JOURNAL GEOLOGICAL SOCIETY OF INDIA
Vol.71, June 2008, pp.763-779

Structural Underprint and Tectonic Overprint in the Angavo (Madagascar) and Western Ghats (India) — Implications for Understanding Scarp Evolution at Passive Margins

YANNI GUNNELL[1] and DAVID HARBOR[2]
[1]Department of Geography, Université Paris-Diderot, CNRS UMR 8591, 2 Place Jussieu, 75205 Paris cedex 13, France
[2]Department of Geology, Washington and Lee University, Lexington, VA 24450, USA
Email: gunnell@univ-paris-diderot.fr, HarborD@wlu.edu

Abstract: The land surfaces on either side of receding escarpments at continental passive margins are formed under the competing influence of drainage systems controlled by two separate base levels of erosion: proximal sea-levels in the coastal belt, and more distant and diverse base levels in upland river systems landward of the escarpment. Unequal erosion is therefore the engine that supports the asymmetric topography and persistence of local relief. A comparative study of the passive margin escarpments of western India and eastern Madagascar suggests that after a certain time has elapsed since initial continental breakup, steep landforms are either underpinned by resistant bedrock or recently formed by tectonics. Lithological controls, through which geological structure receives its topographic expression as the landscape erodes, are dominant. A morphostructural analysis of the Western Ghats escarpment in its Archaean section shows that its relief and morphology today are largely controlled by lithological heterogeneity and form a diverse gallery of homoclinal structures eroded out of the metamorphic and igneous fabric of the craton. Although in Madagascar late Cenozoic faulting locally affords an additional contribution to topographic expression, the growth and persistence of escarpment-supporting bedrock landforms is shown to be strongly pre-ordained by the pre-rift geological fabric. It also depends on the capacity of geomorphic agents in a particular climatic environment to reshape the landscape in response to drainage integration across the hinterland. It is argued that mature passive margin escarpments are essentially residual escarpments underpinned by a diverse assemblage of structurally controlled bedrock landforms.

Keywords: Tectonics, Geological structure, Scarp evolution, Passive margin, Western Ghats, Madagascar.

INTRODUCTION

Maximum and minimum topographic expression of structure, i.e. perfect adjustment of topography to geological structures vs. beveled-off structures forming erosion surfaces, are extreme manifestations of how erosion generates topographic diversity on Earth's surface. Escarpments in particular have focused much curiosity and conceptual debate among geomorphologists. At passive margins, concern for generic models of scarp evolution linking surface processes to lithospheric behaviour (e.g. Gilchrist et al. 1994 and numerous successor studies) has eclipsed the concern for geological structure that preoccupied geomorphologists of a previous era. Disregard for geological structure is rooted in a fairly recent tradition that considers it to be only a passive element of landscape sculpture (e.g. Small, 1970), although other workers have maintained that geological structure sets the stage for differential erosion to produce distinctive topographic patterns (Godard et al. 2001).

The influence of geological structure and lithology is inevitably contextual (e.g. Weissel and Seidl, 1997; Bishop and Goldrick, 2000; Van der Beek et al. 2001; Gunnell and Harbor, 2008), and therefore *a priori* not appealing to law-seeking modelling experiments. Geological structure, whether influenced by lithology or tectonics, may nevertheless hold the key to understanding escarpment morphologies. Concern for structure includes the study of tectonic displacement; strike, dip angles and dip directions; the stratigraphic arrangement of rock masses or layers; the pattern of joints, faults, folds and bedding planes; rock mass strength and lithology; and the susceptibility to weathering of rock minerals. In layered sedimentary structures, for example, the lithological characteristics of the caprock, its thickness and its dip

0016-7622/2008-71-6-763/$ 1.00

account for more than 60% of the total variance in the planform sinuosity (embayment index) of homoclinal scarps (Schmidt, 1988, 1989, 1994). The rate of horizontal retreat of a homoclinal scarp is also usually inversely proportional to the tangent of the dip. This is a clear indication that, whether in a passive or an active role, structure matters.

Here we examine the morphology of two steep plateau edges located at conjugate rifted margins that separated ca. 80 m.y. ago: the Western Ghats of India, and the Angavo of eastern Madagascar (Fig. 1). These regions are often poorly accessible, thickly forested, and deep rock weathering has made structural mapping difficult. Neither of these regions involves sedimentary basins exhibiting layered sedimentary structures, but based on current knowledge we emphasize how in these Precambrian basement settings geological structure and lithological contrast have influenced, or even pre-ordained, the morphology of these elevated passive margin escarpments. One of the reasons is that metamorphic and crystalline rocks with different susceptibilities to weathering often mimic rock sequences and structures normally observed in sedimentary basins. In Madagascar, evidence is also shown where post-rift faulting can dominate the current scarp-face morphology where present, thus adding variety and complexity to a widespread belief that eroding passive margin escarpments have remained self-similar since the time of continental breakup (*see* critique in Burke and Gunnell, 2008).

The East-facing Passive Margin Escarpment of Madagascar

The steep eastern edge of the highlands of Madagascar is over 1000 km long. The escarpment can be subdivided into four structural segments. Three of these, termed here segments 1, 2 and 3, separated from India and are discussed here (Fig. 1a). The fourth, northernmost one separated from the Seychelles microplate. Segment 1 is a fault-dominated horst-and-graben system in the north, and referred to here as the Angavo–Ankay–Betsimisaraka region. Segment 2 is a structurally controlled and rejuvenated, two-tiered scarp further to the south and referred to as the Tsiazompanihy–Andringitra region. Segment 3 is also a bold, structurally controlled escarpment in the deep south. We suggest here that Neogene tectonic movements causally unrelated to rifting 80 m.y. ago explain the present-day morphology of section 1 of the Angavo escarpment, but that structural and lithological factors along this composite escarpment account for scarp position and configuration.

Segment 1: Neogene Rift Overprint on a Cretaceous Passive Margin

The escarpment zone due east of the state capital Antananarivo is conspicuous by its graben structure involving interference between two scarp directions: (1) a set of N20°E–N30°E scarps, parallel to the east coastline, which is attributable to faults generated by the late Cretaceous India–Madagascar rifting event; and (2) a second set of NNW–SSE, and locally N–S scarps which are of a younger Cenozoic age.

Over a 130 km stretch north of the mouth of the Mangoro River, the Angavo is a relatively rectilinear scarp related to the western edge of a rift and separated from the coastal zone by a set of hinge- and pivot-faults which define two graben: the south-tilted Ankay Basin (Fig. 2), drained by the N–S Mangoro River, and the north-tilted Alaotra Basin (Bertil and Regnoult, 1998; Piqué et al. 1999). Several lines of evidence indicate that both sets of faults were active in post-Miocene times: a N20°E alignment of basalt and intrusions of pyroxene-rich nepheline basanite (ankaratrite) occurs on the western shores of lake Alaotra; and throws of 20 m in Pleistocene lake sediments are observed on the edges of the Ankay graben. The faceted scarps are associated with deranged drainage (Petit, 1999). The highest elevations of the Betsimisaraka uplands (ca. 1.5 km) project over the Ankay graben to the footwall highlands of the Angavo (Figs. 2 and 3a). The two surfaces carry identical soil and weathering profiles, suggesting that the fault system fragmented a continuous land surface, which has been age-bracketed by cover sediments in the western part of the island as Paleogene, and is known in Malagasy denudation chronology as surface S2 (Bourgeat and Petit, 1969). The tectonic activity has been loosely correlated with the opening of the Mozambique Channel and the extensional tectonics and volcanism of East Africa, although no definitive study of this specific aspect has yet been conducted (Bertil and Regnoult, 1998; Kusky et al. 2007).

Segment 2: from the Tsiazompanihy Promontory to the Andringitra Massif

South of the 19.5°S, the Angavo escarpment directly overlooks the coastal hills, i.e. without any intervening horst-and-graben structure equivalent to the Ankay–Betsimisaraka unit, and exhibits two morphological tiers (Figs. 1, 2 and 3). Here the escarpment is carved out of the *Système du Vohibory* and *Système du Graphite* (Fig. 4), the latter consisting of isoclinal folds affecting a stratigraphy of migmatites and hornblende biotite orthogneiss. The folds are overturned eastward with axial traces striking N20E to

