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New physical evidence of the role of stream capture in active retreat of the Blue Ridge escarpment, southern Appalachians

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ABSTRACT

The Blue Ridge escarpment of the southern Appalachian Mountains is a striking and rugged topographic feature of the ancient passive margin of eastern North America. The crest of the escarpment generally coincides with an asymmetric regional drainage divide, separating steep streams of the escarpment face from low-gradient streams of the Blue Ridge Upland. Recent exhumation and erosion rate studies suggest that the escarpment has evolved by inland erosional retreat, but the mechanism, timing, and magnitude of retreat remain poorly understood. Longitudinal stream profiles and slope–drainage area relationships of several upland basins draining the divide have led to the identification of 14 previously unknown fluvial terrace deposits preserved at the escarpment crest. These relict terraces and the associated beheaded drainages indicate the role of large stream capture events in producing ongoing escarpment retreat through landward divide migration and subsequent topographic adjustment. Terrace location and preservation suggest that rectilinear drainage patterns and divide asymmetry generate discrete high order captures and episodes of rapid localized retreat that collectively produce slower evolution of the escarpment at large. While overall retreat magnitude and rate remain unknown, roundness of terrace alluvium suggests that the most recent captures have locally produced tens of kilometers of retreat within the limited preservation lifetime of the deposits. In contrast with recent numerical modeling and cosmogenic studies, these data show the potential for stream capture and divide migration to sustain passive margin escarpment evolution long after the cessation of rifting. The fluvial record of divide retreat preserved atop the Blue Ridge escarpment suggests the potential for using field methods to better constrain the histories of younger, taller, and potentially more dynamic passive margin escarpments.

1. Introduction

Major seaward-facing topographic escarpments are common features of rifted passive margins. Such "great" escarpments are believed to initiate during rift-flank uplift and subsequently evolve through erosional processes (Ollier, 1984; Kooi and Beaumont, 1994; Gallagher and Brown, 1997). Rapid erosion focused on the steep flank of a rift may produce inland retreat (Ollier, 1984; ten Brink and Stern, 1992; Young and McDougall, 1993; Tucker and Slingerland, 1994; Seidl et al., 1996), but the controls on the rate, timing, and mechanism of escarpment migration following rifting are poorly understood. Some great escarpments, such as southwestern Africa and southeastern Australia, appear to have migrated little since the early stages of development (Moore et al., 1986; Gilchrist et al., 1994; Bishop and Goldrick, 2000; Cockburn et al., 2000; Matmon et al., 2002; Persano et al., 2002), while other escarpments, such as southeastern Brazil and the Blue Ridge escarpment of eastern North America, may have continued to retreat into the late stages of escarpment development (Bohannon et al., 1989; Gallagher et al., 1994; Steckler and Omar, 1994; Brown et al., 2000; Spotila et al., 2004). The existence of a universal paradigm applicable to great escarpment evolution is thus questionable.

Further constraining the chronology and mechanisms of great escarpment retreat, particularly along mature passive margins, is significant to improving our understanding of the evolution of passive margin landscapes. After rifting, escarpments may be rapidly excavated by downwearing seaward of a fixed drainage divide (van der Beek and Braun, 1999; Matmon et al., 2002) or experience slow but steady retreat in parallel with the divide (King, 1962; Fig. 1). However, no clear global relationship exists between escarpment age (determined by age of rifting) and distance from the coast; the Sri Lanka escarpment (180 Ma, 65 km from the present coastline; Vanacker et al., 2007), the Drakensberg escarpment (130 Ma, 150 km from the present coastline; Moore and Blenkinsop, 2006), and the southeastern Australia escarpment (85–100 Ma, 60 km from the coastline; Weissel and Seidl, 1998) imply different overall retreat distances and long-term average rates. The Blue Ridge escarpment (BRE), a passive margin escarpment often overlooked in great escarpment studies, occurs along the oldest passive margin in the world (initial rifting at ~200 Ma; Pique and Laville, 1995; McHone, 1996), yet it is located within 70 km of inland rift basins and maintains steep, youthful topography (Spotila et al., 2004). The timing of

