escarpment, the width and length of embayments were measured at positions shown at the arrows on the map. By contrast, measurements of the open embayments in the Deccan section plot very near vertical (solid grey line) because of the lack of capture and more linear scarp form (*see* Figure 3B). A similar stream that heads only on the WGE in the Dharwar section, here illustrated by the northern tributary to the Aghnashini River, displays a narrower form. This same shape characterizes the outer reaches of the neighboring canyons (grey dashed lines). The length to width of the gorges (dashed black line) shows a relatively consistent slope for each of the three basins with a gorge. The Sharavati gorge, however, is much shorter, and the outer embayment is encountered closer to the gorge knickpoint.

toward the 60 km length of the neighboring gorges (as permitted by the size and discharge of the basin). The openly embayed part of the valley is increasingly distant from the incising gorge. The more open embayment continues to wear back, but its shape does not change until it is eventually consumed by or merged with the expanding walls of the gorge.

We may tentatively estimate the rate of Deccan scarp retreat using as a control the remnants of the lateritized pediment belt that extends from the Konkan to Kerala (Widdowson and Gunnell, 1999). After Widdowson (1997) and Gunnell (2001), we interpret the sudden eastward termination of the laterite ramp as the trace of the former escarpment (Fig. 9C). The ages of these residual laterite pediments are uncertain, but if we assume their minimum age is middle Miocene (Widdowson and Gunnell, 1999), then the scarp has retreated by 23 km in 13 m.y. This translates as a rate of about 2 km/m.y. This (maximum) rate is clearly conditional upon both our palaeopositioning of the escarpment (cf. Fig. 9C) and the estimated age of the laterite being correct. Given that rifting occurred at the K/T boundary, the lateritized pediment cannot be more than ca. 60 m.y. old, so a minimum rate of scarp recession would have to be 23 km in 60 m.y., i.e. < 0.4 km/m.y. Assuming that the overall Deccan section recession rate is equal to the recession in the coastal scarp of the gorge region, then maximum gorge extension is 20 km/m.y., while minimum rates would be 4 km/m.y. Gorge extension has a limit, however. As the gorge extends into the more semiarid zone east of the Western Ghats and the basin area above the gorge tip shrinks, the discharge energy diminishes and the rate of extension will cease to outpace the rate of widening. At this point the basin will be "filling out" and lowering much of the upper reaches to the new base level of the nearby coast, which is ca. 500–800 m lower than the east-flowing streams. This seems to be the condition of a large embayment south of the gorge area (*see* Fig. 3C, area marked X). Here most of the basin has been excavated and only a small portion of the basin lies near the former base level (see also stream #6, Fig.7).

Concurrent with the development of the gorge is the incision of the upper reaches of the captured basins. The cross-section near the Aghnashini River, which has a smaller gorge, clearly shows the development of these two forms of new relief (Fig. 9). The upper basin part of the eastern basin is steeper with greater relief, and thus incision is likely proceeding faster here than in the low-relief headwaters of the Tungabhadra River, which flows northeastward across the plateau to join the Krishna and, eventually, the Bay of Bengal. Similar contrast in the east and west styles of erosion are evident in the next swath profile to the north (Fig. 9B). Here the eastern side is somewhat steeper, because the plateau relief increases approaching relict erosion surfaces near the southern end of the Deccan Section. However, the western flank of the upland is considerably steeper above the gorge. Both of these profiles contrast strongly with the sharp, strongly uplifted Deccan section profile of the WGE (Fig. 9C), where the escarpment is a narrow zone, no bevel due to capture and gorge extension cuts the edge of the escarpment, and relief is greatly heightened in the area closest to the WGE.