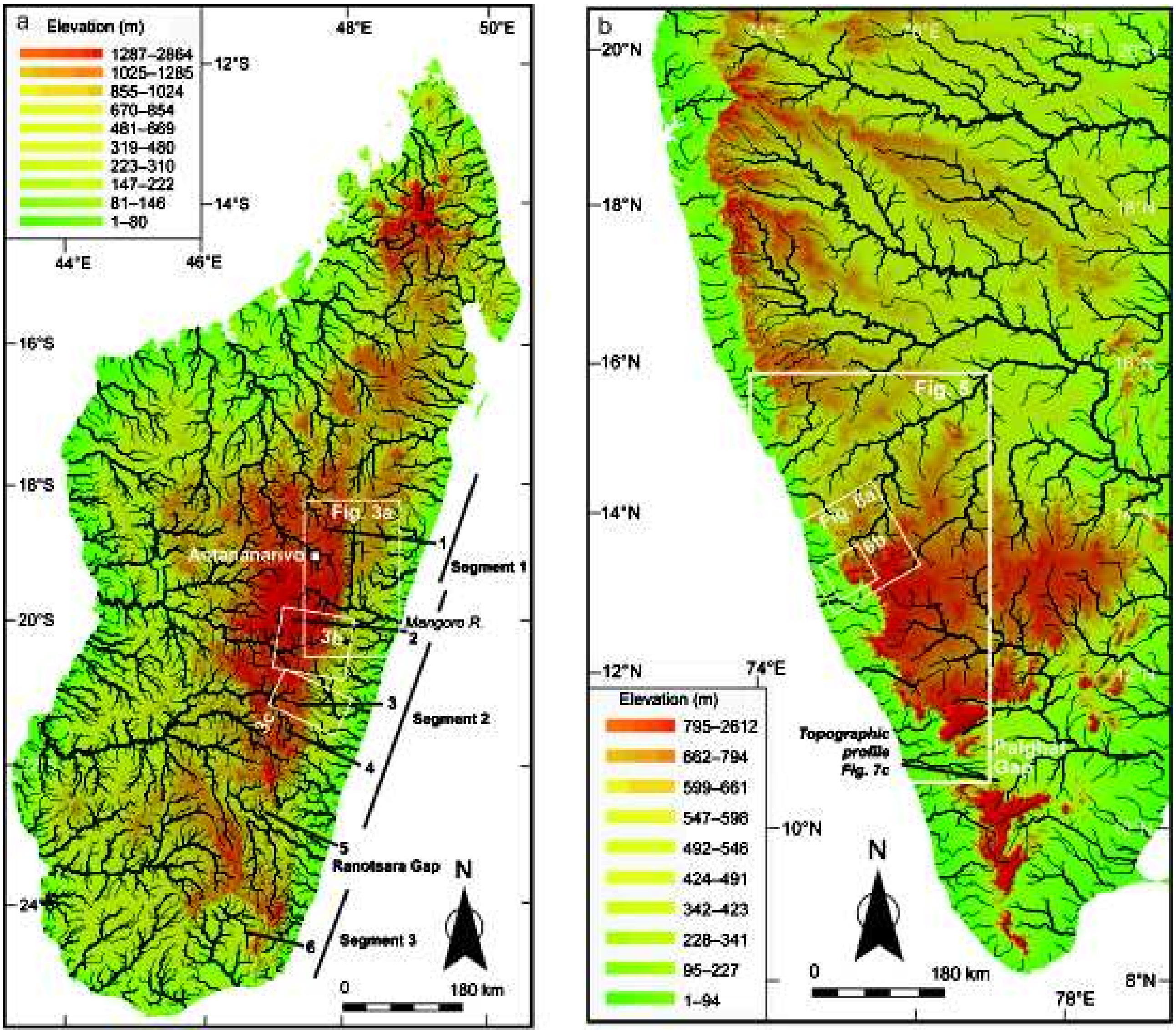

Fig. 1. Digital elevation and drainage maps of Madagascar and SW peninsular India. Digital drainage network is restricted here to Strahler order >5 with line thickness proportional to stream order and 1st order streams defined at a drainage area threshold of 2 km^2. In (a), topographic profiles 1 to 6 are illustrated in Fig. 2. White frames are labelled in reference to oblique aerial views of the escarpments displayed in Figs. 3 and 6. Data source: GTOPO30 (http://edc.usgs.gov/products/elevation/gtopo30/gtopo30.html).

N30E and westerly dips that steepen from ca. 30° landward of the escarpment to 70° at the escarpment itself (e.g. Collins et al. 2003). The coincidence between the N20°E–N30°E strike of the Precambrian *Système du Graphite* and the Cretaceous rift faults suggests that rifting at this margin was predesigned by the fabrics of the cratons and Panafrican mobile belts moulded around them. Receding east-flowing rivers have carved east-facing hogback scarps out of the folded basement structures (Fig. 3b), revealing the contrasting resistance to weathering between the harder upper granitic unit and the softer basal migmatites (Petit, 1999). The boldness of the escarpment, therefore, seems attributable to the structural configuration, which mimics here in basement rocks the steeply dipping homoclinal landforms normally observed in sedimentary basins or fold belts. Unlike further north, the Neogene Ankay faults do not seem to continue in this area.

Further south in this segment the Angavo reaches elevations of 1.6 km and exhibits two topographic tiers. The upper plateau edge descends progressively southward to 1.2 km. The lower tier follows the same trend. Relative relief between the highland plateau and the accordant

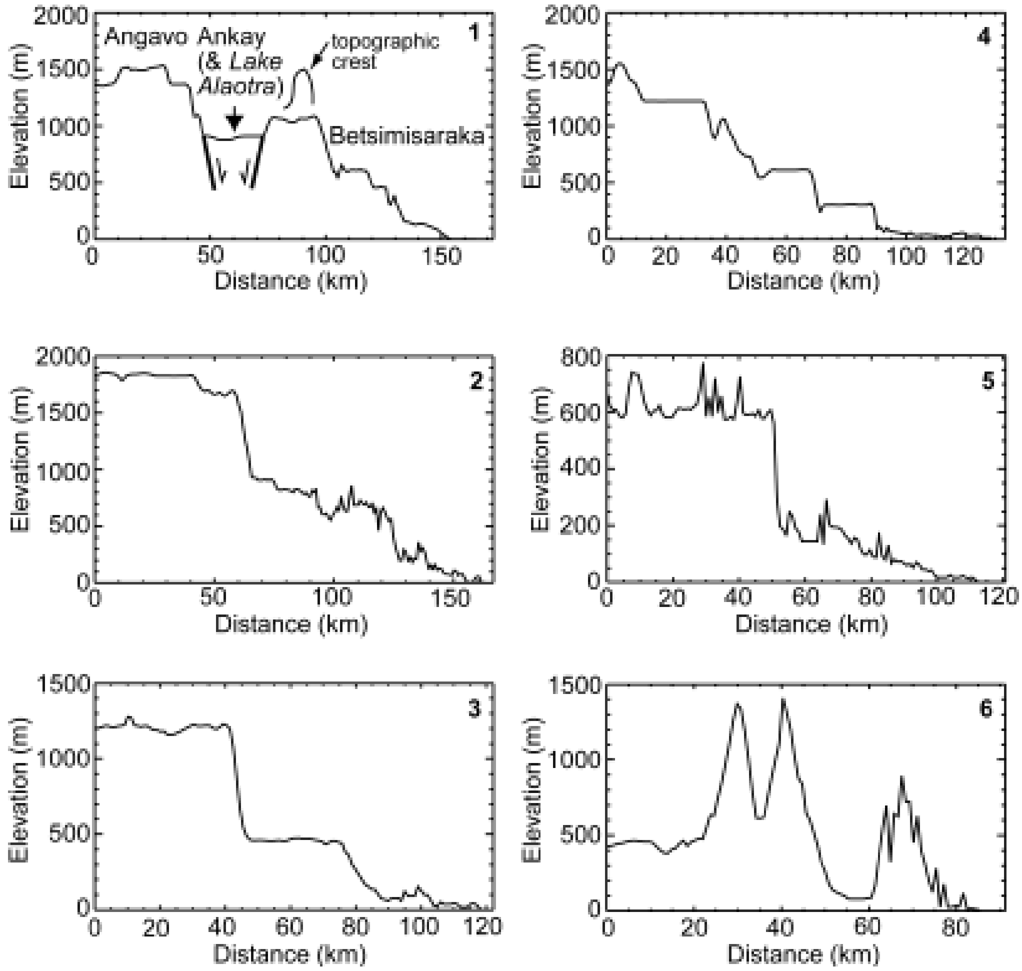

Fig. 2. Topographic profiles across the eastern edge of the Madagascar highlands. Numbers 1 to 6 refer to Fig. 1. The abruptness of scarps in 2 through 5 superficially suggests fault scarps at this scale (profiles are drawn from GTOPO30 digital data, i.e. with a resolution of ~0.8 km), but the morphology is deceptive. These are more likely structural landforms (*see* text).

coastal hilltops is about 1 km. The highest elevations occur landward of the escarpment edge, in massifs such as the Andringitra (2.658 km), which form large residual masses on the plateau. In this segment the escarpment is located close to the western edge of the intensely folded *Vohibory* rocks of the Panafrican shear zone (Fig. 4) and is being held up in the granitic rocks underlying the eastern edge of the highland plateau. This sinuous escarpment exhibits an abundance of structural controls where streams have exploited WNW-ESE fault and fracture zones that strike across the margin (Fig. 3c; Petit, 1999). Farther south in the Ranotsara Gap (see later section), the lower escarpment is found at the contact between the Angavo–Nondiana crystalline belt to the east and the *Sytème du Graphite* to the west in the floor of the gap (Fig. 4). The piedmont tier below the Angavo escarpment is itself incised at the eastern margin, yielding a lower scarp. The eastward tilt of the remnants on the piedmont and the presence of coastal cuestas that project over this surface suggests that this latitude has been uplifted, resulting in a reincision of the scarp base.

Segment 3: the Anosyan Belt

The far south of the Madagascar escarpment coincides with a sheeted granite intrusion, the Anosyan belt, which strikes NNE–SSW for 180 km and dips steeply towards the west (Paquette et al. 1994). Its east-facing, elevated hogback outface forms this southernmost segment of the great Angavo escarpment and reaches elevations of 1.8–1.9 km. The structural landforms in these granulitic basement fabrics exhibit a likeness to structural landforms in alpine fold belts, with synformal granite sheets resting on an underlayer of softer gneiss. In Madagascar, generally (Petit, 1971, 1999) the numerous sheeted granites and their westerly dips have been attributed to Himalayan-type

