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Butte detachment: how pre-rift geological structure and drainage integration drive escarpment evolution at rifted continental margins

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ABSTRACT: The erosional pattern of passive margins often follows the fabric of ancient, compressional geological structures exposed by the topographic energy of rifting. As erosion cuts into these belted outcrop systems they impose initial and boundary conditions that steer drainage recession into the plateau edge and control escarpment-forming conditions. Pattern therefore controls process. Although generic surface process models predict scarp patterns and retreat in settings devoid of geological heterogeneity, they tend to do so only at isolated locations and for periods shorter than the lifespan of the escarpments. Thus, to focus on relatively narrow strike-perpendicular swaths of passive margin topography misses important aspects of drainage integration, which involves mobile drainage basin boundaries shifting across but also along the strike of inherited geological structures and through continental-scale bioclimatic zones. Space-for-time substitution along three passive margin escarpments (Blue Ridge, Western Ghats, Eastern Ghats) reveals the significance of escarpment jumps and the detachment of topographic outliers, here generically termed 'buttes', as key processes of escarpment evolution. The examples show that these continental escarpments are strongly patterned after pre-rift structural and lithological heterogeneities. As seaward sloping drainages cut into the rift margin, they extend their drainage heads in a non-uniform and unsteady fashion. As a result escarpments can form, be destroyed, reform, and leave topographic vestiges (buttes) of the retreating escarpment. Given the pre-rift geological heterogeneities, there are no *a priori* reasons why escarpment landscape change should be uniform, steady or self-similar. Copyright © 2010 John Wiley & Sons, Ltd.

KEYWORDS: butte; rifting; escarpment; drainage integration; structural and lithological heterogeneities

Introduction

Geomorphology commonly seeks relationships and feedbacks between external forcing factors, specifically tectonics and climate, and erosional system response. We propose here that external forcing merely modulates the self-driven process of drainage integration across continental landscapes comprising nonuniform resistance of rock masses to erosive processes. From the moment that tectonic relief is generated, rivers accentuate topographic imbalances by headward retreat (Harbor, 1997) and knickpoint migration (Seidl *et al.*, 1996). Resulting drainage piracy among competing basins (Brookfield, 1998) produces singularities that upset predictable patterns of topographic modification. The potential for erosion and sediment flux caused by drainage rearrangement, as opposed to external forcing such as climate and tectonics, is therefore large but has barely been addressed up to now through contextually illustrated examples. As the locus of competing drainage systems, passive margin escarpments are ideal candidates for examining large-scale morphological responses to drainage integration through time.

Research on passive margin topography has tended to restrict its focus to strike-perpendicular swaths of topography, the main objective being to establish geodynamic links between the initial rift paleotopography and the surviving topography. Given the expectation that topography decays inexorably unless isostatic or dynamic processes restore it through vertical uplift, studies of elevated topography at many passive margins have either postulated (1) late Cenozoic uplift (in which case the topography is relatively young), or (2) delayed decay of Mesozoic topography as ways of justifying its presence (Baldwin *et al.*, 2003). The detail of how passive margin escarpments (PMEs) retreat, however, often remains equivocal due to uncertainties concerning initial rift geometry (Gunnell and Fleitout, 1998), process (compare Gilchrist and Summerfield, 1990 with Brown *et al.*, 2002), and also because thermochronological methods may fail to conclusively resolve denudation geometries at plateau edges (Braun and van der Beek, 2004). The limited sensitivity of available methods consequently leads to indeterminacy (Spotila *et al.*, 2004).

Two extreme views currently define the range of possibilities: King (1955) considered that parallel retreat of the

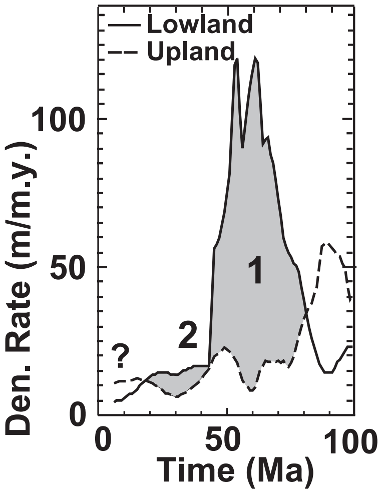

Figure 1. Birth of the Western Ghats (India). Apatite fission-track denudation curves seaward (Lowland) and landward (Upland) of the current escarpment show that between 90 and 40 Ma the coastal zone lost 3–4 km of rift shoulder while the upland lost only a fraction of that. Erosion of a tectonic rift shoulder (1) generated the Western Ghats, which is now the eroded stump of the original rift shoulder (2). Near equalization of erosion rates in- and outboard of the escarpment at fairly low values is interpreted as a balance between denudation rates landward and seaward of the escarpment, but detail of denudation history after 40 Ma is beyond fine resolution of the data (after Gunnell *et al.*, 2003).

Drakensberg escarpment had attained 150 km; meanwhile, Matmon *et al.* (2002) argue that rift escarpments become more sinuous due to unequal stream activity along strike, but do not recede much. An extremely common assumption, inherited from King's work, is that present-day escarpments are a direct legacy of the initial fault scarp generated at the time of continental break-up. The delayed topographic decay theory has therefore gained favour, and goes with the unquestioned assumption that PMEs are monogenetic, i.e. their presence in the landscape has been continuous since break-up. As illustrated for the Western Ghats in Figure 1, low-temperature chronology does suggest that escarpments form as a result of asymmetric erosion, and that escarpments are sustained by the isostatic imbalance driven by asymmetric erosion (Gunnell and Fleitout, 1998). However, as widely shown by the offshore sediment sequences of many passive margins (Coward *et al.*, 1999), rift-generated topography usually erodes within 30–40 m.y. of the rifting event. In the Western Ghats, the equalization of erosion rates between the coastal belt and the Deccan plateau after 40 Ma (Figure 1) thus marks the end of rift shoulder erosion and the beginning of a situation in which the subdued escarpment is merely preserved over time and evolves within a band of fluctuating denudation rates that are sufficiently low to evade resolution by current thermochronological methods. This suggests, therefore, that primary rift shoulders have a finite lifetime unless significantly re-energized later by new forcing processes. Vigorous regrowth of topography could be unambiguously detected in cases of total resetting of low-temperature thermochronological systems by deep erosion, but this is rarely if ever achieved (Braun and van der Beek, 2004). Instead, passive margin relief usually exposes partial annealing zones in which thermochronological datasets remain relatively noisy and hence difficult to interpret in detail.

Here, we hypothesize that elevated PMEs at rifted continental margins older than ~40 Ma are maintained by forcing mechanisms other than the original continental break-up event. Rather, they are perpetuated or resurrected by sporadic drainage integration. Our hypothesis hinges on one key premise: rift propagation and escarpment retreat are not random but follow anisotropic geological fabrics that are often parallel to ancient collisional belts (Tommasi and Vauchez, 2001). Anisotropy prevents uniform and wave-like propagation of headward fluvial erosion into the continent, increases the influence of erosion by streams parallel to the margin, and creates unsteady, nonuniform denudation at a range of passive margins.

This work examined the morphology of three margins on the Indian and North American continents. We first use space-for-time substitution along the strike of the Appalachian PME to observe nonuniform relief that implies unsteady erosion under strike-controlled geological hetereogenity. We then examine the strongly varying geological fabrics at the Indian margins to reveal the key role of geological structure in the style of escarpment recession at these geologically diverse, mature PMEs. The observations at all three margins converge toward a conceptual model depicting a phenomenon that may be widespread.

Erosional Morphology of Ancient Passive Margins

Geological outline of the Appalachians

The Central Appalachians are part of a 2000 km long, eastern North American highland formed in rocks involved in the Late Paleozoic collisional assembly of arc and continental fragments and later in Mesozoic rifting, leaving allochthonous terranes sutured to the Blue Ridge and foreland (Hatcher *et al.*, 1989). From the coast westward, topographic character is nearly coincident with geological zonation (Figure 2), consisting successively of the following geological belts: Mesozoic and Cenozoic sedimentary rocks of the Coastal Plain; metamorphosed, Late Proterozoic through Paleozoic clastic and volcanic strata plus Paleozoic intrusions form the allocthonous terranes of the Piedmont; west of the orogenic suture, the Blue Ridge anticlinorium comprises metamorphosed, late Proterozoic through lower Paleozoic clastics and volcanics plus Grenville-age basement; tightly-folded, Lower Paleozoic rocks in the ~160-km-wide foreland fold and thrust belt, in which Silurian sandstones are the predominant ridge formers and Cambrian-Ordovician carbonates create the Great Valley closest to the Blue Ridge; and comparatively horizontal Upper Paleozoic foreland basin sedimentary sequence of the Appalachian Plateau.