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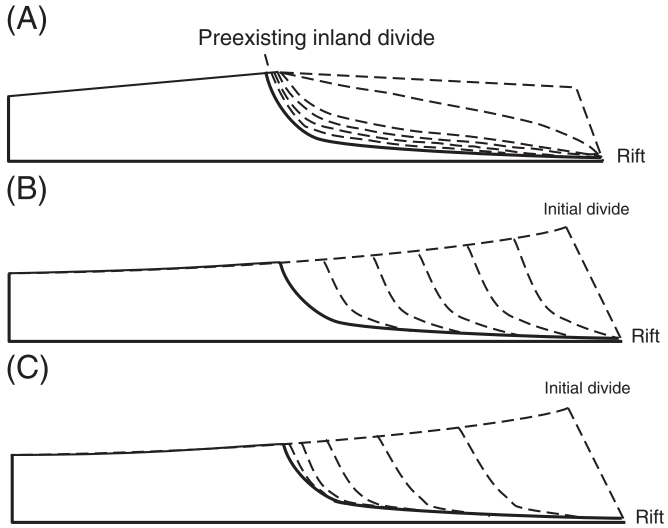


Fig. 1. Comparison of three popular models of passive margin escarpment evolution. Dotted lines trace the development of escarpment topography across equal time intervals. All models ultimately produce escarpments of similar morphology despite differing mechanisms and rates of retreat. (A) Rift-related base level drop seaward of a preexisting drainage divide steepens large streams and rapidly excavates an escarpment at the divide. Subsequent retreat is minimal. (B) Rift flank uplift produces an asymmetric divide atop the rift shoulder. Focused erosion on the steep flank of the divide produces steady parallel retreat of divide and escarpment. (C) The parallel retreat mechanism of B decelerates because of the decrease in escarpment relief. After van der Beek et al., 2002.

exhumation of the area seaward of the BRE is comparable with that observed seaward of the ~100 Myr younger southeastern Australia escarpment, each with low temperature (U–Th)/He apatite cooling ages of ~85–110 Ma (Persano et al., 2002; Spotila et al., 2004). The persistent ruggedness of the BRE, despite its age, makes it unique among great escarpments, and further constraining the mechanism and potentially the timing of retreat is necessary to understanding long-term BRE evolution. The results of this study may, in turn, find application to other great escarpments, where establishing additional controls over long-term retreat mechanisms may enhance the interpretation of existing cosmogenic and thermochronologic data sets.

In this paper, we examine fluvial terraces preserved at the crest of the BRE and physical characteristics of beheaded upland drainage basins as a possible record of ongoing parallel escarpment retreat. Terraces were systematically located through the analysis of upland drainage basin morphology. Rounded to well-rounded alluvium from the terraces was subsequently sampled for clast roundness measurements, which were used to estimate clast transport distance. The use of field-based data aids in testing recent models for the origin and evolution of the BRE generated by apatite thermochronometry (Spotila et al., 2004), cosmogenic radionuclides (Sullivan et al., 2007), and drainage basin geometry (Bank, 2001). Terraces provide new field evidence of significant parallel retreat of the escarpment and divide continuing throughout the Cenozoic. Analysis of beheaded drainages provides an additional indicator of escarpment retreat and drainage divide encroachment. The preservation and predictable location of surficial and topographic evidence of BRE retreat also suggests the possibility of using field techniques to better characterize the evolution of younger, and potentially better preserved, passive margin escarpments.

2. Background

2.1. Long-term evolution of great escarpments

Clearly identifiable great escarpments occur along approximately one-third of the world's passive margins (Ollier, 1984). These escarpments exist as topographic steps separating low-elevation, low-relief coastal plains from elevated continental interiors. Great escarpments are typically ~0.3–1 km high and exist as narrow bands (~5–20 km) of rugged topography separating the lower relief coastal plain and upland surfaces. They are generally classified as either "shoulder-type" or "arch-type," depending on the position of the regional divide in relation to the crest of the escarpment (Matmon et al., 2002). The hypothesis of escarpment evolution by landward retreat after rifting is based on observations of active rift margins, where dynamic continental uplift and base level drop seaward of the divide produce focused erosion and steep, seaward-facing landforms.