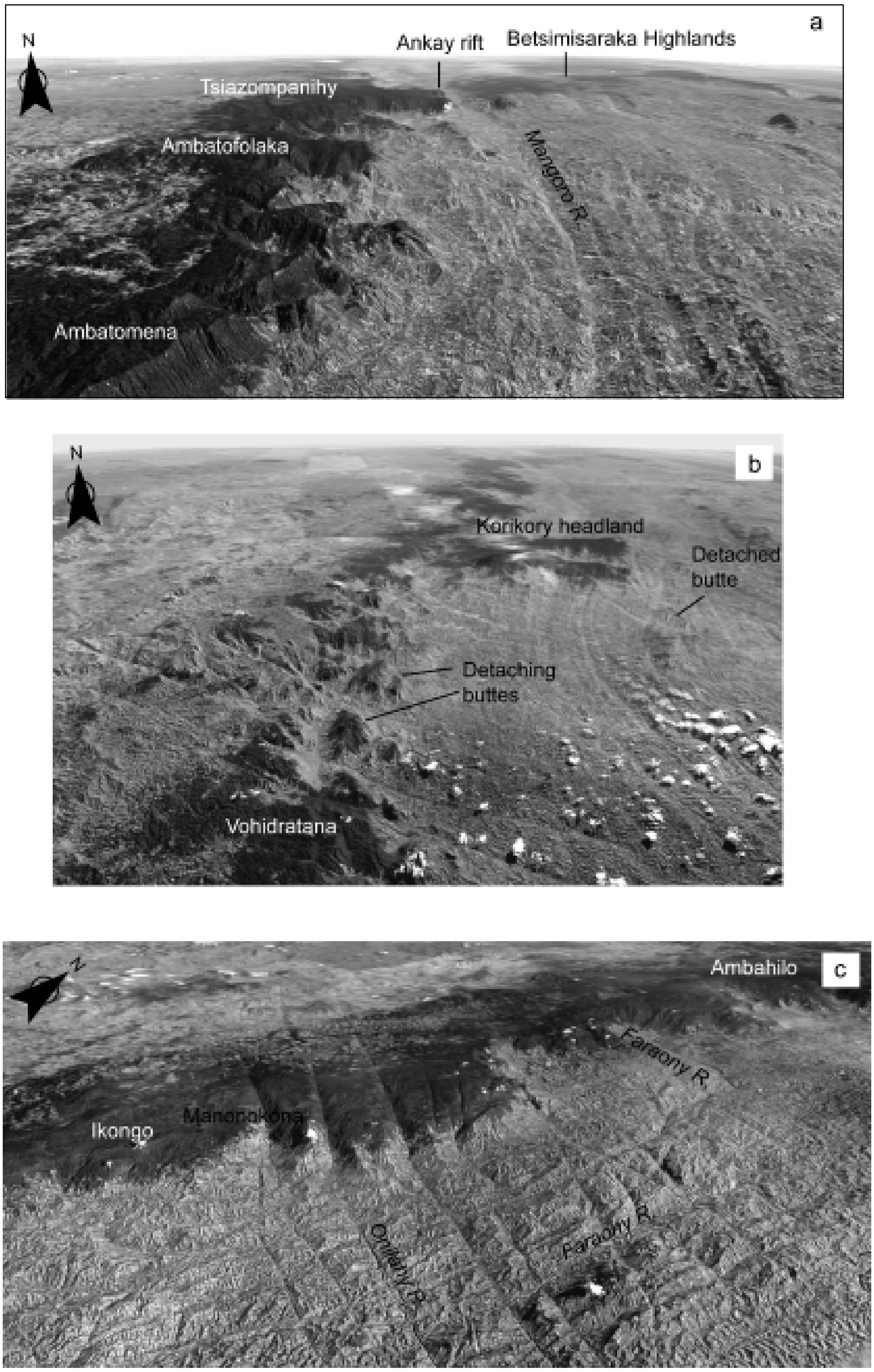

Fig. 3. Oblique aerial views of the Angavo escarpment at successive locations from north to south. See Fig. 1 for location. Note scarp sinuosity and scarp headlands, which militate against fault control, and the belted outcrop pattern forming an erosional plain in the coastal lowland and in the process of being sculpted by differential erosion in the forested escarpment topography. This suggests structural control, and concurs with field knowledge of strike-parallel homoclinal and folded geological structures. Mention of 'detaching' buttes, which eventually become part of the belted outcrop plain and thus disappear from the landscape, refers to a model of structurally controlled scarp evolution presented in Gunnell and Harbor (2008). Source: Google Earth, vertical exaggeration 2x.

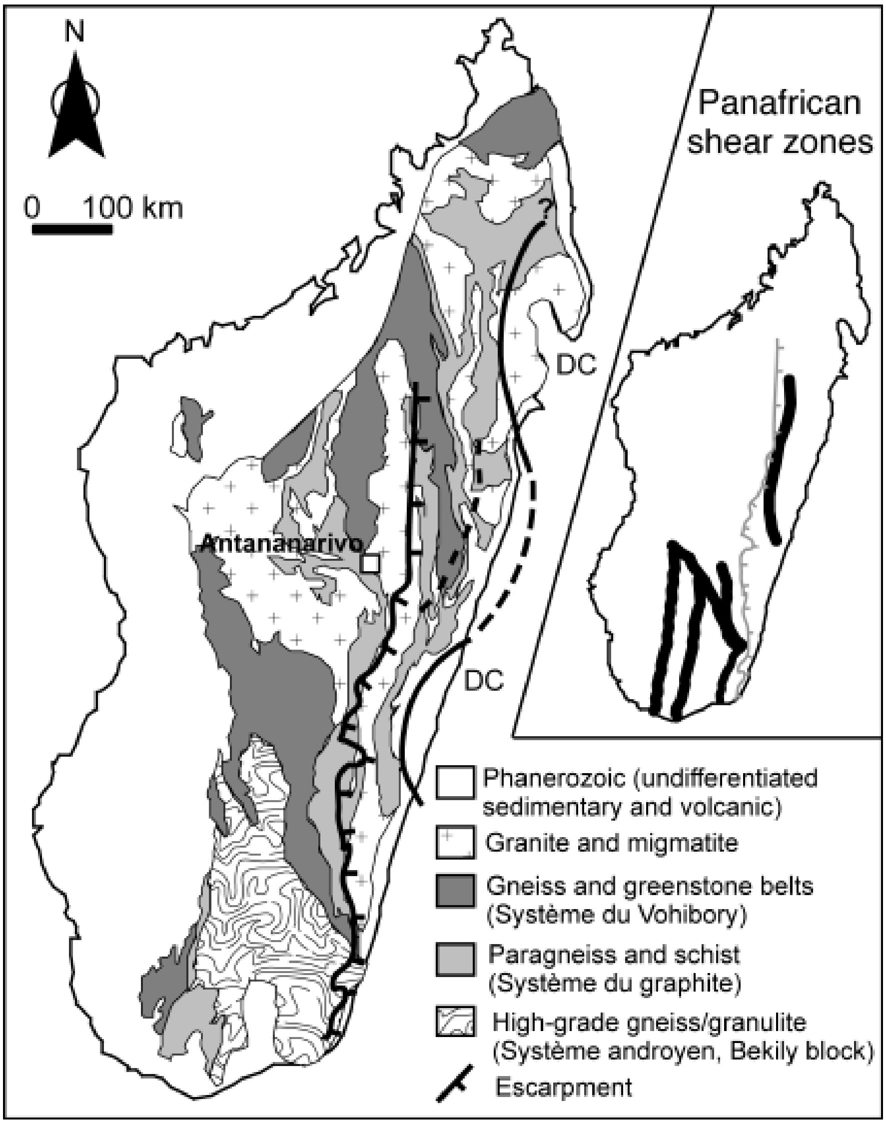

Fig. 4. Simplified lithological map of Madagascar (detail of Neogene sediments and volcanics omitted). DC: fragment of the Archaean Dharwar craton, known as the Antongil block, are little affected by Proterozoic tectonism and therefore supposed to lie east of the Panafrican (or Betsimisaraka) suture of the Mozambique belt (thick black line, dashed offshore). DC outcrops all occur east of the escarpment and consist of biotite granite, granodiorite, orthogneiss, migmatite and micaschist. Some of those lithologies, notably quartzite, form hills in the coastal belted outcrop plain, which in its distal part is also unconformably covered by Cretaceous basalt, dacite and sedimentary rocks. The granite and migmatite outcrop in which the escarpment is currently formed is known as the Angavo–Nondiana belt (source: Bésairie, 1973; Collins et al. 2003; de Wit, 2003; Raharimahefa and Kusky, 2006).

continent–continent collision involving east-vergent thrust stacks in the so-called Mozambican belt of the Panafrican orogen, of which Madagascar was an eastern outpost (Windley et al. 1994) moulded around the Dharwar craton of Peninsular India. Like most of the segments of the Angavo further north, Neogene fault tectonics here play little or no part in escarpment morphology. Differential erosion around more resistant cores of sheeted bedrock is the key controlling factor. Geological structure and lithological contrast explain the boldness and persistence of this segment of the escarpment.

The West-facing Western Ghats Escarpment of India: Geological Fabric and Escarpment Morphology in its Archaean Segment

The Western Ghats escarpment is 1500 km long. Although, the northern volcanic segment has been most studied for its flood basalts, this large continuous landform can be divided into three structural segments: the Deccan volcanic, Archaean granite–greenstone (Dharwar craton), and southern granulite provinces, only interrupted once by the Palghat Gap (Fig. 1b). Contrary to some parts of the Madagascan margin, there is no convincing evidence of any topography at the Western Ghats scarp face having been generated by recent fault tectonics. Structural controls, on the other hand, are particularly clear-cut and explain in places the sinuosity, and in others the boldness and straightness, of the escarpment where it is developed in Archaean rocks. Here we do not address the cliff-and-bench topography of the Deccan basalt province, which is not relevant to the comparative analysis elaborated here between India and Madagascar.

Outcrop Configuration in the Granite–Greenstone Terrain

In the Dharwar craton (Fig. 5), the folded supracrustal rocks are stratigraphically discordant upon the tonalite-trondhjemite orthogneiss (TTG), which acquired its own set of folds during an antecedent high-grade migmatitic event (Chadwick et al. 1997). The greenstone belts of the Dharwar craton share lithological and structural features with most other Archaean basement regions of the world in that they consist of stacks of volcanic and sedimentary sequences in which metamorphism has been sufficiently low-grade for the original stratification (i.e. S_0) to have been preserved. Outcrops correspond to narrow, elongated basins of variable depths irregularly distributed between gneiss domes. Outcrop lengths range between 10 and 400 km and exhibit length/width ratios of 10:1. The greenstone belts constitute ca. 20% of the surface area of the craton, which makes it comparable to the Yilgarn, the South Superior Province or the Kaapvaal/Zimbabwe cratons.