DISCUSSION

The initial rift shoulder generated by the rifting away of the Madagascar and Seychelles plates has long been eroded (Gunnell et al. 2003), and the current Western Ghats likely represent a residual escarpment that bears only distant relation to the initial rift-flank scarp either in terms of relief magnitude or geographic position. However, this escarpment is dynamic, and persists despite erosion relentlessly fraying the plateau edge. A key engine to escarpment persistence appears to be the monsoon climate since ca. 15 Ma, and (given the presence and antiquity of bauxites capping the Deccan basalts) its equally humid antecedents since 60 Ma. The monsoon provides a plentiful supply of runoff, but more fundamental, as shown here, is the interplay between the drainage and geologic structure. Where bedrock is homogeneous both lithologically and structurally, as in the Deccan basalt province, the drainage divide and escarpment coincide, short-wavelength scarp sinuosity is minimal, and the width of the coastal plain varies little. When variability occurs at the basaltic escarpment, for instance the large embayment northeast of Mumbai, we find that the fracture net also exhibits a wider range of azimuths. The geomorphological consequence is that the drainage net, which is narrowly underprinted by the fracture net, has been presented with greater opportunities for stream capture and overall scarp recession than further south, where strike-parallel fractures are fewer (though conspicuous when present: cf. Fig. 4). These observations also suggest that scarp sinuosity, which is often used in morphometric studies to infer the relative ages of fault scarps, is an ambiguous measure of scarp age because structural factors may also mimic the age dependency that is commonly assumed in fault line dissection. In fact, Matmon et al. (2002) use sinuosity as a substitute for margin age to infer a morphologic transition with age. Based on our data, we suggest that, at the local scale, escarpment sinuosity may appear and disappear as