Distinct NE–SW physiographic provinces (Fenneman and Johnson, 1946) are almost directly defined by geological belts, with two significant exceptions (Figure 2). First, the Piedmont physiographic province extends from the Piedmont geological belt into the Blue Ridge rocks, particularly in central and northern Virginia. A prominent east-facing escarpment known as the Blue Ridge Front forms the western edge of the Piedmont south from Pennsylvania. However, the escarpment moves from the Blue Ridge rocks in the north into the Piedmont rocks in southern North Carolina. The escarpment is likely related to rifting starting in the Late Triassic (Withjack *et al.*, 1998), which formed a set of NE–SW half grabens through the Piedmont and Blue Ridge geological provinces.

The second way in which topography does not strictly follow geological division is in the Continental Divide. Drainage systems controlled by the Atlantic base level have established themselves mostly perpendicularly to this structural fabric and delivered sediment to the margin since the

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time of rifting. Since the early days of Appalachian geology (Davis, 1889), rivers have been thought to erode headward into the rift margin, reverse major streams and push the drainage divide toward the Appalachian foreland and basin. In Pennsylvania, the continental divide is 200 km inland from the rift basin cut obliquely into Blue Ridge rocks, and follows the highlands of the Appalachian Plateau. In southern Virginia, the continental divide lies in Blue Ridge rocks not more than 50 km from the nearest Triassic rift basin. South of the Roanoke River, the Continental Divide is nearly coincident with the Blue Ridge escarpment, but to the north, the steep escarpment between the Blue Ridge and Piedmont physiographic provinces is entirely within the Atlantic drainage basins.

Spatial patterns of topography, thermochronology, and evidence of changing erosion rate confirm these early ideas of retreat of the drainage divide into the continental interior. The Blue Ridge escarpment in southern Virginia exhibits a thermochronological signature characteristic of retreat (Spotila *et al.*, 2004) rather than plateau degradation *sensu* Braun and van der Beek (2004). Heavy mineral provenance studies (Naeser *et al.*, 2001, 2004; Braun *et al.*, 2003) in the coastal plain have been more persuasive in suggesting that integration of the Susquehanna River to the Valley-and-Ridge was pre-Miocene, and show that the Potomac drainage divide remained near the Piedmont–Valley and Ridge boundary until ~20 Ma, after which it migrated westward (Figure 2). Moreover, coastal plain depocentres shifted from New Jersey in Middle Miocene times towards northern North Carolina during the Pleistocene (Poag and Sevon, 1989), coincident with the current location of highest stream incision rates and local relief in the central Appalachian Valley and Ridge (Erickson and Harbor, 1998). Thus, a space-for-time substitution from south to north suggests the stepping of drainage divides across resistant units in the Piedmont and Blue Ridge, followed by wholesale capture of the strike drainage of the Valley and Ridge and headward extension into the Plateau.

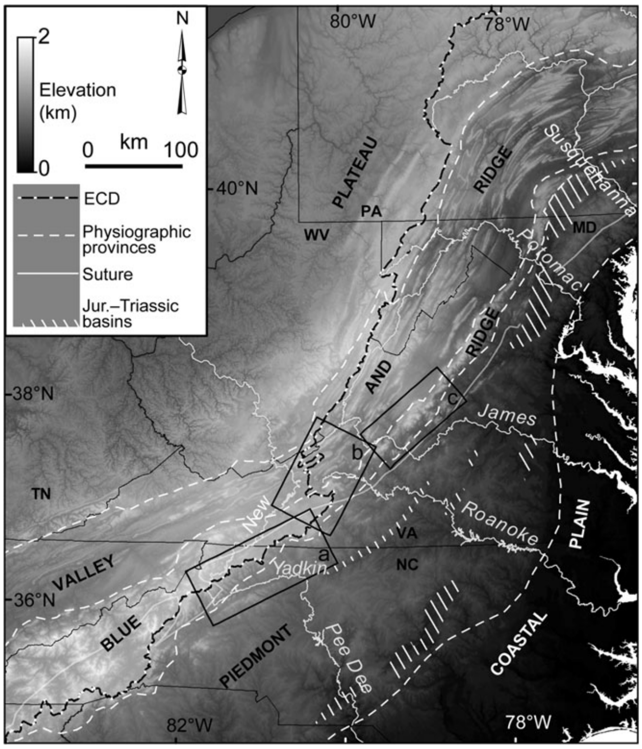

Figure 2. First-order zoning of Central Appalachian topography, drainage, and geology. Physiographic provinces are nearly coincident with geological belts except at the Blue Ridge escarpment. In the north, the Blue Ridge topography (dashed white boundary) is narrower than the width of the Blue Ridge rocks, but in the south the Blue Ridge physiographic province is wider than the region underlain by Blue Ridge rocks. Physiographic provinces follow Fenneman and Johnson (1946) and geological boundaries are after Hatcher *et al.* (1989). The eastern continental divide (ECD) jumps from the Blue Ridge northwest to the Plateau in south-western Virginia. Shaded relief from GTOPO30 data (USGS, 2004). Frames a, b, and c locate panels in Figure 5. VA: Virginia, NC: North Carolina, WV: West Virginia, PA: Pennsylvania, TN: Tennessee, MD: Maryland.

Geological outline of peninsular India

Peninsular India presents a comparably long girdle of highland topography fringing its western and eastern continental margins. It is known and conventionally subdivided into the Western and Eastern Ghats, respectively, because western India rifted away from Madagascar at ~80 Ma, but eastern India rifted from Antarctica much earlier, at ~130 Ma. As in North America, rifting roughly followed the fabric of either pre-existing orogenic belts such as the Panafrican belt (Acharyya, 2000; Raval and Veeraswamy, 2003), or Archean granite–greenstone fabrics. The geological underpinnings of the Western Ghats escarpment (WGE) north of the Palghat Gap (Figure 3) can be divided into three broad sections: the homogeneous Deccan traps in the north; a central belt comprising heterogeneous, folded rocks of the Precambrian craton; a variable, but uniformly resistant highland underlain fractured high grade metamorphic rocks in the south. The Eastern Ghats is developed in igneous and granulite facies metamorphic rocks in the south changing to a Proterozoic fold belt north of 14°N. The folded and faulted structural roots of these units inherited from the assembly and subsequent break-up of Gondwana have been sculpted by differential erosion into valley-and-ridge landforms (Figures 3 and 4d), particularly in the northern Eastern Ghats.

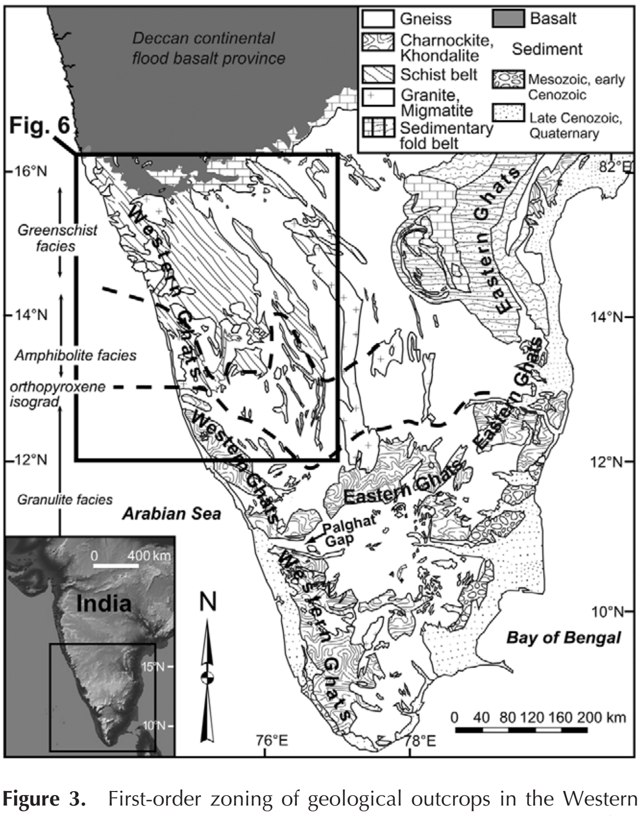

Figure 3. First-order zoning of geological outcrops in the Western and Eastern Ghats. Note belted outcrop systems even at this simplified scale.