Despite these features, the Dharwar greenstone belts differ by the widespread occurrence of gently undulating and relatively open fold structures that contrast with the tighter and more upright isoclinal folds of other cratonic settings. All major folds have NNW-trending axial planes, i.e. form a low angle with the current coastline and strike of the Western Ghats escarpment. The stratigraphic sequences were subjected to one, and only sometimes two or three, cycles of folding, so that for the purpose of structural landform definition the geology remains relatively simple to decipher. The ratio between metavolcanic and metasedimentary rocks is also balanced in favour of sedimentary lithologies both in terms of volume and outcrop area. The base of the greenstone belts is lined by an oligomict conglomerate containing gneiss pebbles, which is well documented in some areas (e.g. Chadwick et al. 1991) and indicates that the sequences rest unconformably on the gneiss basement. This contrasts with gneiss–greenstone contacts in other settings, which are frequently intrusive or migmatitic, and highlights greater affinities between rocks belonging to the Archaean Dharwar Supergroup and comparatively younger sequences such as the Lower Proterozoic Witwaterstrand in South Africa, the Hamersley Ranges or Mount Isa in Australia (Ramakrishnan, 1993). Given these geological conditions, it seems acceptable to interpret the greenstone landforms of the Dharwar craton in the same way as one would analyse structural landforms developed in more recent, unmetamorphosed sedimentary fold belts.

Lithology, Structure, and their Links with the Escarpment

At many places along its strike in the Archaean rocks, the Western Ghats escarpment is underpinned by a variety of steeply dipping stratoid and homoclinal geological structures (black arrows, Fig. 6). On the plateau, geological outcrops that tend to systematically occupy low-relief topography are the meta-argillites and the gneisses. The meta-argillite is fine-grained, thin-bedded containing a mosaic of microgranular quartz and phyllosilicates (chlorite, biotite, muscovite). Metagreywacke bands within the argillite contain 40% quartz. The argillite is prone to deep weathering as it contains large quantities of clay, Fe_2O_3 (8.6–13.5%, *see* Naqvi et al. 1988), and pyrite, which release sulphides and greatly accelerate weathering. Accordingly, these outcrops are widely lateritized but are not associated with high relief. The gneiss contains 3 to 5 times less Fe_2O_3 and is therefore less susceptible to lateritization than the argillites. It is nonetheless vulnerable to weathering due to large quantities of biotite, calcic plagioclase and a granoblastic texture, and outcrops of gneiss correspond in several areas to locations where the rivers have found ways through the supracrustal fold belts headward into the plateau (Fig. 5).

The azimuth and angle of dip of fold limbs and schistosity fabrics illuminate the relationship between bedrock structures and the trace and sinuosity of the Western Ghats escarpment. At sites where the weathered mantle has been removed and the metamorphic bedrock is visible, such as at major waterfalls of the main gorge-type segment of the Western Ghats (Fig. 5), an easterly dip of the schistosity and foliation is observed. At Magod falls, on the Gangavali River, headward recession and drainage piracy by a west-flowing stream can be seen to work against the ca. 35° easterly dip of the chlorite schists. At Jog falls, on the Sharavati River, the metamorphic foliation also dips in an easterly direction. It is reported that the magmatic bodies of the Ghats canyon area near Karwar (Fig. 5) are

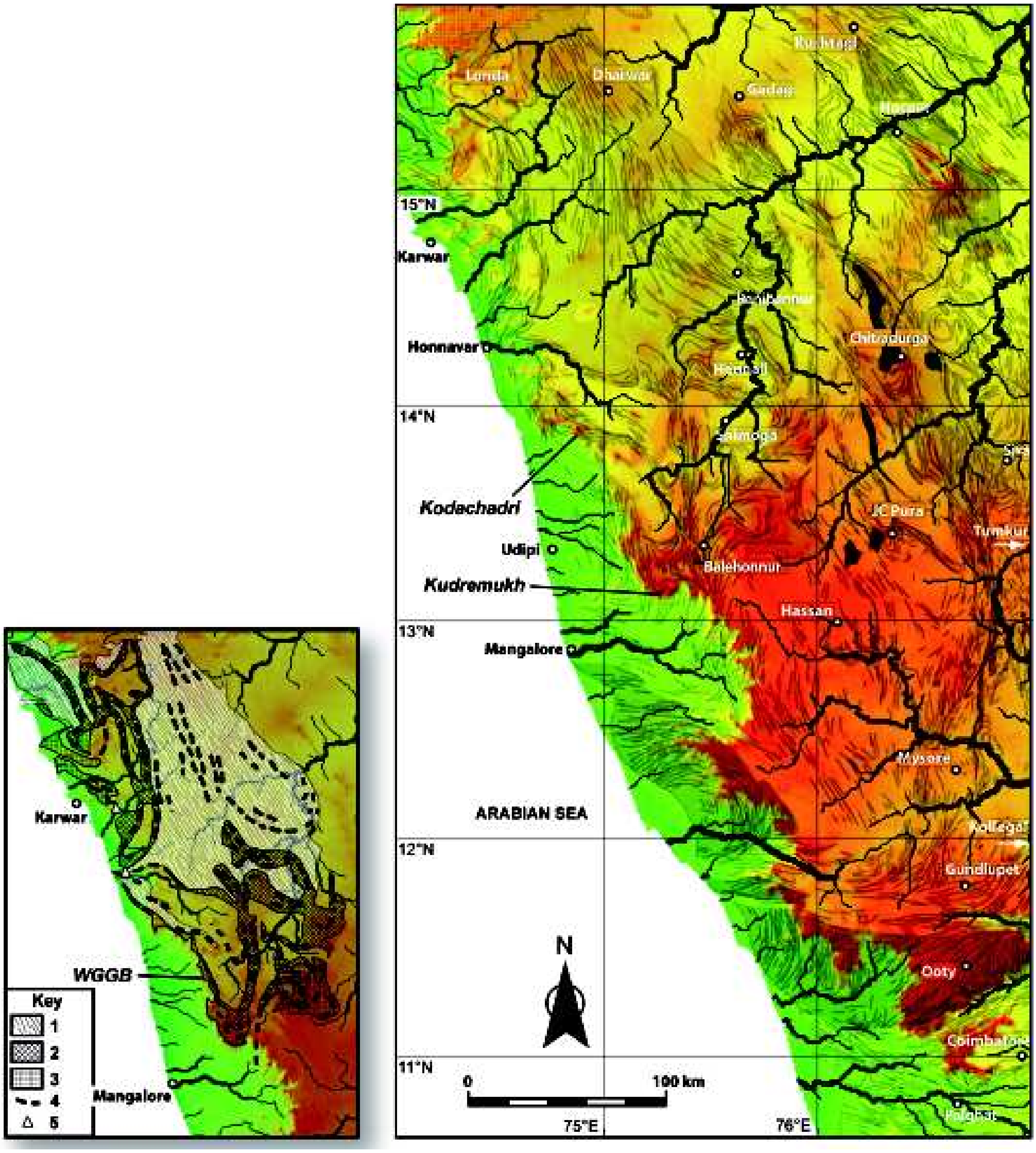

Fig. 5. Geology and tectonic fabric map of the western Dharwar craton overlayed on topography and drainage. *Main panel:* structural units and textural and compositional fabrics of the craton (thin black curvilinear or linear features after Chardon et al. 2008). Pale grey: greenstone belts; dark grey (in south): charnockite; grey with crosses (in NE): granite; black: alkaline granite. *Left panel:* excerpt of main panel emphasizing the lithology of greenstone belts in the vicinity of the Western Ghats (*source:* Geological Survey of India, 1981). **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; **5**: isthmus of gneiss linking the low-elevation gneiss outcrops of the coastal zone to those of the plateau. These are weak spots prone to drainage ingress from the west and where river capture has been documented. Note how continuous girdles of resistant greenstone rocks still underpin the escarpment. *Data source:* GTOPO30.

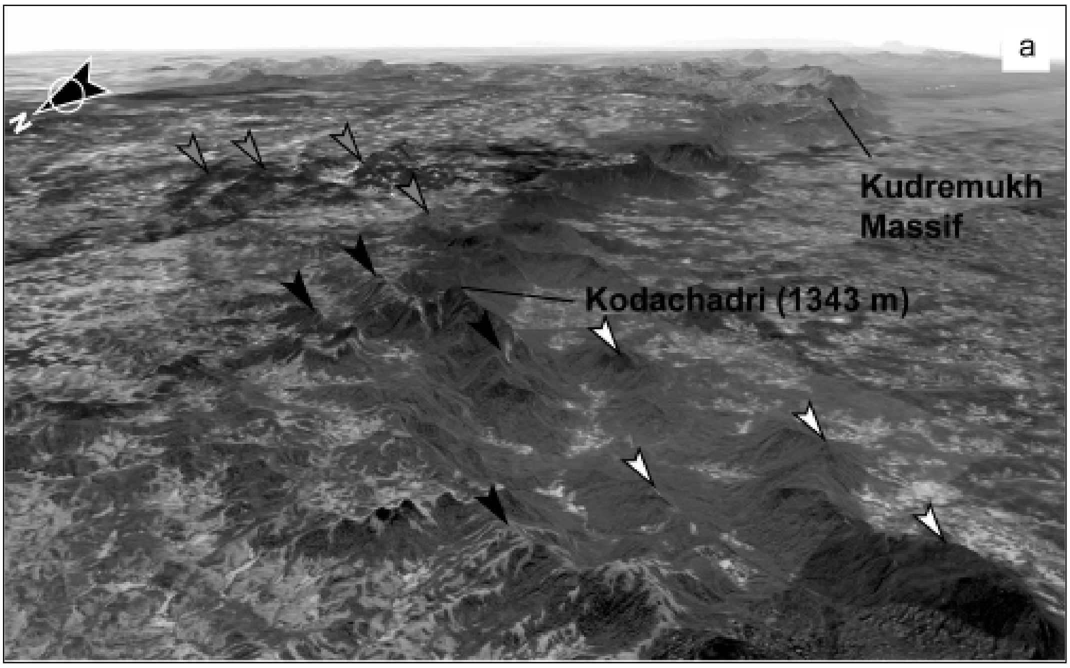

Fig. 6. Oblique aerial views of the Western Ghats escarpment at successive locations from north to south. **a**: Kodachadri–Kollur area. **b**: Kudremukh and the Western Ghats greenstone belt. See Fig. 1b for location. Black arrows point to examples of structurally controlled hogback ridges underpinning the current escarpment. White arrows show residual hogbacks forming isolated buttes in the erosional plain in the trail of scarp recession. Grey arrows indicate hogback rigdes on the plateau that may in the future control the receding scarp as west-flowing drainage makes further inroads into the hinterland. *Source:* Google Earth, vertical exaggeration 2x.