Recent studies of thermochronometry, cosmogenic radionuclides, and offshore sedimentary data have suggested some escarpments evolve by initially rapid erosion that slows considerably as seaward-flowing streams begin to adjust to rift-related base level (Drakensberg escarpment (Fleming et al., 1999), Namibia (Rust and Summerfield, 1990; Cockburn et al., 2000; Bierman and Caffee, 2001), Sri Lanka (von Blanckenburg et al., 2004; Vanacker et al., 2007), and southeastern Australia (van der Beek and Braun, 1999; Persano et al., 2002)). Continued knickpoint retreat on these seaward-flowing rivers may, however, increase escarpment sinuosity over time with little retreat of the topographic front (Weissel and Seidl, 1998; Heimsath et al., 2000; Matmon et al., 2002). In contrast, other data suggest significant escarpment retreat continues long after rifting. Inferred exhumation histories of escarpments surrounding the Atlantic basin, such as eastern Brazil, southwest Africa, and eastern North America are consistent with continued late-stage retreat (Gallagher et al., 1994; Brown et al., 2000; Spotila et al., 2004). Drainage patterns along the Western Ghats escarpment suggest continuing capture of upland streams, leading to overall parallel retreat of the drainage divide and escarpment (Harbor and Gunnell, 2007).

Numerical modeling has shown the influence of pre-rift topography, particularly the location of the regional drainage divide, on the rate and mechanism of escarpment evolution (Fig. 1). Modeling by van der Beek and Braun (1999) and van der Beek et al. (2002) showed that initial rapid evolution and subsequent stability are consistent with downwearing from a preexisting inland divide (arch-type of Matmon et al., 2002). Large streams flowing seaward from the divide are energized by rift-induced base level drop and rapidly excavate an escarpment at the divide as they equilibrate to the new base level. Following this equilibration, the lower-energy seaward stream headwaters accomplish minimal additional retreat (Fig. 1A). The more traditional model of prolonged, steady escarpment retreat involves the formation of a new, asymmetric regional divide, which retreats in parallel with the escarpment as a result of constant, focused erosion on the steep flank and upland stability (King, 1962) (Fig. 1B).

While cosmogenic data indicating very slow retreat of many mature escarpments are consistent with the downwearing model (e.g., Cockburn et al., 2000; Brown et al., 2002), slow escarpment erosion could result from reduced relief and thus be consistent with the parallel retreat model as well. Climatic effects have also been suggested as a means of accelerating or slowing parallel retreat (Partridge, 1998). Thermochronological data do not clearly distinguish between downwearing or parallel retreat because of low geothermal gradients and modest escarpment relief of ~1 km or less (Braun and van der Beek, 2004). The contrast between these models makes constraining retreat mechanism an important step toward describing the origin and evolution of escarpments. Downwearing and parallel retreat scenarios have been modeled to ultimately produce escarpments of similar morphology despite different rates (Fig. 1), suggesting that the present morphology of escarpments may not provide clues to the mechanism of their evolution (Braun, 2006). The application of field methods aimed at determining the role of the drainage divide may add a useful additional constraint to the modeling of escarpment evolution.

Understanding escarpment retreat mechanisms has equally profound implications for the maintenance of rugged landforms over time. The relief-reducing processes of Davis (1902) and Penck (1953) explain low-relief upland and lowland surfaces, but fail to account for passive margin escarpment steepness. Parallel slope retreat as explained by King (1957) allows for the maintenance of relief over time, as the high potential energy of steep hillslopes focuses erosion while allowing upland areas to remain comparatively stable. This concept is now viewed as largely dependent upon lithology and structure, such as resistant caprocks and escarpment-parallel jointing that stabilize uplands and ease removal of material from the escarpment face (Munro-Perry, 1990; Moore and Blenkinsop, 2006; Gunnell and Harbor, 2008). In contrast, Penck (1953) hypothesized that uplands should erode along with the steeper escarpment face, reducing relief over time. This long-standing debate of landform evolution may find some resolution in the study of old passive margin escarpments.