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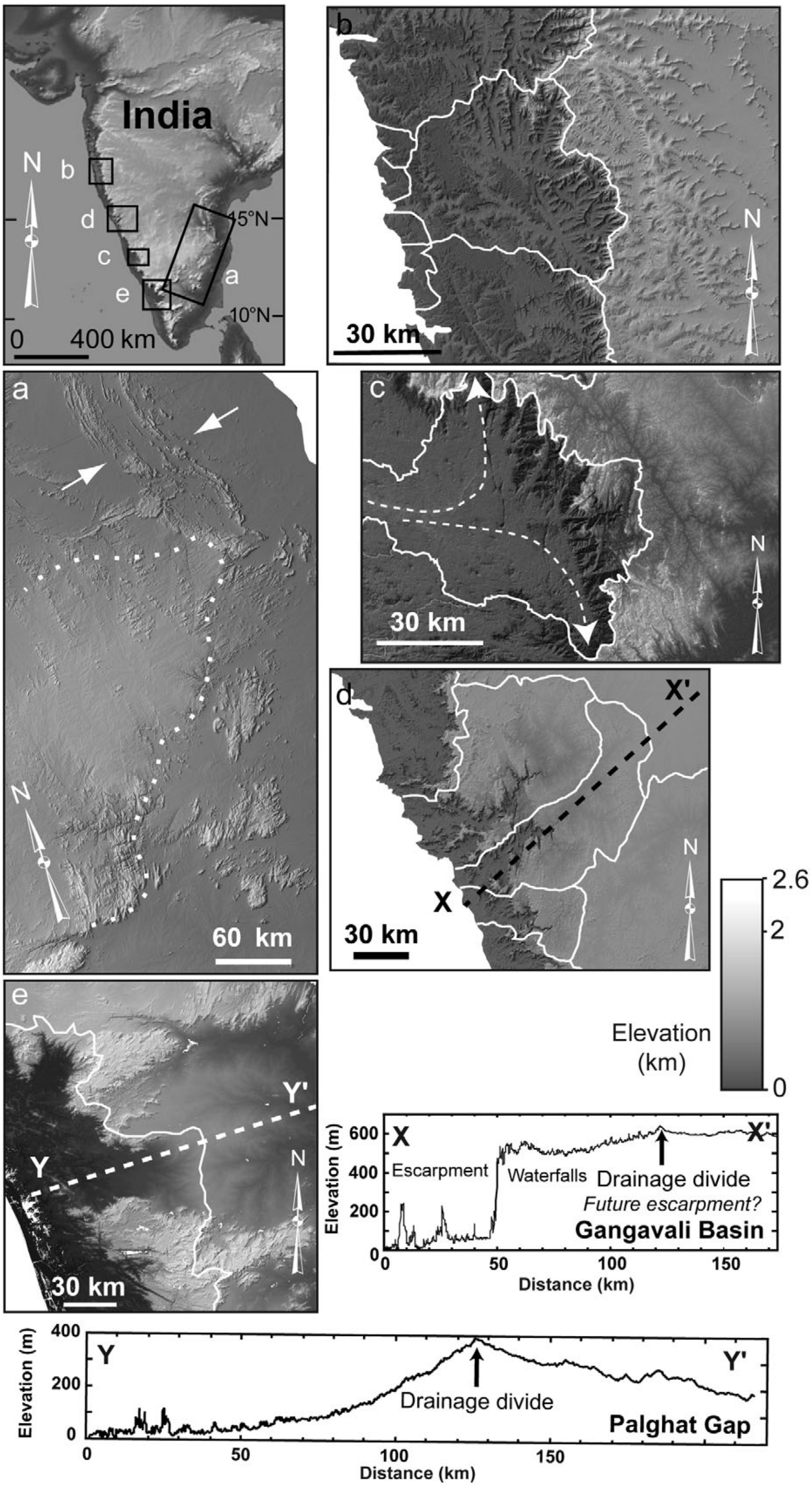

Figure 4. Structure, topography and drainage instability at the Eastern (a, white dashes) and Western Ghats (b–e) escarpments. Maps derived from SRTM (2004). (a) Divide-type margin in the Deccan basalts; note orientation of strike-parallel valleys both in the coastal plateau and the upland, suggesting strike-parallel fractures within the lava pile. Note threat of (c) and consequence of (d) drainage capture in Precambrian granite-greenstone terrain. In (c), note strike-parallel drainage on the plateau, prefiguring drainage capture by the receding continental divide. Embayed escarpment in (c) reflects the ballooning (arrows) of watershed boundaries into the plateau edge. Deep drainage embayment with gorges in (d) is due to divide repositioning: section X–X′ prefigures an 'escarpment in tatters' as seen in (a), hence also providing insight into past states of the Eastern Ghats (a) where the escarpment has bypassed a fold belt (arrows) and resistant buttes (SE corner). (e) The Palghat Gap, a topographic ramp (Y–Y′) caused by drainage asymmetry, but not an escarpment. Note clear link with the absence of lithological heterogeneity or transverse geological structures. Solid white line (all panels): drainage divide.

Drainage networks and escarpment morphology in the Central Appalachians

We begin by observing the nature of drainage basin and escarpment morphology and the relationship between the drainage network and patterns of high relief or erosional potential to outline common responses at disparate geological margins. In the Piedmont, Blue Ridge, and Valley and Ridge, major streams, drainage divides, and drainage basins are focused along strike by fault zones (Yadkin and James rivers) and strike-parallel changes in bedrock resistance (New and Potomac rivers), even though the ultimate course of each drainage network is across the structural grain (Figures 2 and 5). The continental divide and the Blue Ridge Front, both steep escarpments topped by more gentle uplands, also generally fall along strike at major structural trends, except where the continental divide cuts across the Valley and Ridge. Regardless of its location relative to geological boundaries, the continental divide is characterized by asymmetrical relief juxtaposing uplands against incising Atlantic drainages. Relief is more than 200 m in Valley and Ridge carbonates and approximately 600 m in crystalline rock. Relief on the Blue Ridge Front approaches 1 km, and is usually 500 m or more.

The PME exhibits a variety of forms where it is located in the Blue Ridge. At some locations near the headwaters of the Yadkin River (Figure 5a) it is a strike-parallel, relatively linear but with scalloped indentations, very narrow (<2 km), steep scarp separating low-relief, low-order basins of the New River basin from the Atlantic drainage. Other locations exhibit a wider, more complexly incised landscape with narrow gorges and protruding headlands separating the Blue Ridge upland from the Piedmont drainage. In these areas where the drainage divide and escarpment are locally separated, streams have gentle profiles until they plunge off the escarpment,