partially metamorphosed layered intrusions in which the foliation exhibits a steep easterly dip (Vasudev and Ranganathan, 1994). In the Dandeli area (15°15'N, 74°35'E), some distance inland from the escarpment itself, the phyllites dip consistently eastward at an angle of 52° and form hogback ridges (Fig. 6a; Durg, 1969). In the Kodachadri area (13°53'N, 74°50'E), the Precambrian metavolcanic group of andesitic and basaltic composition in the amphibolite facies, containing interlayers of banded magnetite quartzite (BMQ) and chert attaining thicknesses of 300 m, shows easterly to northeasterly dips varying between 15 and 40° (Fig. 6a). The formations at places change their attitudes to E–W strikes with 25 to 50° northerly dips, and frequently reveal a duplication of beds as a consequence of isoclinal folding (Sreeramachandra Rao et al. 1977). The soft interlayers consist of quartz-sericite-chlorite schist, and play the same role as clays and marls in the classic scarped landforms of artesian sedimentary basins and alpine fold belts. Throughout the Kodachadri–Kollur area (Fig. 4), the Western Ghats escarpment coincides with the east-plunging noses of isoclinally folded siliciclastic beds, which thus form west-facing layered hogback scarps (Fig. 6a), some of which can be confused from a distance (Valdiya, 2001) with faceted fault scarps.

Further south, the steep and precipitous Western Ghats escarpment continues to coincide with the outer face of similar homoclines, with elevations and scarp relief increasing in the Kudremukh massif (*see* Fig. 6) and thereby perhaps suggesting greater uplift at that latitude. The Western Ghats Greenstone Belt (WGGB; *see* Ramakrishnan and Harinadha Babu, 1981), where topography culminates at 1892 m at Kudremukh peak (Fig. 6b), develops a long, strike-parallel limb of metavolcanic and polymict conglomerate beds, and local relief between the coastal plateau and Kudremukh peak reaches nearly 1.8 km. The entire structure of this WGGB has been described as an overturned syncline with its axial plane dipping 45° towards the north-east (Krishna Rao et al. 1977). The stratigraphy of Kudremukh is a stack of amphibolite, Banded Iron Formation (BIF) and schist intruded by dolerite sills and quartz veins (Srivastava and Prasad, 1984). The prominent BIF layers (chert protolith) dip locally at steep angles (45–74°) towards the north-east, and some beds reach individual thicknesses of 80–100 m (Chikka Reddy, 1987). Beds of magnetite quartzite range in thickness between 120 and 200 m and their strike is traceable continuously for ca. 50 km. The resulting morphology is illustrated in Fig. 6b.

Passive Margin Escarpments and Geological Structure: Summary and Discussion

Comparative Overview

Structure and lithology explain at most scales the many morphological features of the Western Ghats escarpment. The same is also true for the Angavo, where faulting is an additional and locally dominant feature. Earlier geomorphological reconnaissance suggested that much of the Angavo was fault-derived (Bésairie, 1957), i.e. had its origin on an older but unidentified fault situated either in the coastal belted outcrop plain or off shore. It is true that scarp salients such as those visible in Fig. 3 superficially recall bedrock spurs that locate fault segment terminations at active range fronts in arid environments such as the Wasatch Range (Utah, USA: *see* Machette et al. 1992). However, even in the Ankay rift segments between bedrock salients are much more sinuous and dissected that Wasatch-type range fronts. This suggests that in this humid environment faults have to be both very recent and very active in order to control escarpment morphology: over longer time spans fault scarps will recede rapidly, become enmeshed in the structural fabric of the Panafrican mobile belt, and increase their sinuosity. It thus remains difficult to prove any link between the current Angavo scarp and Cretaceous or later master faults. Despite the widely recognised intraplate seismicity of the region (Bertil and Regnoult, 1998; Piqué et al. 1999), geological structure in this geodynamic environment currently appears to exert the dominant control on scarp position and configuration.

In India, the Dharwar craton presents a set of large elongated greenstone belts where low metamorphic grades dominated by sedimentary protoliths have been affected by a single cycle of folding with subsequent shear motions and secondary folds. Together, these features make the geological structure analogous to that of Phanerozoic sedimentary fold belts, for which the range of structural landforms is well established in classic textbooks. The greenstone belts form a chequered arrangement of units dispersed among the intervening gneiss outcrops. Due to this configuration, the evolution through space and time of the Western Ghats escarpment depends on the manner in which expanding drainage systems negotiate the parallel belts, either cutting through them (water gaps) or circumventing them where they plunge or pinch out (Gunnell and Harbor, 2008).

Though operating on a different scale and perhaps at different rates because tectonic deformation and continental sedimentation rates are much higher, the logic of this process is similar to the way in which drainage systems integrate across thrust belts and mountain fronts in active orogens. In these settings, the rivers avoid some active zones and skirt between thrust fronts along transfer zones. Initially, the drainage basin rarely scales with the entire width of the orogen, and so the rivers deal with fronts following a similarly piecemeal and chequered path through the successive structural obstacles (Indus, Brahmaputra, Yellow River, Red River, etc.; *see* Brookfield, 1998).

Despite the unavailability of detailed geological quadrangle maps and geological cross sections that would help to further refine and illustrate the Indian setting, the foregoing synopsis indicates that the Western Ghats escarpment is controlled by large structural landforms. These structures all reflect the NNE–SSW fabric of the

Dharwar craton. The Great Escarpment at many sites coincides with the outface of a homocline, or assemblage of homoclines, carved in the supracrustal rocks of the Precambrian craton. The lithologies involved at different localities explain changing configurations on a more local scale such as the sinuosity index, as well as lateral variations in local relief (Harbor and Gunnell, 2007). Sampat Iyengar (1913) had considered that the Western Ghats escarpment was the result of differential erosion between the stratigraphically unconformable 'hornblende schists' of the greenstone belts and the underlying gneisses that crop out in the coastal region. This early view is probably mostly correct for the tract between Goa and Mangalore as there is everywhere evidence that the inward retreat of the river headwaters through the coastal gneisses has been arrested by the resistant girdles of steep, easterly-dipping metasedimentary and metavolcanic homoclines of the WGGB rock suites as defined by Ramakrishnan and Harinadha Babu (1981) (Figs. 5 and 6).

Where the river headwaters receding eastward from the Arabian Sea coast have reached the western outer margins of the greenstone belts, the slopes of the Western Ghats escarpment have steepened as a consequence of the mechanical resistance of the greenstone lithologies to erosion. Undercutting of the gneiss would have occurred in a manner similar to the dramatic structural controls that characterize sedimentary scarps governed by abrupt vertical changes in lithology (*see* Twidale, 1991 for a similar view on scarp evolution). It is hypothesized that rates of scarp recession are considerably limited by these structural controls, although much more so at places where lithological factors, i.e., the high resistance of layers of conglomerate, chert, BMQ or BIF, reinforce the mass strength of the easterly-dipping structure, than at places where the easterly dipping fabrics involve softer and more homogeneous rocks (e.g. metagreywackes, meta-argillites). It is thus in the north, where the metavolcanic stacks of amphibolite facies rocks interrupt (Fig. 5) and where outcrops become dominated by more weatherable gneisses (Jog falls) or greenschist-facies argillites (Magod falls, Unchalli falls), that rivers have succeeded, in the presence of these weaker geological impediments, in cutting back deep canyons and forming the gorge-type escarpment known as the Ghats Breaches. Accordingly, it is in this region that drainage piracy has been operating most actively. Meanwhile, and in support of this interpretation, the coincidence between plateau edge and continental drainage divide is almost perfect further to the south, between Jog Falls and Mangalore, where eastward-dipping structures involve the resistant outcrops belonging to the WGGB (Fig. 5). This example suggests that escarpments where scarp crest and continental drainage divide coincide are more static when the continental divide hinges on lithological boundaries. This is probably difficult to quantify although comparative rates of river knickpoint recession measured on contrasting lithologies in lithologically heterogeneous drainage basins have shed some light on this question (Harbor et al. 2005).

A Suggested Common Thread: the Palghat and Ranotsara Gaps

The 50 km-wide Palghat Gap is the only major topographic breach in the Western Ghats (Figs. 7a,b) because it coincides with the Palghat–Cauvery dextral shear zone, which is believed to cross-cut structures from India through Madagascar (Ranotsara Gap) to East Africa (e.g. Yoshida et al. 1999; Acharyya, 2000; D'Cruz et al. 2000; Reeves and de Wit, 2000; Torsvik et al. 2000; de Wit, 2003; Raval and Veeraswamy, 2003; Collins et al. 2007). The continuation of the Precambrian shear zone into Madagascar also locates a topographically low point in the Angavo escarpment known as the Ranotsara Gap. On either side of the Palghat Gap, to its north and south, the Nilgiri and Anamalai/Palni summits stand at similar elevations. Since the early assertions of Blanford (1858), the engrained belief that the Nilgiri massif is a Neogene or even Quaternary footwall uplift has somehow maintained its momentum, with many subsequent authors uncritically furthering this received view (Demangeot, 1975). If the Nilgiri massif really was a consequence of block uplift, it would be unlikely for it and the other scattered summits of South Asia such as the Anamalai, Palni or Highlands of Sri Lanka to have risen independently to almost exactly identical elevations. Furthermore, if the Palghat Gap were a graben, one would expect to find an infill of sediment proportional to the relative relief of the bordering mountains — for instance similar to the Ankay graben in Madagascar (Figs. 1 and 3). The Palghat Gap, however, is entirely free of sediment and exhibits mostly weathered Precambrian bedrock exposures.