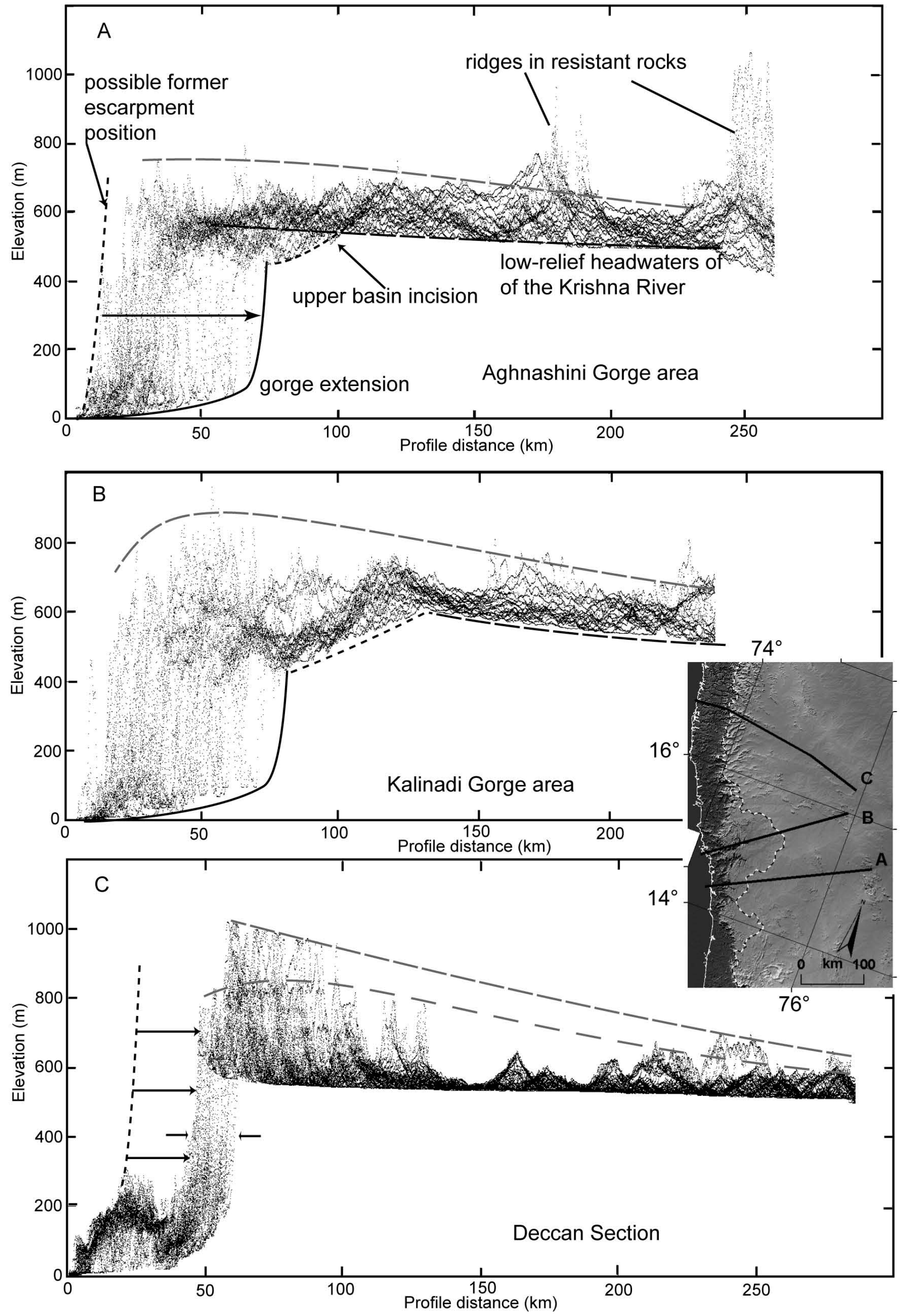

Fig.9. Swath cross-profiles of the topography in the Dharwar and Deccan sections. **A:** near the Aghnashini River basin. The profile is drawn from SRTM digital data (3 second, or approximately 90 m spacing) along the profile line and in similar parallel lines over a width of 25 km. This cross profile permits the visualization of multiple components of the landscape at a single position relative to the escarpment. The rivers eroding up from the west are undercutting the low-relief basins in the Tungabhadra River (base level is shown by thick dashed line), which is an upper tributary to the Krishna River, both through gorge retreat (solid line) and incision above the gorge knickpoint (thin dashed line). **B:** near the Kalinadi River. This swath profile is 40 km wide to characterize the greater width of the captured basin. Slopes and relief are greater in this basin nearer to the margin of the Deccan basalt onlap. **C:** near the middle of the Deccan section. This strongly contrasting profile (25 km wide swath) shows a very linear escarpment (shown by a narrow range of profiles at the escarpment face), a shelf of lateritic paleosurfaces in the coastal zone (cf. Widdowson, 1997), and heightened relief in the immediate vicinity of the WGE. Grey dashed lines suggest former levels of erosion (as recorded in summits) that have been elevated, tilted and incised as a consequence of margin uplift. The shape of the lines, although highly speculative, are significantly different in the three swaths.

the drainage divide is driven across regions of varied structure and lithology. Generally, it is the scarp-parallel fractures, and hence streams, such as the Koyna in the upland or a variety of similar streams in the coastal plateau (Fig. 1), that appear to play a major role in drainage integration and scarp jumps. This counter-intuitive role played by scarp-parallel streams, rather than just scarp-perpendicular trunk streams, has been mostly ignored in previous studies of passive margin escarpments, but may play a far more general role than previously recognized.

Many feedbacks operate between geological conditions and the geomorphic expression and evolution of the WGE. In the Dharwar Craton, lithological heterogeneity and fold directions in supracrustal rocks are much clearer controls on scarp sinuosity. The structural template involves scarp-parallel ridges of quartzite, which are clearly detectable in the topography and locate strike-parallel streams that likely play a role analogous to the fractures mentioned in the Deccan lava pile. Whereas the rate of retreat is determined by headward growth in most of the Deccan basalt section, this headward growth takes place in the face of drainage away from the scarp and continued upwarp of the margin in a way that reinforces the persistence of the divide. Thus the relief seems to follow the morphology of the escarpment and its erosion in a self-organized arrangement. Coming south into the Dharwar Craton, the retreat rate is lower due to the shorter distance of the escarpment from the coast, and its lower relief. Even though the dominant rocks in the gorge section are less resistant (metagreywackes, meta-argilites), significant structural barriers may make the background rate of scarp retreat quite low. This appears to be, however, punctuated by periods of extensive erosion following drainage rearrangement and deep movement of the continental divide into the plateau, not by retreat but by drainage capture, gorge extension, and basin expansion. Looking further south, the end result may be a realigning of the escarpment at a greater distance from the coast. The gorge extension rate suggested here is quite high; it is ten times the rate observed in the SE Australian passive margin (Weissel and Seidl, 1997), and possibly reflects the tremendous energy provided by 5 to 7 m of annual rainfall in the Indian case. If this rate is of the correct order of magnitude, then gorge extension is an indicator of the rapid jump that the WGE is about to take in the region between 15 and 13ºN. Presumably, because the erosional unloading is not taking place at a narrow and fixed distance from the WGE, the flexural response to this style of erosion will be different, and may engender further responses of the geomorphic system in the ongoing balance of uplift, erosional and escarpment retreat.