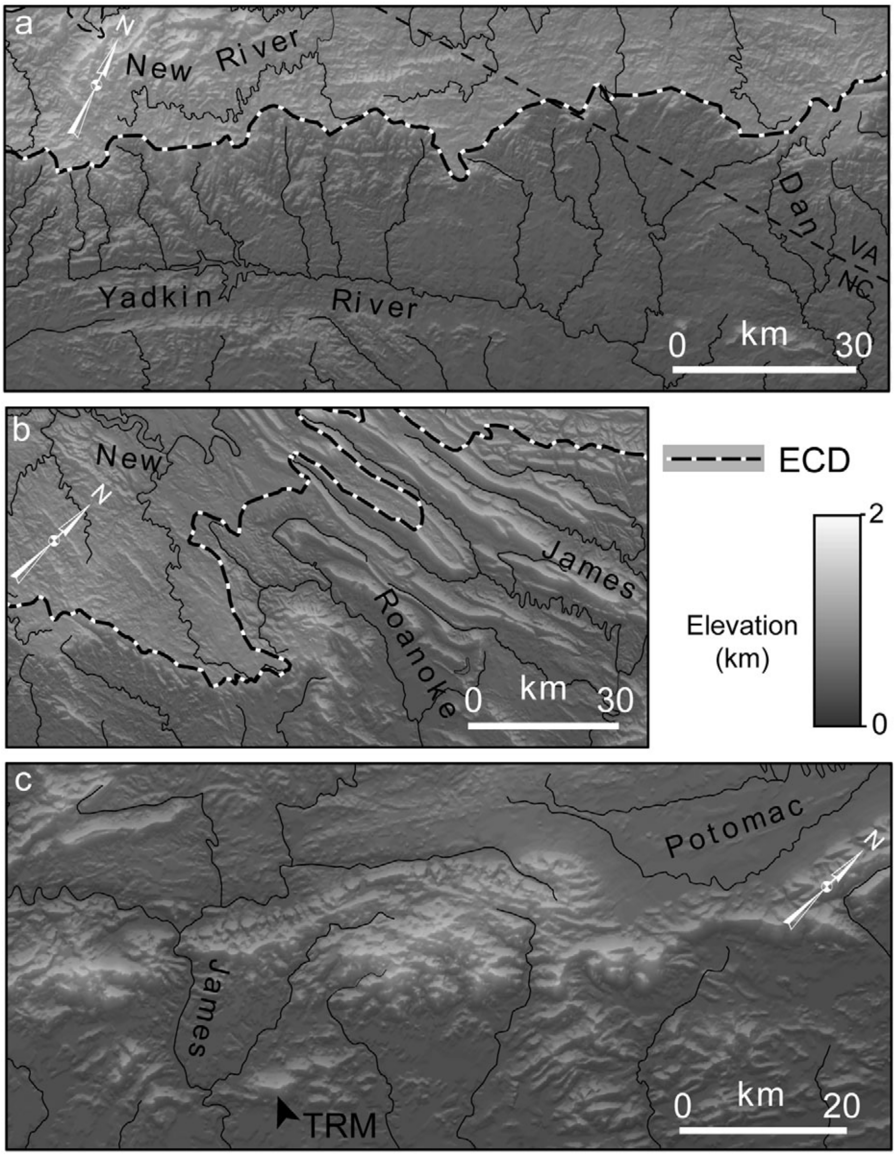

Figure 5. Detailed topography of the Appalachian margin showing the jump in the drainage divides (ECD) and butte detachment. (a) Headward retreat ornaments an escarpment formed by capture of the Yadkin strike valley while encroaching on strike drainage of the Blue Ridge. The Dan River has captured a tributary of the New, leaving a gorge and a separation between escarpment and drainage divide. (b) Butte detachment occurs by escarpment outflanking via softer rocks of the Great Valley carbonates of the Valley and Ridge, leaving a low-relief upland of Blue Ridge rocks flanked on three sides by erosional scarps. (c) Substantial capture events isolate large buttes and permit rivers to dissect the upland from behind, as is likely to occur when the upper Roanoke and James rivers capture the northwest-flowing New River (see (b)). Here the tributaries of the James are consuming the last of the low-relief uplands in the Blue Ridge butte. TRM: Tobacco Road Mountains, a detached butte. Shaded relief from 3-arcsecond data (USGS, 1996).

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descending several hundred metres of elevation in less than 10 km. Farther south in North and South Carolina, the PME is highly sinuous where cross-strike geological weaknesses steer major upland drainage, and escarpment streams carve narrow gorges along strike.

Inselbergs, or buttes, in resistant units occur seaward of the escarpment south of the Roanoke River (Figure 5b), and east of the Blue Ridge escarpment farther north. They develop in locally resistant rocks – like the Tobacco Row Mountains immediately north of the James River and just east of the Blue Ridge escarpment (Figure 5c) – but can be surrounded by other rocks of similar resistance that do not stand as high. The buttes are separated from the escarpment by strike drainage, and some have low-relief summits.

The scale of variability in scarp morphology and location and in butte size changes abruptly where the Roanoke River is the southernmost Atlantic drainage to reach the weaker rocks of the Great Valley. Here, the degree of scalloping of the PME reaches many tens of kilometres by looping behind the Blue Ridge. The escarpment locally follows resistant ridges through the upper Roanoke and James River headwaters but cuts deeply into fractured and folded, nonresistant shales and carbonates towards the New River. The Blue Ridge upland between the incising headwaters of the Roanoke River is nearly detached from the rest of the Blue Ridge high topography by streams cutting into it from the east and west. North of the James River water gap through the Blue Ridge (Figure 5c), the Blue Ridge upland itself has a butte morphology, comprising a low-relief upland surrounded by erosional escarpments cut into the eastern and north-western margins. Following the Blue Ridge along strike to the north-east, this upland grows narrower and then disappears as the Blue Ridge relief decreases into Pennsylvania. To the north-west, the continental divide escarpment is nearly coincident with a major structural boundary at the edge of the Plateau, with only minor scalloping where Potomac River headwaters drain the Plateau out through the Valley and Ridge.

Drainage and morphology in south India

The control by geological fabric of strike-parallel geomorphic features that is so characteristic of drainage basins and escarpments in the Appalachians takes a wider variety of forms in the Indian subcontinent (Figure 4). Where lithology is homogeneous, as in the Deccan basalts (Figures 3 and 4b), streams generally follow the regional slope away from the escarpment. Fault and fracture lines generate strike-parallel valleys along the plateau edge of only minor length or integration. When lithology is heterogeneous, as in the Precambrian craton (Figures 3 and 4c, d), opportunities for larger, strike-parallel drainage are again provided by fracture patterns (Figure 4c) but also by sharper contrasts in resistance between rock units (Figure 6). Where the WGE and continental divide coincide, the PME is located on geological boundaries where supracrustal fold structures dip steeply eastward and consist of quartzite, metabasalt and banded iron. In the gorge-type segments, i.e. where escarpment and drainage divide separate and hinterland streams flow toward the escarpment (Figure 4d), schistosity strikes N143° with easterly dips of ~50° (Durg, 1969) and explains the hogback-like form of the escarpment. However, the resistant bands of the supracrustal fold belts are

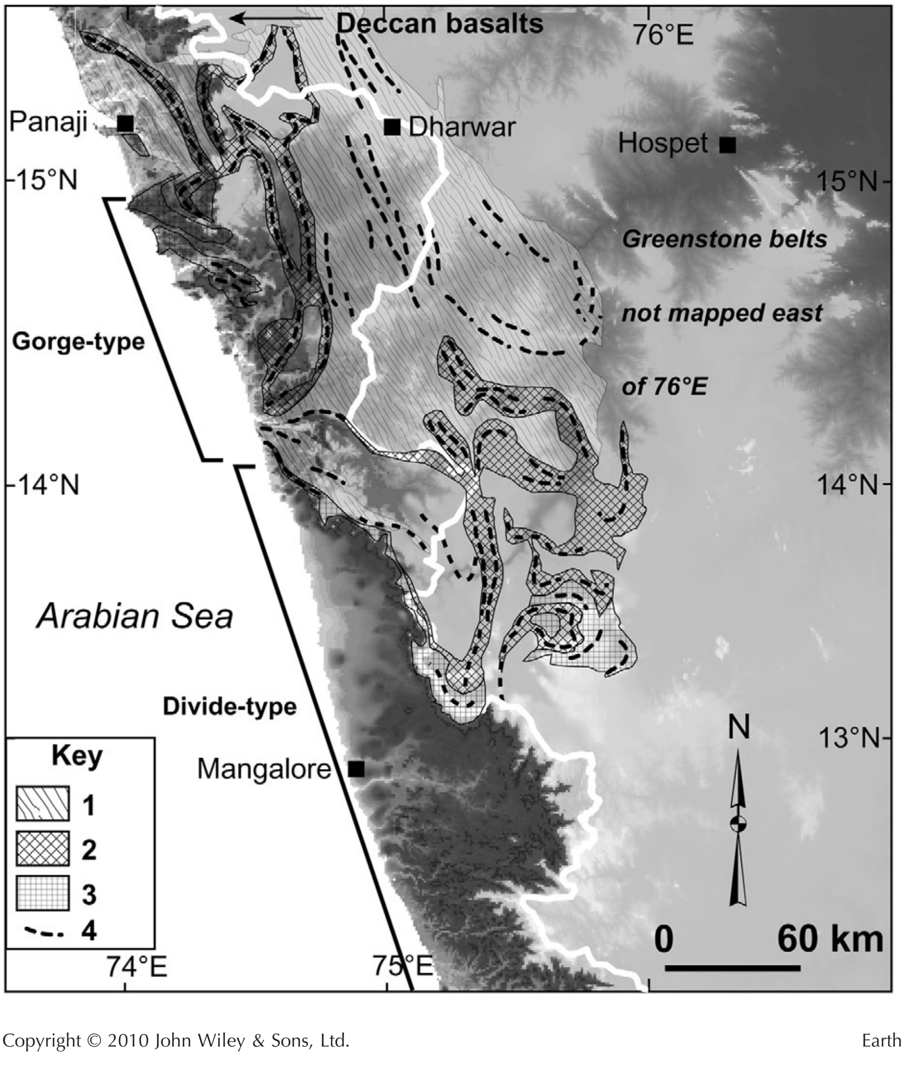

Figure 6. Gorge-type and divide-type scarp segments in the Western Ghats in relation to scarp-parallel geological structures and simplified lithology (after Geological Survey of India, 1981). The topographic elevation base map (derived from GTOPO30 digital data) has been enhanced so as to bring out higher elevations in white and lighter grays, and lower elevations in darker grays. Inroads made by expanding drainage, whether from west or east, are clearly apparent. Ornaments of the simplified geological overlay are restricted to the greenschist and amphibolite facies outcrops of the Dharwar craton, but show the spatial distribution of resistant rocks. Key to ornaments: 1 metagreywackes and meta-argillites; 2 schist and banded iron formation (BIF) or banded ferruginous quartzite (BFQ); 3 metabasalts; 4 BIF, BFQ or conglomerate beds forming prominent topographic ridges north of 13° latitude. Gneiss and granite oucrops are left transparent. Note how continuous girdles of resistant rock still pin the escarpment in the divide-type area, while others have already been cleared by rivers in the coastal belt in the gorge-type zone. Others, further inland, still await drainage divide repositioning. The gorge section is located where virgations and pinch-outs in the resistant metamorphic girdles occur. Also note how drainage basins have made inroads or deepened where granitoid rocks occur. South of 13° latitude, the craton is dominated by granulite facies rocks in which charnockites buttress the divide-type escarpment whereas gneiss, as further north, behaves as the softer lithology.