The key to explaining the Palghat Gap is, again, lithological and structural. Major ductile shear zones are located between all the large charnockite massifs of Tamil Nadu (Chetty, 1996), and they are distinctly more vulnerable to weathering than the charnockite massifs themselves. The Palghat shear zone is a major component of the basement fabric, and a minimum of two sheared and mylonitised bands, 4 to 6 km wide, have been identified on its northern and southern edges (Kesavamani and Bose, 1979; Vijaya Rao and Rajendra Prasad, 2006; Chetty and

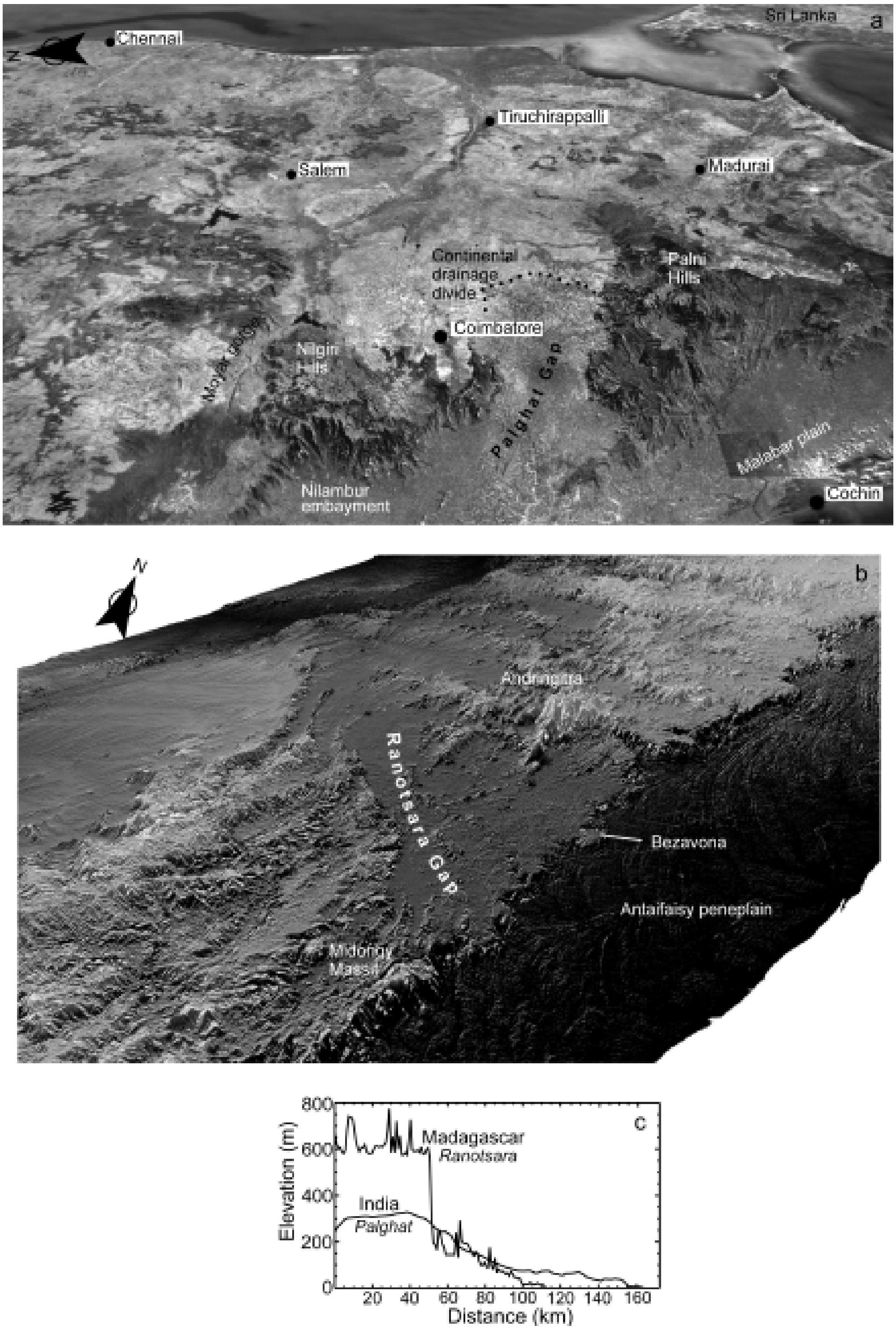

Fig. 7. Oblique aerial views of the Palghat and Ranotsara topographic gaps in the great escarpments of India and Madagascar, respectively. See Fig. 1 for location. **a**: Palghat Gap (source: Google Earth); note absence of topography in the Palghat topographic corridor and narrow isthmus between the Moyar gorge (a Precambrian shear zone) and the Nilambur embayment. **b**: Ranotsara Gap (*source:* SRTM, http://srtm.csi.cgiar.org/); note structurally controlled topographic step extending across the shear zone between coastal plain and upland. **c**: scaled topographic profiles across the Palghat and Ranotsara topographic gaps, both controlled by the Palghat–Cauvery crustal shear zone and its continuation westward into Madagascar. Note contrast between the more gentle erosional ramp in India, where neither young faults nor resistant geological structures control the topography, and the steep vertical drop in the Ranotsara Gap that erroneously suggests recent vertical fault motions.

Bhaskar Rao, 2006). The presence of Panafrican syenite pluton alignments both on the northern and southern edges of the Gap has been interpreted as due to an extensional episode that occurred during Panafrican events, but there is no indication that extensional tectonics have occurred more recently. The syenite intrusion corresponding to the Andringitra massif, which forms the most elevated nonvolcanic topography of Madagascar (Figs. 1a and 7b), may be a westward continuation of this structural trend. The presence of carbonatites (Grady, 1971) and anorthosic plutons along the Bhavani lineament, which is the eastern extension of the Palghat Gap shear zone, is a confirmation that the shear zones correspond to deep-seated crustal discontinuities.

Joints, fractures and ductile shear zones have guided stream erosion and embayment recession in the Palghat area. Jacob and Narayanaswamy (1954) and Subramanian and Muraleedharan (1985) have supported an erosional origin for the Palghat Gap, and it may not be a fortuitous coincidence that the Gap is located at the only point in the 1500-km-long escarpment where a major hornblende and biotite gneiss outcrop bridges the Arabian Sea and Bay of Bengal base levels without any geological structures such as greenstone belts barring the courses of east- or west-flowing rivers, and therefore hampering the headward conquest of the escarpment by streams (Fig. 7a). Furthermore, the rock is intensely jointed (Mani and Kumar Basu, 1973), shear planes and rock fabrics dip steeply (60–70°) towards the south, thereby facilitating the deepening of weathering fronts. Likewise, the deep Moyar gorge is guided by a Precambrian Moyar shear zone (Fig. 7a). It may in the future rejoin the Nilambur embayment, which is consuming the Moyar shear zone from its other (Arabian Sea) extremity, and thus form a second major gap through the Western Ghats. The lithologically resistant Nilgiri massif (Gunnell and Louchet, 2001) would thus become topographically disconnected from the Karnataka plateau to the north. Although a river catchment exists on the western flank of the Palghat Gap (Fig. 4), it is important to emphasize that the Palghat Gap is a continental divide and not a simple paleovalley or water gap (Fig. 7a), even though long-term fluvial erosion must have been responsible for excavating this 50 km-wide topographic corridor.

Quite unlike what can be observed on the Indian side, the abrupt topographic step visible in the Ranotsara Gap on Fig. 7b and the profile in Fig. 7c highlights the prominence of the uplift and westward tilting of the interior in shaping the plateau edge in Madagascar. By contrast, the Palghat Gap is just a gentle topographic ramp between the continental divide and the ocean.

Wider Implications: Static vs Dynamic Escarpments

Elevated escarpments are often assumed to remain self-similar over long periods of geological time, but the diversity of escarpment forms and histories at passive margins is a challenge to the simplicity of surface process models. The timing of erosion of rift shoulders at continental margins has been based on interpretations mostly inferred from sedimentary sequences at continental margins such as those of Africa (Burke and Gunnell, 2008). In this perspective, relief at the rift shoulders is reduced by thermal subsidence and erosion, and shoulder elimination is usually complete in 30–40 m.y. From that time onward, rivers flowing from the interior towards the continental margin breach the declining shoulder topography, creating water gaps and/or waterfalls such as the Aughrabies Falls in SW Africa. Accordingly, the first development of a delta prograding onto the continental shelf is often considered the best indicator of rift shoulder degradation.

Geomorphologists in recent years have qualified this model by pointing out that Great Escarpments at passive margins can persist for much longer than the 30–40 m.y. characteristic subsidence time. The absence of deltas at the Western Ghats margin was an ‘anomaly’ pointed out by Audley-Charles et al. (1977), and the same could be said of eastern Madagascar. But the reasons for this departure from the tendency observed at African passive continental margins has not so far received a clear explanation. Long-term persistence of passive margin escarpments does not challenge the general rationale behind the cycle of uplift, subsidence and sedimentation. Rather it challenges the postulated <30 m.y. timescale following which relief at rift shoulders is believed to decline.

Faults are not absent from the Western Ghats region. En-echelon fault lines have been inferred from satellite imagery in the coastal belt of the Deccan basalts (Kundu and Matam, 2000) or observed in the Bombay area (Dessai and Bertand, 1995). The corresponding lineaments strike NNW–SSE and are therefore parallel to the Precambrian fabrics that exert such a strong control over escarpment morphology in the Precambrian basement further south. However, these faults are probably syn-rift and none currently control the Ghats escarpment. Instead, they mostly underprint the drainage pattern and guide barbed drainage patterns in the coastal zone, such as in the Vashishti river basin (Harbor and Gunnell, 2007). Their direct geomorphic expression in the topography is imperceptible so that the escarpment cannot be interpreted as a normal fault scarp separating footwall highlands from a hanging-wall coastal belt.