2.2. The Blue Ridge escarpment

The BRE stretches over 500 km along the eastern edge of the southern Appalachian highlands (Fig. 2). Rising in 300–600 m of relief above the 200–300 m Piedmont, the BRE represents an abrupt topographic boundary between the lower-relief Piedmont and Blue Ridge Upland (or simply, the "Upland") surfaces. Long wavelength slopes average 24° in the BRE zone in Virginia, with steeper slopes developed on granitoid rocks in North Carolina (Spotila et al., 2004). In contrast to most high-relief zones in the Appalachians, the steep topography of the BRE does not coincide with the outcrop of a resistant lithology. Bedrock units on either side of the escarpment offer essentially equal resistance to erosion, and contacts between units cut across the BRE at varying angles. The BRE also shows no clear relationship to the nearby Brevard/Bowens Creek fault zone (Fig. 3), which crosses the BRE in western North Carolina (Fig. 3) (Dietrich, 1959; Hack, 1973; Virginia Division of Mineral Resources, 2003). Landward of the BRE, the Blue Ridge Upland forms a broad plateau, termed the Floyd Surface by Dietrich (1957), which extends southwest from Roanoke, Virginia and is characterized by rolling hills, thick soils and saprolites, and aggraded valleys (Fig. 2). Average slope atop the Upland in Virginia is ~10°, but the surface becomes increasingly rugged to the southwest (Spotila et al., 2004). The Upland extends ~40 km from the crest of the BRE northwest to the Valley and Ridge fold-thrust belt (Figs. 2, 3A). Northeast of Roanoke, the Blue Ridge highlands rise above the Piedmont as a narrow ridge isolated from the highlands farther west. This ridge morphology appears to have developed as a result of Atlantic basin rivers (e.g., Roanoke, James, and Potomac) breaching the western margin of the Upland and rapidly eroding the weak sedimentary rocks of the eastern Valley and Ridge (Harbor, 1996). In contrast, the Blue Ridge Upland forms a plateau that remains physically and fluvially connected to the westward-draining areas of the Valley and Ridge and Appalachian Plateau to the north and west. Several large westward-flowing streams with headwaters on the Upland surface ultimately drain portions of all three provinces (Fig. 2).

As a shoulder-type escarpment, the majority of the crest of the BRE coincides with the Eastern Continental Divide (ECD), an asymmetric regional drainage divide between Gulf of Mexico (west-flowing) and Atlantic (east-flowing) streams (Hayes and Campbell, 1894; Davis, 1903; Wright, 1927; Dietrich, 1957; Hack, 1973) (Figs. 2, 3). The low gradient of the westward-flowing streams draining the Upland contrasts strongly with the steep headwaters of streams draining the narrow BRE zone (Fig. 4). The steep escarpment slopes provide energy to Atlantic basin streams plunging toward the Piedmont whose erosive power is evident in cascading bedrock reaches and oversteepened fluvial profiles. Hack (1973) viewed the atypical steepness of the escarpment slope streams compared to Upland and nearby Piedmont streams draining the same lithology as evidence of fluvial disequilibrium along the BRE. These streams flatten rapidly upon reaching the low-relief Piedmont where generally symmetrical drainage divides and lower stream gradients suggest a more equilibrated landscape. Some Atlantic basin streams draining the escarpment appear to have captured Upland streams, such as the Dan