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discontinuous (Figure 6), which explains opportunities for gorge cutting and drainage ingress into the plateau (Harbor and Gunnell, 2007; Gunnell and Harbor, 2008). The spatially dominant lithologies are also weaker (meta-argillites), which seems conducive to the formation of larger drainage networks.

Substituting space for time, the Eastern Ghats passive margin escarpment sharpens the insight by extending the appreciation of escarpment development to an older margin. The plateau edge is nearly twice as old as the Western Ghats and never forms a continental drainage divide. Whereas the younger Western Ghats are still predominantly a divide-type PME (*sensu* Weissel and Seidl, 1998), rivers overpass the Eastern Ghats from the interior plateau forming a rugged terrain of ridges, passes, buttes and gorges (Figure 4a). Escarpment-like segments are defined both by lithological boundaries and by bands of high relief pocked by deeply incised valleys. In the structurally more homogeneous southern section, large charnockite buttes, cut out along Precambrian shear and fracture zones, have detached from the plateau (Figure 4a). These buttes have 500 to 800 m relief, are drained by low-order streams with extraordinarily steep knickpoints, and are very sharply defined. In the more heterogeneous fold belt of the northern Eastern Ghats, incision leaves high relief on the quartzite ridges (Figure 4a) as incision currently carves into the crystalline rocks of the interior craton.

A butte-detachment model of passive margin escarpment retreat

We begin our conceptualization of an evolutionary model in the Appalachians and seek further illustrations from the Ghats. Divide migration resulting from asymmetry and drainage capture have been proposed for the Central and Southern Appalachians for over a century (Davis, 1903; Wright, 1927; Thompson, 1939; Dietrich, 1959). The engine of escarpment retreat is the local asymmetry of the divide that we observe along the Appalachian continental divide. Given that divide migration illustrated by the south to north space-for-time substitution continues, the variation in processes is found in the topography. In North Carolina and southernmost Virginia, the Blue Ridge escarpment may appear to be eroding by simple headward retreat, as modelled by Spotila *et al.* (2004). Low-order basins compete with one another along a scalloped linear front (Figure 5a) and given greater overall erosion of the steeper escarpment streams, the divide is modelled to migrate slowly landward (Tucker and Slingerland, 1994). Notably, even though escarpment retreat has been documented (Wright, 1927; Spotila *et al.*, 2004), slow headward retreat of the escarpment as a whole has not been confirmed by process studies at the Blue Ridge escarpment. If, instead, the divide is currently pinned on more resistant units within the schists and gneisses where the escarpment is narrow, then relief at the divide is progressively sharpened rather than moved by the differential erosion. The idea that the escarpment does not migrate so much as it becomes more asymmetric is shown by the contrast between the northern and southern sections of the Blue Ridge escarpment at the Virginia–North Carolina state line (Figure 5a). The PME here is flanked by orogen-parallel rivers following major orogen-parallel faults (Yadkin River) or weaker lithological units along the strike of the Blue Ridge (New River). These strike streams could not have evolved by slow divide migration.

If the escarpment migration is not dominated by the slow retreat of drainage divides, then the retreat must, instead, involve jumping and reforming. Headward retreat is not everywhere impeded completely, and so by headward erosion, both small and enormous drainage basins can be diverted by escarpment streams. Incision of the captured basin, particularly where it occupies a long strike basin, isolates and detaches an upland butte along the former divide as it jumps to the plateau edge of the drainage basin. By ‘butte’ we mean here any topographic outlier inferred to have been connected to the eroding plateau in the past regardless of shape or size. Buttes are being cut out along the length of the Appalachians, but form persistent features only in resistant lithology.

The butte detachment process is well illustrated in southern Virginia, where the continental divide shifts 60 km northwestward from the Blue Ridge to the western edge of the Valley and Ridge (Figure 5b). Capture of Valley and Ridge drainage (Roanoke and James rivers) abruptly transferred the drainage divide to the boundary of the Appalachian Plateau, leaving detaching or detached buttes south of the Roanoke River (Figure 5b) and surrounding the James River water gap through the Blue Ridge (Figure 5c). On the south-east side of these buttes, the Blue Ridge escarpment attains nearly a kilometre of relief, while incision through Valley and Ridge carbonates has carved a similarly steep precipice to the north-west. The Blue Ridge north of the James River still retains pockets of low-relief upland that characterize the escarpment edge in southern Virginia and North Carolina. That upland disappears even farther north-east as the butte is attacked at both flanks by drainage. Unless they are lithologically controlled hills, the degraded buttes to the south-east of the escarpment in the Piedmont are likely to be the remnants of an even older divide jump. For example, a high relief remnant located seaward of the Yadkin River has been separated from the Blue Ridge upland by the stream system and has developed in a major Appalachian shear zone. Another example is the previously mentioned Tobacco Row Mountains north of the James River.

The Appalachian topography clearly shows that the continental divide is propagating westward, but the position of the escarpment itself is controlled by major jumps in the drainage divide. Where divide migration occurs by headward erosion (Figure 4b), it merely ornaments the divides created by capture and butte detachment (Figure 5) until a new weakness is exploited and a new basin is captured. We propose that if PMEs are likely to persist after erosion of the initial rift shoulder (*cf* Figure 1) it is principally because scarp-parallel bedrock landforms control drainage expansion. Extensive resistant rock outcrops found preferentially at basin boundaries impede scarp recession, while localized structural weaknesses and strike-oriented drainage enable capture and divide jumping (Gunnell and Harbor, 2008). These two structural conditions maintain escarpment steepness in the face of an expected tendency for PMEs to dissect and degrade.

The escarpment morphology of the Indian Ghats provides further evidence for butte detachment as a process critical to both PME persistence and retreat. The Deccan basalt section of the Western Ghats lacks lithological heterogeneity but the layer-cake structure promotes headward erosion and small-scale drainage capture as mechanisms of retreat for both the drainage divide and the escarpment. Accordingly, the PME is relatively linear but highly fretted or scalloped by headward erosion, forming a steep, very narrow zone, in part facilitated by flexural uplift (Gunnell and Fleitout, 1998) focused on the PME.

In the presence of stronger lithological heterogeneity and weaker rocks able to be exploited as larger drainage basins (Figure 4d and Figure 6), drainage capture is more readily facilitated, larger buttes become detached, and the escarpment and continental divide become separated (Figure 4c, d Figure 7 stage n° 3, and Figure 8b). Depending on the type of

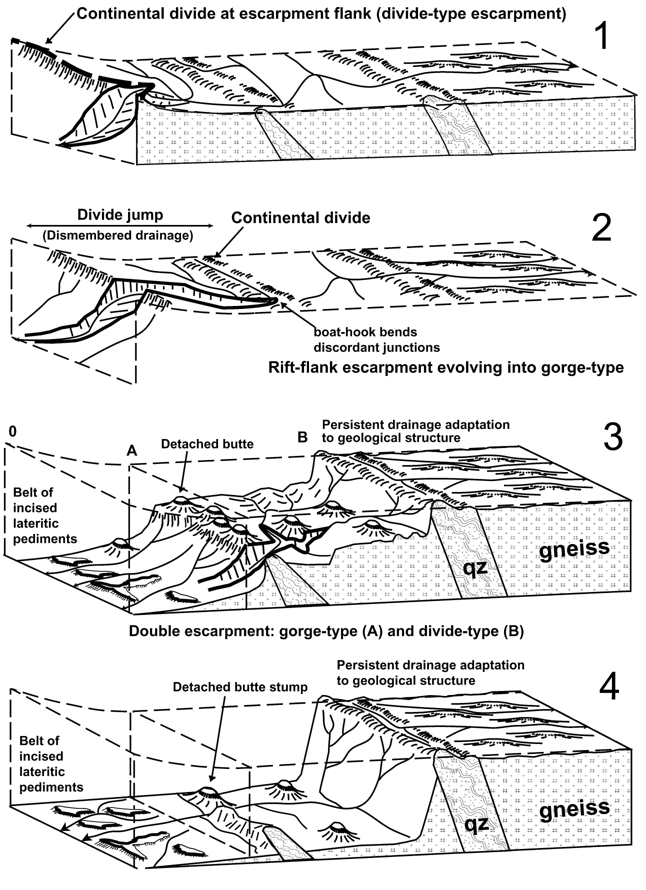

Figure 7. Gorge-type and divide-type system states at the Western Ghats escarpment and their plausible succession through time. Space-for-time substitution suggests that valid examples of this occur worldwide, such as the Eastern Ghats and the Appalachians. In stage 4, note that the butte stump illustrates only one possible state of degradation. The elevations of other buttes abandoned in the trail of the receding escarpment may still be concordant with the plateau edge, as in parts of the Blue Ridge (Figure 5). If entirely eroded (and if, for instance, detected as such by thermochronological data), they might be referred to as 'ghost' buttes.