As in the Indian setting, no single given portion of the existing escarpment morphology in Madagascar can be unequivocally attributed to primary Cretaceous rift tectonics. The escarpment overlooks a coastal belted outcrop plain, where coast-parallel geological structures beveled by long-term erosion are conspicuous (Fig. 3). The legacy of late Cretaceous relief development today survives mostly through non geomorphic features such as the strike of the coastline and the direction of rift-related volcanic dyke swarms (Kumar et al. 2001). Instead, sheeted granitic outcrops eroded out of the Panafrican collision belt are commonplace. Because these form spectacular sets of cuestas and hogbacks, they kindled interest among geomorphologists (Petit, 1971) long before geologists studied them in detail (e.g., Nedélec et al. 1994, 1995). Although such structural landforms in the Madagascan highlands and at the escarpment itself are widespread, scarp development at restricted segments in the northern part (Ankay and Alaotra rift zones) is nevertheless ascribable to Neogene to recent (i.e. post-rift) faulting.

As rift-flank escarpments erode over time, it becomes increasingly difficult without resorting to careful field geological surveys and DEM analysis to separate their evolution from lithological and structural control or, as in the case of eastern Madagascar, from neotectonic overprints. Despite belonging to sharply distinct geological provinces in terms of age, evolution, lithology and structure, both the Western Ghats and Angavo escarpments are currently consistent with a 'Type-2' escarpment *sensu* Pazzaglia and Gardner (2000), namely one which is well adjusted to rock type and crustal structure. Unless neotectonic activity becomes dominant, as locally in Madagascar, drainage systems through time organise themselves around the resistant bedrock outcrops and denudation becomes increasingly weathering-limited, with differential erosion becoming the main relief-generating process within the broader frame of competing drainages as the key reenergizing forces of escarpment evolution. The early, syn-rift relief has partly or mostly decayed due to deep denudation of the primary rift shoulders (Gunnell et al. 2003). As a result, establishing the exact nature of syn-rift lithosphere mechanics becomes over time increasingly irrelevant to explain the currently observed morphological attributes of the escarpment.

Structural and lithological impediments to landward scarp recession and to breaching by drainage systems of the continental divide are possibly the most significant parameters responsible for delaying the decay of relief at passive margins in weathering-limited environments such as the humid or seasonal Tropics. Geological structures ensure that geomorphic systems driven by unequal fluvial erosion on either side of a plateau edge get reenergized (Gunnell and Harbor, 2008) and maintain high local relief. Where geological structures parallel to the strike of the initial rifted margin are absent, situations such as in the Palghat Gap indicate that long-term denudation does indeed obliterate escarpment morphology (Fig. 7a). Structural inheritance should therefore play a critical role in extending the life of rift-shoulder escarpments beyond the 30–40 m.y. characteristic time commonly estimated from African exemplars. Structure would therefore also explain why some escarpments in weathering-limited environments might be relatively static for long periods of time despite high runoff promoted by humid climatic conditions. In other words, what appear to be persistent escarpments are likely to be either resistant escarpments (as in the Archean portion of the Western Ghats) or recently reformed escarpments (as in recently rifted northern Madagascar).

CONCLUSION

Rifting in Santonian to Campanian times between India and Madagascar affected a welt of collisional structures moulded around the Archaean Dharwar craton and corresponding to a Panafrican cordillera known as the Mozambique belt. Few overlaps exist between the two structural provinces despite the presence of a few units exhibiting Dharwar affinities in the easternmost, coastal part of Madagascar. In India, the Western Ghats correspond to an assemblage of structural landforms that hinge on lithological contrasts within the Precambrian fabric of the craton. The east Madagascar escarpment exposes a similar agenda of passive margin evolution but includes a portion of relief that has been generated by late Neogene and Quaternary faulting. The search for, and recognition of structural landforms in basement regions has been the subject of few systematic efforts (Godard et al. 2001) and has been mostly treated as a black box in numerical models of long-term landscape development at passive margins. This leads to an odd situation in which mega-geomorphology is largely decoupled from geology. Greater attention paid to structural and lithological aspects may in future assist in acquiring a more balanced appreciation of passive margin morphology in which endogenous factors (traditionally the preserve of geophysicists), structural fabrics (traditionally the preserve of structural geologists and petrologists), exogenous factors (traditionally the preserve of geomorphologists) and time are given balanced attention. Whether the Madagascan and Indian examples happen to be atypical representatives of a much more diverse spectrum of possibilities remains to be investigated, but the long-term persistence of passive margin escarpments through geological time may owe more to the stability of the structural landforms that underpin them that commonly believed.

Acknowledgements: We thank an anonymous reviewer for helpful comments on the manuscript, and Dr Harsh K. Gupta for reaching out to us for this contribution to the Geological Society of India Golden Jubilee celebration.

References

Acharyya, S.K. (2000) Break up of Australia–India–Madagascar block, opening of the Indian Ocean and continental accretion in southeast Asia with special reference to the characteristics of the peri-Indian collision zones. Gondwana Res., v.3, pp.425-443.

Audley-Charles, M.G., Curray, J.R. and Evans, G. (1977) Location of major deltas. Geology, v.5, pp.341-344.

Bertil, D. and Regnoult, J.M. (1998) Seismotectonics of Madagascar. Tectonophysics, v.294, pp.57-74.

Bésairie, H. (1957) Madagascar, Essai de carte géomorphologique, 1:1,000,000. Three sheets. Service Géologique de Madagascar, Antananarivo.

Bésairie, H. (1973) Carte géologique au 1:2,000,000 de Madagascar. Service Géologique de Madagascar, Antananarivo.

Bishop, P. and Goldrick, G. (2000) Geomorphological evolution of the East Australian continental margin. *In*: M.A. Summerfield (Ed.), Geomorphology and Global Tectonics. John Wiley and Sons Ltd., Chichester (UK), pp.225-254.

Blanford, H.F. (1858) On the Geological Structure of the Nilgiri Hills. Mem. Geol. Surv. India, v.1, pt.2.

Bourgeat, F. and Petit, M. (1969) Contribution à l'étude des surfaces d'aplanissement sur les Hautes-Terres centrales malgaches. Ann. Géogr., v.426, pp.158-188.

Brookfield, M.E. (1998) The evolution of the great river systems of southern Asia during the Cenozoic India-Asia collision: rivers draining southward. Geomorphology, v.22, pp.285-312.

Burke, K. and Gunnell, Y. (2008) The African erosion surface: a continental-scale synthesis of geomorphology, tectonics, and environmental change over the past 180 million years. Geol. Soc. Am. Memoir, v.201, 66p.

Chadwick, B., Vasudev, V.N. and Hegde, G.V. (1997) The Dharwar craton, southern India, and its Late Archean plate tectonic setting: current interpretations and controversies. Proc. Indian Acad. Sci. (Earth Planet. Sci.), v.106, pp.249-258.

Chadwick, B., Vasudev, V.N., Krishna Rao, B. and Hegde, G.V. (1991) The Dharwar Supergroup: basin development and its implications for Late Archaean tectonic setting in western Karnataka, southern India. Geology Department (key centre) and University Extension, The University of Western Australia, Publ. no. 22, pp.3-15.

Chardon, D., Jayananda, M., Chetty, T.R.K. and Peucat, J.-J. (2008) Precambrian continental strain and shear zone patterns: the South Indian case. Jour. Geophys. Res., 2007JB005299, in press.

Chetty, T.R.K. (1996) Proterozoic shear zones in southern granulite terrain, southern India. *In:* M. Santosh and M. Yoshida (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.

Chetty, T.R.K. and Bhaskar Rao, Y.J. (2006) The Cauvery Shear Zone, southern Granulite terrain, India: a crustal scale flower structure. Gondwana Res., v.10, pp.77-85.

Chikka Reddy, F.V. (1987) Kudremukh geology, *In:* National Seminar on Geology, Ecology and Environment of the Western Ghats. Papers and Abstracts, Department of Marine Geology, Mangalore University, Mangalore, India, pp.72-73.

Collins, A.S., Clark, C., Sajeev, K., Santosh, M., Kelsey, D.E. and Hand, M. (2007) Passage through India: the Mozambique Ocean suture, high-pressure granulites, and the Palghat–Cauvery shear zone system. Terra Nova, v.19, pp.141-147.

Collins, A.S., Fitzsimons, I.C.W., Hulscher, B. and Razakamanana, T. (2003) Structure of the eastern margin of the East African Orogen in central Madagascar. Precambrian Res., v.123, pp.111-133.

D'Cruz, E., Nair, P.K.R. and Prasannakumar, V. (2000) Palghat Gap—A dextral shear zone from the South Indian Granulite Terrain. Gondwana Res., v.3, pp.21-31.

De Wit, M.J. (2003) Madagascar: heads it's a continent, tails it's an island. Annu. Rev. Earth. Planet. Sci., v.31, pp.213-248.

Demangeot, J. (1975) Recherches géomorphologiques en Inde du Sud. Z. Geomorph., v.19, pp.229-272.

Dessai, A.G. and Bertrand, H. (1995) "Panvel Flexure" along the western Indian continental margin: an extensional fault structure related to Deccan magmatism. Tectonophysics, v.241, pp.165-178.

Durg, N.L. (1969) A structural study of the phyllites near Dandeli, Mysore state. Quart. Jour. Geol. Min. Metal. Soc. India, v.41, pp.153-156.

Geological Survey of India (1981) Geological and Mineralogical map of Karnataka and Goa, 1:500,000, 4 sheets. Geological Survey of India, Calcutta.

Gilchrist, A.R., Kooi, H. and Beaumont, C. (1994) Post-Gondwana geomorphic evolution of southwestern Africa: Implications for the controls of landscape development from observations and numerical experiments. Jour. Geophys. Res., v.99, pp.12211-12228.