In summary, we find that the size of plateau drainage-basin annexation by river piracy affects the rate of escarpment retreat. Annexation of large drainage basins such as the Gangavali or the Sharavati potentially generates wide steps of scarp jump because it offsets the continental divide far into the plateau interior. However, this process also generates longer gorges piercing the plateau, so there is more work to be achieved in terms of gorge widening and a greater mass of trailing terrain to erode between the parallel gorges before the escarpment can catch up with its relocated position at the new continental divide. Logically, it takes much longer to achieve scarp migration than if scarp jumps occur on shorter length scales. We therefore suggest that gorge-type escarpments are typical of drainage piracy having diverted broad areas of plateau drainage, whereas divide-type escarpments reflect either (i) shorter jumps (for instance of the kind detectable in Figure 4, where strike-parallel fracture spacing north of Chiplun is ca. 5 km and does not much exceed 15 km), or (ii) situations where girdles of highly resistant rocks generate stagnant escarpments with little chance of recession (e.g. the Kudremukh "headland", which corresponds to a continuous BIF and quartzite hogack structure towering at nearly 2 km a.s.l., "K" on Fig. 1). This does not mean that scarp recession in divide-type settings does not also involve gorge cutting followed by gorge widening, but we suggest that the gorges are much shorter in length and poorly distinguishable from the background noise of scarp sinuosity. Such gorges, which occur in homogeneous geologic settings (here: the Deccan basalts) would also be shorter-lived because relaxation times between the drainage piracy event and the scarp reformation event at the new drainage divide are much shorter than in gorge-type settings with hetoerogeneous lithologies. Because the gorges are much shorter-lived, there is a much higher probability of there not being any conspicuous gorge at a given time, hence the divide-type morphology. In that sense, we suggest that river capture and drainage rearrangement is one end member of the normal mode of escarpment retreat at mature passive margins, and that divide-type escarpments simply represent the other end member of this model when either homogeneous bedrock conditions or structural blocking by a large resistant bedrock landform occur. Along the length of the WGE, averaging the various sinuosity lines shown on Figure 2 suggests that the average overall pace of scarp retreat is uniform but that variation of rate increases in the gorge-type end member. Significant variance in scarp morphology is therefore not necessarily an indication of heterogeneous mean rates of retreat. Further work is needed to test whether all linear escarpments are stagnant (Bierman and Caffee, 2001); or whether, as we hypothesize here, the retreat of the linear Deccan section is equal to that of the other sections because the long-term average recession-rate homogenizing factor is the fairly uniform monsoon climate along the entire strike of the Ghats. Nevertheless, it is clear from the topographic analysis that the gorge-type escarpment is likely to recede by a significant amount at geologic time scales. In that respect, the dynamics of divide-type escarpments are more ambiguous to trace through space and time unless, as we proposed earlier (cf. Fig. 9C), geomorphic traces of its paleoposition can be ascertained.

CONCLUSION

From the maps and diagrams crafted for this study, insight has been gained into the dynamics of a continental-scale great escarpment. We suggest that in areas of heterogeneity, scarps recede in jumps driven by drainage capture rather than by parallel scarp retreat. The persistence of parallel scarp retreat in the Deccan basalts, for instance, is conveyed by the current coincidence of the scarp and the drainage divide as well as relative scarp rectitude. We argue that those attributes are made possible by the collaboration between fracture-guided scarp-perpendicular and scarp-parallel streams; and by geological homogeneity, which denies erosional advantage to any one stream while also allowing a more rapid and uniform destruction of the residual topography that survives on the coastal plain in the wake of the successive scarp jumps. In the Dharwar Craton, geological heterogeneity is the engine for drainage rearrangement. Given that monsoon rainfall provides the main fuel for river discharge and cutting power, climatic aridity in the escarpment rainshadow is potentially the main limitation on indefinite gorge recession into the interior. However, we have seen that the gorge section of the Ghats is also that of lowest relief (0.4–0.5 km), and hence the weakest barrier to monsoon rainfall. The presence of the gorges at those latitudes is a chicken or egg issue that is not easily resolved: did the gorges make inroads because the Ghats form a topographic saddle that allows monsoon flow to enter the plateau? Or does the saddle exist because the argillites and greywackes of that segment were more easily eroded compared to areas to the north and south of this zone? Or is the low relief a response to delayed erosion and a limited flexural response to erosion distributed across a broader zone? Passive margin scarp evolution cast in terms of rift-flank decay and isostatic adjustments appear valid for the initial few tens of millions of years when the initial rift shoulder loses several kilometres of rock. However, when magnitudes of erosion drop significantly once the shoulder has been eroded (Gunnell et al., 2003), the scarp finds a new topographic state similar to the one currently observed and the hierarchy of driving mechanisms changes. We suggest that site-specific feedbacks between climate, drainage, and geological structure along the strike of continuous escarpments at mature passive margins are key to understanding scarp dynamics and scarp persistence. The manner in which the evolution of drainage boundaries across strike affect morphology and the distribution of isostatic rebound along strike seem essential.