obstructing geological structures, drainage recession occurs faster at some sites than at others. Due to structural opportunities for rivers to cut back into the plateau edge, competing drainage basins are varyingly successful at expanding into the hinterland and outflanking each other. The result is the emergence of Type-1 streams, that are short and rise in the coastal plain itself, and Type-2 or scarp-front streams, that drive the scarp migration process (Figure 9) and potentially make major inroads into the plateau. In the case of plateau drainage piracy, they become hinterland streams (*cf* Figures 4d and 8b).

Divide retreat by capture in the crystalline highlands section of the Western Ghats (Figure 4c) would produce topography like the southern section of the older Eastern Ghats where resistant buttes are separated from the erosional wave farther inland (Figure 4a). These buttes remain due to their extreme resistance and the likely presence of thresholds of erosion in the escarpment retreat process. The buttes in the comparatively weaker rocks of the Blue Ridge in southern Virginia (Figure 5a) are more degraded, lacking this threshold condition that keeps the high relief at the butte edge. Elongate 'buttes' caused by divide jumps across the Proterozoic fold belt in the northern Eastern Ghats (Figure 4a, arrows) might have germinated in a landscape that looked much like the gorge segment of the Western Ghats (Figure 4d, X–X′). The gorges heightened into either valley-and-ridge topography in the northern Eastern Ghats, or detached to form the isolated buttes of the south where rock type is more homogenous. The more pronounced heterogeneity and along-strike basin orientation occurring in the northern Eastern Ghats as well as the Appalachian Valley and Ridge have facilitated escarpment retreat over a greater distance than in areas of more homogeneous rocks, analogous to the variability in divide-to-escarpment distance of the Western Ghats.

Of critical importance to the idea of a metastable divide episodically driven into the continental interior is the rate of basin deepening, or time from drainage capture to divide-repinning, in comparison with escarpment age. Although one does observe basins in the midst of an excavation event following diversion at both the Appalachian and Western Ghats margins, it is clear that captured basins can be quickly eroded

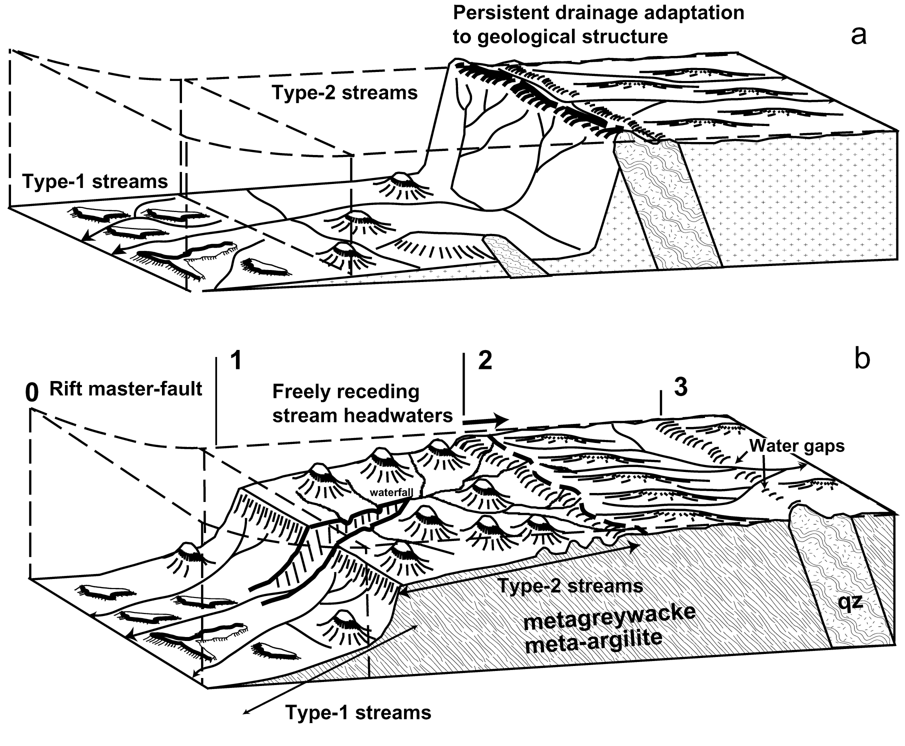

Figure 8. Sketch diagrams of the gorge-type and divide-type situations encountered at the WGE. (a) Divide-type escarpment, in gneiss, typical of the situation observed between 12 and 14°N where the escarpment is pinned by a girdle of resistant quartzites and metabasalts. The belt of lateritic pediments (grey mesas) is also observed in the Deccan volcanic province. By analogy with situation (b), it is suggested to mark a former trace of the escarpment (Harbor and Gunnell, 2007). (b) Gorge-type escarpment, in schist, typical of the situation shown in Figure 4c. Eroded rift shoulder now corresponds to coastal belt, with residual escarpment at position n°1. Residual escarpment n°1 is cut by a gorge. The current drainage divide is situated farther back on the plateau, where it is forming a cyclic knick-zone and escarpment at position n°2. Position n°3, where a girdle of quartzite (qz) occurs, is likely to pin the migrating divide and generate a future escarpment at that location.

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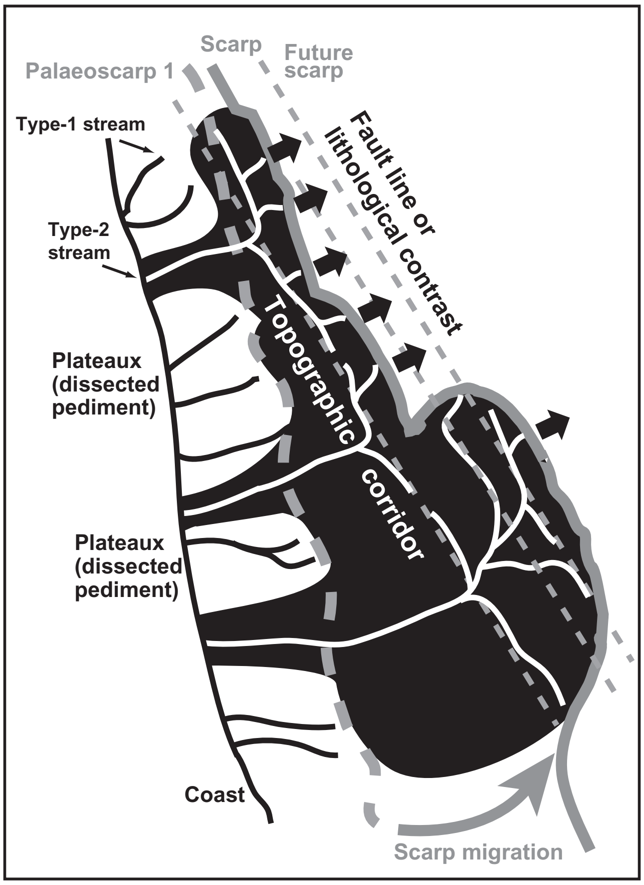

Figure 9. Sketch summarizing the distinction between Type-1, or coastal-plain catchments (white areas, black drainage) and Type-2, or scarp-front catchments (black areas, white drainage) (see Figures 4b and 4c). This scenario is equally valid for the Deccan basalts and the Precambrian craton. The increased distance of divide migration in the bottom portion of the escarpment follows on the prominent strike-oriented drainage that facilitates retreat (compare with real-world settings of Figures 4 and 5).

down to base level as the escarpment relocates to the interior basin margin. Bishop *et al.* (2005) and Crosby and Whipple (2006) document transient landscapes responding to incision events where knickpoints generated by base level fall migrate upstream in proportion to drainage basin area. These studies yield very rapid knickpoint migration, in part because they reflect erosion of relatively weak materials in a postglacial landscape where knickpoints migrate on the order of 10 km ka^{-1} in 100 km^2 basins. These rates do not represent knickpoint retreat by bedrock erosion on passive margins, which are orders of magnitude less at rates of just metres per ka (Nott *et al.* 1996; van der Beek *et al.* 2001; Haviv *et al.*, 2006) for comparably sized basins. Harbor *et al.* (2005) find that basin area exerts a first-order control on knickpoint retreat, making it reasonable to assume that knickpoint migration rate is a nearly linear function of drainage area (Bishop *et al.*, 2005).