Godard, A., Lagasquie, J.-J., Lageat Y. and Gunnell, Y. (Eds.) (2001) (Transl.), Basement Regions. Springer Verlag, Heidelberg, 306p.

Grady, J.C. (1971) Deep main faults in South India. Jour. Geol. Soc. India, v.12, pp.56-62.

Gunnell, Y. and Louchet, A. (2000) The influence of rock hardness and divergent weathering on the interpretation of apatite fission track denudation rates. Evidence from charnockites in South India and Sri Lanka. Z. Geomorph., v.44, pp.33-57.

Gunnell, Y. and Harbor, D. (2008) Butte detachment: where pre-rift geologic structure and drainage integration drive escarpment evolution at rifted continental margins. Earth Surf. Proc. Land., *in press*.

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.

Harbor, D., Bacastow, A., Heath, A. and Rogers, J. (2005) Capturing variable knickpoint retreat in the Central Appalachians, USA. Geogr. Fis. Din. Quat., v.28, pp.23-36.

Harbor, D. and Gunnell, Y. (2007) Along-strike escarpment heterogeneity of the Western Ghats: a synthesis of drainage and topography using digital morphometric tools. Jour. Geol. Soc. India, v.70, pp.411-426.

Jacob, K. and Narayanaswami, S. (1954) The Structural and Drainage Pattern of the Western Ghats in the vicinity of the Palaghat Gap. Proc. Nat. Inst. Sci., India, v.20, pp.101-118.

Kesavamani, M. and Bose, R.N. (1979) Evolution of Palghat Gap — Geophysical appraisal. *In:* Third Workshop on Status, Problems and Programmes in Indian Peninsular Shield. Institute of Indian Peninsular Geology, Hyderabad, pp.178-185.

Krishna Rao, J.S.R., Murthy, P.S.N. and Murthy, D.S.N. (1977) Mineralogy and petrology of the amphibolites and dolerites from Kudremukha, Karnataka state, South India. Quart. Jour. Geol. Min. Metal. Soc. India, v.49, pp.75-84.

Kumar, A., Pande, K., Venkatesan, T.R., and Bhaskar Rao, Y.J. (2001) The Karnataka Late Cretaceous dykes as products of the Marion hot spot at the Madagascar–India breakup event: evidence from ^{40}Ar-^{39}Ar geochronology and geochemistry. Geophys. Res. Lett., v.28, pp.2715-2718.

Kundu, B. and Matam, A. (2000) Identification of probable faults in the vicinity of Harnai-Ratnagiri region of the Konkan coast, Maharashtra, India. Curr. Sci., v.78, pp.1556-1560.

Kusky, T. M., Toraman, E. and Raharimahefa, T. (2007) The great rift valley of Madagascar: An extension of the Africa–Somali diffusive plate boundary? Gondwana Res., v.11, pp.577-579.

Machette, M.N., Personius, S.F. and Nelson, A.R. (1992) The Wasatch faut zone, USA. Ann. Tect., v.6, pp.5-39.

Mani, G. and Kumar Basu, A. (1973) Origin of the Palghat gap, in Symposium on Peninsular Shield (Abstract). Geology Department, Osmania University, Hyderabad, p.8.

Naqvi, S.M., Sawkar, R.H., Subba Rao, D.V., Govil, P.K. and Gnaneswar Rao, T. (1988) Geology, geochemistry and tectonic setting of Archean greywackes from Karnataka Nucleus, India. Precambrian Res., v.39, pp.193-216.

Nédélec, A., Paquette, J.-L., Bouchez, J.-L., Olivier, P. and Ralison, B. (1994) Stratoid granites of Madagascar: structure and position in the Panafrican orogeny. Geodinamica Acta, v.7, pp.48-56.

Nédélec, A., Stephens, W.E. and Fallick, A.E. (1995) The Panafrican stratoid granites of Madagascar: alkaline magmatism in a post-collisional extensional setting. Jour. Petrol., v.36, pp.1367-1391.

Paquette, J.L., Nédélec, A., Moine, B. and Rakotondrazafy, M. (1994) U-Pb, Single Zircon Pb-Evaporation, and Sm-Nd Isotopic Study of a granulite Domain in SE Madagascar. Jour. Geol., v.102, pp.523-538.

Pazzaglia, F.J. and Gardner, T.W. (2000) Late Cenozoic landscape evolution of the US Atlantic passive margin: insights into a North American Great Escarpment. *In*: M.A. Summerfield, (Ed.), Geomorphology and Global Tectonics. John Wiley and Sons Ltd, Chichester, pp.293-302.

Petit, M. (1971) Contribution à l'étude morphologique des reliefs granitiques à Madagascar. Publ. Faculté Lettres, Antananarivo, 307p.

Petit, M. (1999) Présentation physique de la Grande Ile Madagascar. Agence de la Francophonie, Antananarivo, 192p.

Piqué, A., Laville, E., Chotin, P., Chorowicz, J., Rakotondraompiana, S. and Thouin, C. (1999) L'extension à Madagascar du Néogène à l'actuel: arguments structuraux et géophysiques. Jour. Afr. Earth Sci., v.28, pp.975-983.

Raharimahefa, T. and Kusky, T.M. (2006) Structural and remote sensing studies of the southern Betsimisaraka suture, Madagascar. Gondwana Res., v.10, pp.186-197.

Ramakrishnan, M. (1993) Tectonic evolution of the granulite terrains of South India. *In*: B.P. Radhakrishna (Ed.), Continental crust of South India. Mem. Geol. Soc. India, no.25, pp.35-44.

Ramakrishnan, M. and Harinadha Babu, P. (1981) Western Ghat Belt. *In*: J. Swami Nath and M. Ramakrishnan (Eds.), Early Precambrian Supracrustals of Southern Karnataka. Geol. Surv. India Mem., v.112, pp.147-162.

Raval, U. and Veeraswamy, K. (2003) India–Madagascar separation: breakup along a pre-existing mobile belt and chipping of the craton. Gondwana Res., v.6, pp.467-485.

Reeves, C. and de Wit, M. (2000) Making ends meet in Gondwana : retracing the transforms of the Indian Ocean and reconnecting continental shear zones. Terra Nova, v.12, pp.272-280.

Sampat Iyengar, P. (1913) The geology of Kudremukh-Gangamula region. Rec. Mysore Geol. Dept., v.12, pp.45-77.

Schmidt, K.-H. (1988) Rates of scarp retreat: a means of dating neotectonic activity. *In:* V.H. Jacobshagen, (Ed.), The Atlas System of Morocco. Springer Verlag, Berlin, pp.445-462.

Schmidt, K.-H. (1989) The significance of scarp retreat for Cenozoic landform evolution on the Colorado Plateau, USA. Earth Surf. Proc. Land., v.14, pp.93-105.

Schmidt, K.-H. (1994) The groundplan of cuesta scarps in dry regions as controlled by lithology and structure. *In*: D.A. Robinson and R.G.B. Williams (Eds.), Rock Weathering and Landform Evolution. John Wiley and Sons Ltd, Chichester, UK.

Small, R.J. (1970) The study of landforms: a textbook of geomorphology. Cambridge University Press, Cambridge.

SREERAMACHANDRA RAO, K. (1977) Stratigraphy, structure and origin of the iron formations of Kodachadri region, Shimoga district, Karnataka state. Quart. Jour. Geol. Min. Metal. Soc. India, v.49, pp.71-86.

SRIVASTAVA, V.C. and PRASAD, K.N. (1984) Geomorphic and tectonic features aroud Kudremukh, Chikmagalur District, Karnataka. Rec. Geol. Surv. India, v.114, pp.80-83.

SUBRAMANIAN, K.S. and MURALEEDHARAN, M.P. (1985). Origin of the Palghat Gap in South India – a synthesis. Jour. Geol. Soc. India, v.26, p.28-37.

TORSVIK, T.H., TUCKER, R.D., ASHWAL, L.D., CARTER, L.M., JAMTVEIT, B., VIDYADHARAN, K.T. and VENKATARAMANA, P. (2000) Late Cretaceous India–Madagascar fit and timing of break-up related magmatism. Terra Nova, v.12, pp.220-224.

TWIDALE, C.R. (1991) A model of landscape evolution involving increased and increasing relief amplitude. Z. Geomorph., v.35, pp.85-109.

VALDIYA, K.S. (2001) River response to continuing movements and scarp development in central Sahyadri and adjoining coastal belt. Jour. Geol. Soc. India, v.57, pp.13-30.

VAN DER BEEK, P.A., PULFORD, A. and BRAUN, J. (2001) Cenozoic landscape development in the Blue Mountains (SE Australia): lithological and tectonic controls on rifted margin morphology, Jour. Geol., v.109, pp.35-56.

VASUDEV, V.N. and RANGANATHAN, N. (1994) Vanadium and sulphide-bearing titaniferous magnetite bodies in western Dharwar craton. *In*: B.M. Ravindra and N. Ranganathan (Eds.), Geo Karnataka. Karnataka Assistant Geologists' Association, Department of Mines and Geology, Bangalore, pp.168-181.

VIJAYA RAO, V. and RAJENDRA PRASAD, B. (2006) Structure and evolution of the Cauvery Shear Zone system, Southern Granulite Terrain, India: evidence from deep seismic and other geophysical studies. Gondwana Res., v.10, pp.229-40.

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

WINDLEY, B., RAZAFINIPARANY, A., RAZAKAMANANA, T. and ACKERMAND, D. (1994) Tectonic framework of the Precambrian Madagascar and its Gondwana connections: a review and reappraisal. Geol. Rundsch., v.83, pp.642-659.

YOSHIDA, M., MUHONGO, S., RAMBELOSON, R. and JANARDHAN, A.S. (Eds.) (1999) Madagascar within Gondwanaland. Gondwana Res., v.2, pp.335-502.

(Received: 21 November 2007; Revised form accepted: 26 March 2008)