Acknowledgements: We wish to thank Narayana Allu for soliciting our contribution to this Special Volume on Sahyadri, and Vishwas Kale for his formal review of the manuscript. We dedicate this paper to B.P. Radhakrishna, whose past pioneering insights into the Western Ghats have spawned much interest world wide.

References

Bierman, P.R. and Caffee, M. (2001) Slow rates of rock surface erosion and sediment production across the Namib desert and escarpment, Southern Africa. Amer. Jour. Sci., v.301, pp.326-358.

Chetty, T.R.K. (1996) Proterozoic shear zones in southern granulite terrain, southern India. *In:* M. Santosh and M. Yoshida, M. (Eds.), The Archean and Proterozoic terrains of southern India within eastern Gondwana. Gondwana Research Group Memoir, v. 3, Faculty of Science, Osaka University, pp.77-90.

Goldrick, G. and Bishop, P. (1995) Differentiating the roles of lithology and uplift in steepening bedrock river long profiles: an example from Southeastern Australia. Jour. Geol., v.103, pp.227-231.

Gunnell, Y. (2001) Morphology and scarp recession rates of the Western Ghats escarpment. *In*: Y. Gunnell and B.P. Radhakrishna (Eds.), Sahyadri, the Great Escarpment of the Indian Subcontinent. Patterns of Landscape Development in the Western Ghats. Mem. Geol. Soc. India, No.47, Bangalore, pp.89–117.

Gunnell, Y. and Radhakrishna, B.P. (Eds) (2001) Sahyadri, the Great Escarpment of the Indian Subcontinent. Patterns of Landscape Development in the Western Ghats. Mem. Geol. Soc. India, No.47, Bangalore, 1054p.

Gunnell, Y., Gallagher, K., Carter, A., Widdowson, M. and Hurford, A.J. (2003) Denudation history of the continental margin of western peninsular India during the Mesozoic and Cenozoic. Earth Planet. Sci. Lett., v.215, pp.187-201.

Jet Propulsion Lab (2002) http://www2.jpl.nasa.gov/srtm/index.html

Matmon, A., Bierman, P. and Enzel, Y. (2002) Pattern and tempo of great escarpment erosion. Geology, v.30, pp.1135-1138.

Radhakrishna, B.P. (1964) Evolution of Sharavati drainage, Mysore State, South India. Jour. Geol. Soc. India, v.5, pp.72-79.

SRTM (2004) ftp://edcftp.cr.usgs.gov/pub/data/srtm

Tucker, G.E. and Slingerland, R.L. (1994) Erosional dynamics, flexural isostasy, and long-lived escarpments: a numerical modeling study. Jour. Geophys. Res., v.99, pp.12229-12243.

Wandrey, C.J. and Law, B.E. (1998). Maps showing geology, oil and gas fields and geologic provinces of South Asia, US Geological Survey Open-file Report 97-470C. Digital data retrieved from http://energy.cr.usgs.gov/energy/WorldEnergy/WEnergy.html, June, 2003.

Weissel, J.K. and Seidl, M.A. (1997) Influence of rock strength properties on escarpment retreat across passive continental margins. Geology, v.25, pp.631-634.

Widdowson, M. (1997) Tertiary palaeosurfaces of the SW Deccan, Western India: implications for passive margin uplift. *In:* M. Widdowson, (Ed.), Palaeosurfaces: Recognition, Reconstruction and Palaeoenvironmental Interpretation. Geol. Soc. London Spec. Publ., v.120, pp.221-248.

Widdowson, M. and Gunnell, Y. (1999) Lateritization, geomorphology and geodynamics of a passive continental margin: the Konkan and Kanara coastal lowlands of western peninsular India. *In*: M. Thiry, and R. Simon-Coinçon (Eds.), Palaeoweathering, Palaeosurfaces and Related Continental Deposits, Internat. Assoc. Sediment., Spec. Publ., v.27, pp.245-274.