Combining these findings permits the prediction of the excavation of a captured basin (Yadkin River, see Figure 5a). Calibrating the retreat rate for a 100 km^2 basin to other passive margin rates (1 m ka^{-1}) shows the potential speed of basin excavation in these settings (Figure 10). The interior of the basin is hollowed out in 1 to 10 Ma but the outstanding butte remains prominent for tens of millions of years while the upper reaches of the escarpment tributaries become increasingly sharp if the divide remains pinned. The details of slope form and escarpment character depend on many factors beyond simple stream power control of knickpoint migration (Tucker and Whipple, 2002; Baldwin *et al.*, 2003), but even this crude model suggests that basin jump and butte detachment processes represent just a fraction of the timescale of passive margin persistence.

In the Indian setting, our case for the importance of escarpment-parallel structures in ensuring the permanence of escarpment topography at passive margins is verified by their absence in the Palghat Gap, a 30 km-wide topographic breach through the Western Ghats defined by the scarp-perpendicular Palghat–Cauvery Precambrian shear zone (Figure 4e). Not a

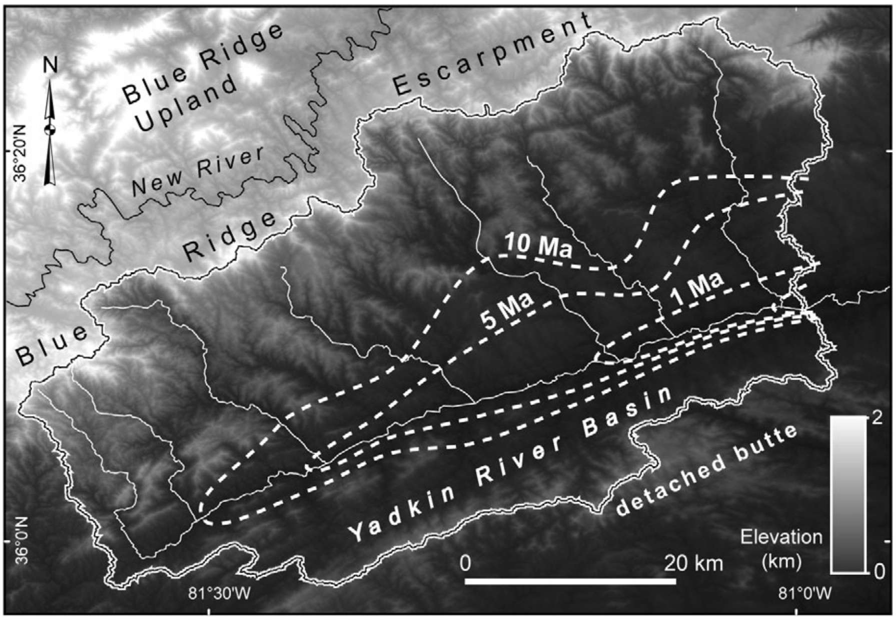

Figure 10. Digital topographic map (elevation ranges from 1350 to 300 m) showing the outline of the digitally-derived drainage network for the uppermost part of the Yadkin River basin (see Figure 5a for location). Given the hypothetical capture of this strike-oriented stream, the dashed lines show the position of the knickpoint migrating through the basin, assuming a simple law of knickpoint retreat given by $v = cA^p$, where v is the knickpoint migration rate (m yr), c is a coefficient calibrated to yield a retreat rate of 1 m ka^{-1} (in this case, 10^{-13}), A is the drainage area (m^2), and p is 1·125 after Crosby and Whipple (2006). The results show that the drainage basin is excavated quickly (<10 Ma), but the butte persists and the steepening of the new escarpment could be a very long-lived stage.

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single strike-parallel geological structure is present to impede drainage recession or pin the continental divide at that location. A topographic asymmetry is generated by the drainage asymmetry, but the resulting topographic ramp on Section Y–Y′ (Figure 4) answers by no means to the description of an escarpment. This observation in the Palghat Gap suggests that PMEs cannot be generated or maintained for periods of geological time exceeding ~40–50 m.y. without some structural control. Based on this evidence, we propose a qualitative model in which the relative positions of resistant and weak structures determine the modalities of scarp evolution.

Discussion

Surface process models usually seek generality and simplicity, and for that reason will tend to treat local variability as noise. We have argued instead that geological structure and lithological heterogeneity make a critical difference in patterns of scarp recession and scarp longevity because they constitute major internal forcing factors in long-term escarpment dynamics. In weathering-limited cratonic landscapes, structural predesign underprints drainage networks and focuses fluvial erosion, but resistant geological masses also extend timescales of topographic decay by obstructing drainage recession. This accentuates the already abrupt spatial juxtaposition between plateau and scarp erosion rates that otherwise typifies passive margins. Even at low scarp retreat rates, scarp erosion by streams encounters small to enormous drainages, creating episodic drainage capture. At the WGE and in the Appalachians, autocyclic reenergizing of topography occurs because rapid differential erosion in the humid climate allows relief to regrow around girdles of resistant bedrock. Accordingly, denudation patterns along strike are nonuniform through time.

Expected trends in the thermochronological record seaward of the WGE, such as age younging (or, conversely, age uniformity) from the coast to the scarp foot, fit end-member models of scarp recession that are only conceivable within narrow, geologically homogeneous topographic swaths. Instead, and not unlike other margins (Spotila *et al.*, 2004; Braun and van der Beek, 2004), in the Western Ghats we observe a scatter of fission-track ages between the coastline and the WGE (Gunnell *et al.*, 2003). This pattern suggests the importance of variability due to local, gorge-like fluvial incision and associated lags in denudational response of buttes trailing in the wake of gorge recession. Such age dispersion is partly attributable to the fact that PMEs expose apatite partial annealing zones in which track annealing and age scatter are the rule, but it is also consistent with the idea of spatially nonuniform denudation rates within competing paleodrainage basins contending with strike-parallel geological obstacles (Figure 9).

We also observe in the Western Ghats that it is where the strike-parallel structural backbone is weakest (i.e. where strike-parallel greenstone belts pinch out between 14 and 15°N, see Figure 6) and lithologies are weakest (low-grade meta-argillites) that escarpment topography is lowest (~0·4 km a.s.l.) and that monsoon influence from the west penetrates deepest into the plateau. Drainage capture there is at its most effective, and this area corresponds to the highest concentration of deep gorges and waterfalls along the entire WGE. The consequences for sediment routing to the continental margin of gorge cutting and drainage diversion from the plateau are felt in the offshore sediment record. At the latitude of the gorge-type section of the Western Ghats (see Figure 6), thicknesses of late Neogene and Quaternary sediments detected in the few existing offshore exploration wells are higher than anywhere in boreholes occurring seaward of the divide-type portions of the escarpment (Gunnell, 2001). This suggests that gorge cutting was rapid, occurred in the last 10 Ma or less, and therefore scales with the crude calculations of knickpoint retreat and basin excavation presented earlier and in Figure 10.

In the case of the Central Appalachians, our qualitative model is tentatively supported by sediment provenance stratigraphy in the coastal basins (Naeser *et al.*, 2001, 2004; Braun *et al.*, 2003). It suggests that geological structure is a pace-setting parameter in scarp evolution. Escarpments are thus neither stagnant (Matmon *et al.*, 2002) nor in topographic steady state (Gilchrist and Summerfield, 1990): landscape evolution is punctuated, with pulses of sediment output that mirror the sequence of drainage expansion into the continental interior. Structural impediments to drainage generate pauses in denudational signals and force erosion to focus around weak points. In India, for instance, climate has been relatively homogeneously humid seaward of the Western Ghats since at least 15 Ma (Gunnell, 1998b), and possibly since 24 Ma (Clift, 2006). Thus it can be assumed that energy expenditure per unit stream length is uniform. However, geological heterogeneity acts as a gatekeeper locally controlling scarp sinuosity, incision rate, and effective rates of scarp migration.

Due to structural controls and drainage jumps, escarpments can degrade or steepen both successively in a given strike segment (*cf* schematic in Figure 7, based on observation in the Western Ghats; see also Figure 4d, section X–X′, perhaps leading to the condition shown in Figure 4a and simultaneously in adjacent segments (Figure 4b, c, d). This pattern could explain the local heterogeneity of low-temperature thermochronological ages commonly observed seaward of PMEs (Gunnell *et al.*, 2003). In the Appalachians, Spotila *et al.* (2004) document an apparently incoherent geographic distribution of apatite-helium (AHe) ages where topographic evidence argues, in our view, for ongoing butte detachment seaward of the current Blue Ridge escarpment (Figure 5).

In the plateau degradation model of long-term rifted margin evolution (*cf* Braun and van der Beek, 2004), drainage at the time of rifting remains pinned at some location in the hinterland for unrealistically long periods of geological time (Brown *et al.*, 2002), and the escarpment arises from the erosion of a plateau mass occurring between the pinned continental divide and the rift master fault. Our emphasis on geological structure highlights instead the fact that PMEs neither just recede in wave-like fashion, nor simply erode a plateau edge between arbitrarily fixed boundaries, or 'pins'. Instead of these end-member scenarios, scarps jump repeatedly. Our butte detachment model therefore also draws attention to the futility of calibrating the recession rates of continental-scale escarpments using, for instance, waterfall or knickpoint recession rates measured over very short geological time scales. Following captures that produce escarpment jumps, gorges form and drainage basins deepen while the innermost divide sharpens along preexisting strike-parallel ridges formed in resistant rock. The buttes along the outer margins of the newly annexed basin degrade faster because they are surrounded by a lower base level. In this way, scarp migration over the long term may occur across distances greater than 100 km. As a result, King (1955) was potentially correct about magnitudes of recession, although probably not about process (i.e. parallel scarp retreat).

Mean rates have no realistic meaning in the face of escarpment jumps and episodically switching boundary conditions. Just as some segments jump, girdles of resistant rock at other sites may limit scarp recession to <10 km over the same time

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interval. This gives equal credence, although only in a local sense, to the views of Matmon *et al.* (2002), who argued that escarpments are mostly static. Given that strike-parallel resistant structures have finite length due to faults, plunging fold noses, pinch-outs, cross-cutting shear zones etc. – as commonly observed in the Appalachians but also the Eastern Ghats, Western Ghats, and probably other margins – scarp-modifying drainage basins at more active segments of the escarpment eventually outflank the girdles of resistant rock at adjacent, less dynamic scarp segments. Maximum drainage activity and scarp repositioning thus continues to operate from the rear, effectively leaving the previous escarpment in the position of an outlying butte. Viewed at the broadest scale, or at the low resolution of thermochronometry, this is steady state retreat, but in geomorphic detail it is highly nonuniform. Others have shown escarpment jumps (Pazzaglia *et al.*, 2002), and have hinted at the change of divide types through time (Weissel and Seidl, 1998) or opportunity for piecemeal capture to accomplish retreat (Spotila *et al.*, 2004), but the process as a pervasive, controlling, and arguably general aspect of PME evolution has not been recognized.

In the Introduction, we suggested that external forcing factors, namely tectonics and climate, merely act to modulate a self-driven geomorphic process of drainage integration. As with tectonically produced topographic asymmetry, climatic asymmetry as an engine for scarp persistence can be significant. For instance, even though the Western Ghats escarpment cross-cuts three distinct geological provinces of late Mesozoic, Archean and Proterozoic age, its topographic unity is at least partly determined by climatic asymmetry as a driving mechanism of escarpment retreat because the outboard receives the monsoon rainfall while the inboard is uniformly much drier (Harbor and Gunnell, 2007). In generic terms, however, climatic forcing also becomes secondary to drainage capture and butte detachment through two-way positive feedback: if moist climates prevail at the coast, with the escarpment itself acting as a climatic barrier (e.g. the Western Ghats, where perennial monsoon rivers have been conquering intermittent or ephemeral plateau streams), the climatic asymmetry plays in favour of scarp recession. If moister climates prevail inboard of the escarpment, streams guided by structural weaknesses are likely to conquer comparatively better supplied hinterland drainage and suddenly harness great discharges towards the drier seaboard. This contributes to a repositioning of the continental divide, erosion of the plateau edge and renewed escarpment dynamics. Escarpments are only likely to become relatively stagnant where arid climates prevail both inboard and seaward of the escarpment, e.g. in Namibia (Bierman and Caffee, 2001).

Butte detachment as an overarching aspect of PME evolution forces us to reprogram the way we deal with landscapes as either time slices or topographic swaths. Escarpments are continuous laterally and evolve continuously through time. Space-for-time substitution reveals that multiple local causes can generate a large-scale result that mimics the unifying causes advocated in models of PME evolution in which escarpments persist as self-similar landforms after continental break-up. Here, local detail is not just a subsidiary ornament to some global simplifying explanation: it steers entire systems towards new states in a nonuniform (this term describing changes in space) and unsteady (this term describing changes through time) fashion.

Such nonuniformity and unsteadiness in patterns of scarp evolution has been captured by the bucket concepts of 'nonlinearity' and 'complexity', with internal distinctions between dynamic instability and multiple equilibria (Phillips, 2003). Multiple equilibria occur when there are two or more possible system states or modes of adjustment to a given set of inputs and boundary conditions. Those system states are defined either at a specific moment in time or as developmental trajectories, and can coexist along the strike of a single escarpment (*cf* Figure 7). Dynamic instability implies that the effect of a small perturbation to drainage tends to grow over finite time, and is disproportionately large and long-lived compared with the initial perturbation. If drainage diversion is involved, the system can suddenly reorganize without any intervention of external forcing. Small-scale scarp sinuosities, favoured by a fault-line or an outcrop of weaker rock, may grow into major inroads allowing trunk streams to outflank escarpments and degrade them from behind (Figures 4 and 5; see also Harbor and Gunnell, 2007; Gunnell and Harbor, 2008). This is the sinew of drainage integration. Not only does it affect the record of denudational signals through space and time, but it may explain local anomalies all too easily dismissed as data noise in AFT and AHe cooling patterns at passive margins. Crucially, because of its self-contained dynamics, it may frustrate conventional attempts at correlating peaks of erosion and pulses of sediment output to basins with independent chronologies of external forcing events such as eustatic fluctuations, glaciation, and varyingly well constrained tectonic stresses.

In the case of the WGE, the strengthening of monsoon circulation in Miocene times appears to have reenergized scarp evolution at a time when local relief had declined (*cf* Figure 1). However, the erosion that occurred subsequently, although inferred from the deranged drainage and the morphology, cannot be detected by fission tracks due to recognized detection limitations of the method in its lowermost temperature range (Gunnell, 1998a; Braun and van der Beek, 2004). Nevertheless, although the climatic imbalance causing perennial monsoon streams to conquer an ephemerally drained semi-arid Deccan plateau is undoubtedly the fuel driving scarp recession as a whole, kilometre-scale variation in scarp-crest altitudes along the strike of the WGE is unlikely to have been determined by long-term zonal contrasts in climatic conditions: the interplay between geological structure and drainage basin expansion at escarpments <~1 km high remains the all important factor of scarp persistence.

Conclusion

Through real-world examples examined in this study we have highlighted the relief-creating potential of rivers over rock within the heterogeneous, weathering-limited substrate that typifies most tropical cratons and many mid-latitude mountainous uplands. While existing PME models dichotomize between moving divides and pinned divides (Braun and van der Beek, 2004), arch-types and shoulder-types (Matmon *et al.*, 2002), high-elevation and low-elevation categories (Gilchrist and Summerfield, 1990), gorge-types and divide-types (Seidl *et al.*, 1996), the process of butte detachment advocated here is probably the most widespread mode of scarp evolution because it unifies all of these into a realistic and interactive model through contextual interplay with geological structure. Butte detachment highlights the tendency for passive margin topography to self-organize through drainage integration. Being a long-lived phenomenon, it provides the topographic conditions needed to reenergize drainage basins at rift margins and develop rugged gorges and escarpments in what should be decaying topography. Such disequilibrium challenges generalizing statements on magnitudes and styles of so-called scarp 'retreat' over time, whether radiometrically detected or otherwise, because significant lags exist between

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the erosion of fast-track drainage inroads, and the erosion of buttes (either still upstanding or now entirely eroded) abandoned in the trail of the receding escarpment. The examples presented in this paper illustrate that scarp jumping is a real, if underappreciated process. The extent to which it characterizes all escarpments has yet to be determined, and the design of appropriate geochronological sampling strategies to capture such processes requires further thought. Due to the limited sensitivities of AFT and AHe thermochronology in certain settings, better constraints on offshore chronostratigraphy could tell whether the post-rift timing of erosional events along the strike of continental margins was punctuated by major external forcing factors, such as climate or tectonics, that can be globally correlated, or whether pulses of sediment input, as suggested here, followed an independent chronology dictated by the on–off switch of drainage integration.

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