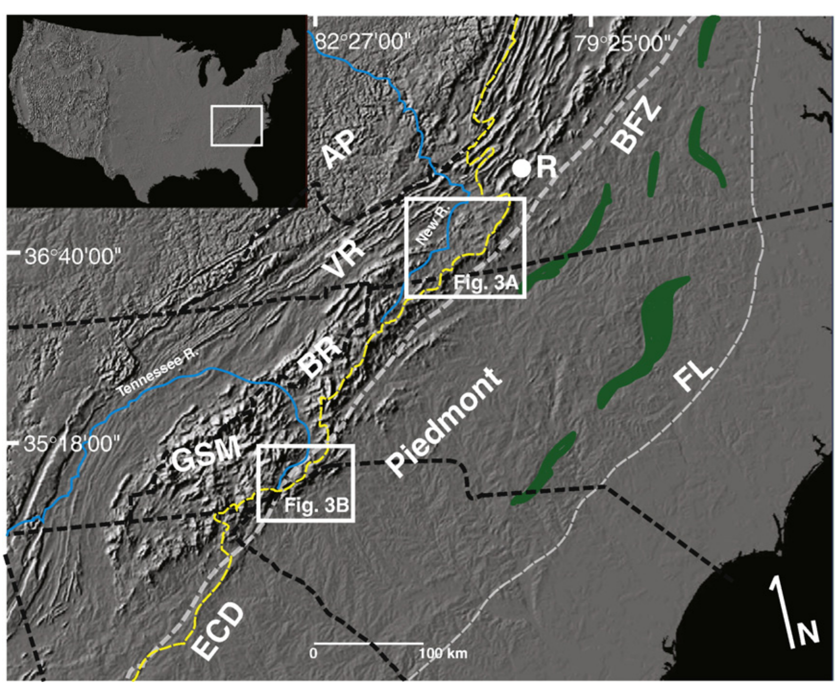
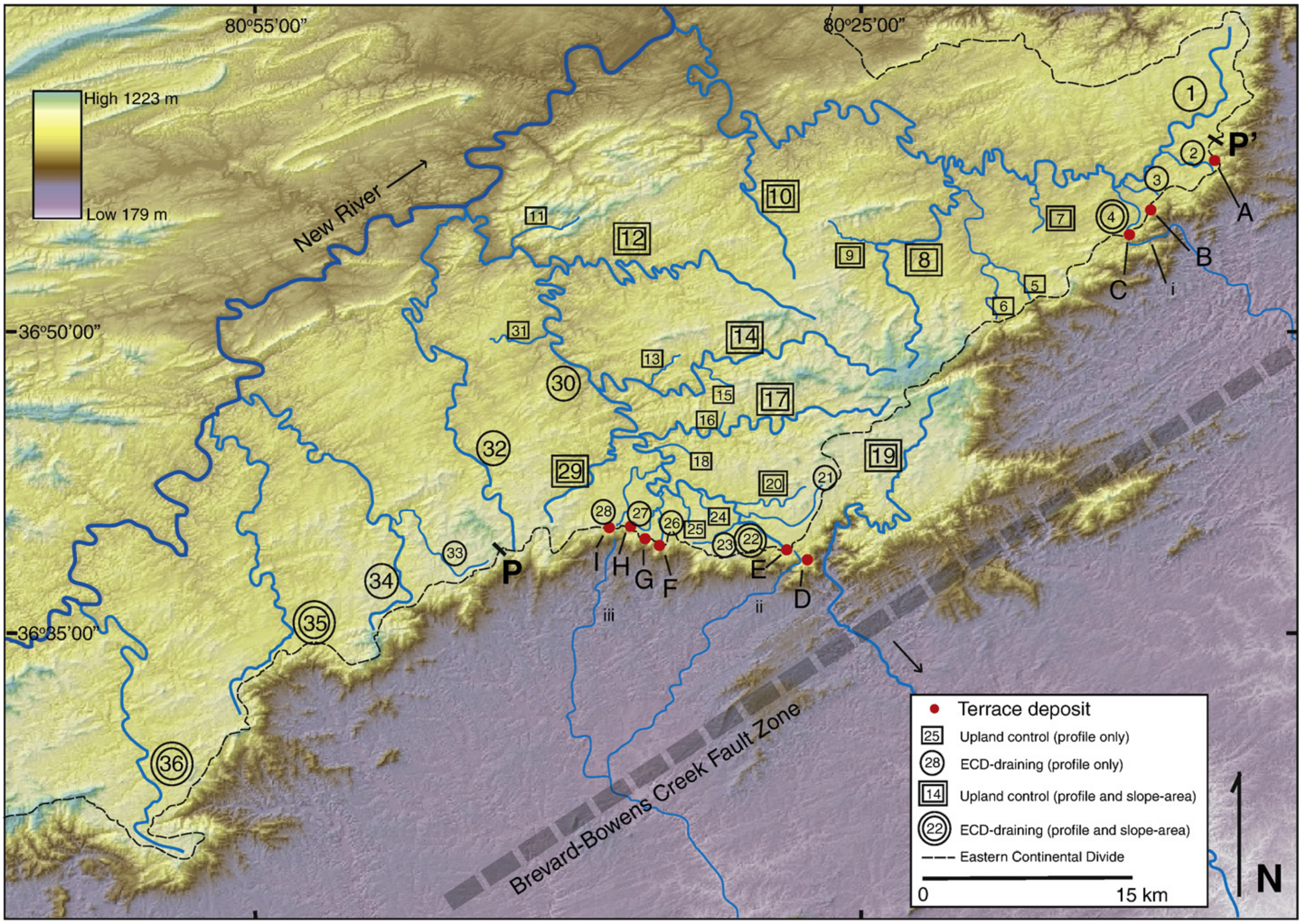


Fig. 2. Location of the Blue Ridge escarpment and Eastern Continental Divide (ECD) in relation to relevant topographic and geologic features of the southern Appalachians. The escarpment is the area of steep topography separating the Blue Ridge (BR) and Piedmont physiographic provinces. South of Roanoke, Virginia (R), the escarpment coincides with the ECD (yellow line). Mesozoic basins in the Piedmont are shown in green. Brevard/Bowens Creek fault zone (BFZ) is identified by red line. Fall line (FL) is denoted by gray line. VR = Valley and Ridge, AP = Appalachian Plateau, and GSM = Great Smoky Mountains. Boxes denote locations of Fig. 3A and B.

(A)


80°55'00"
80°25'00"
36°50'00"
36°35'00"
High 1223 m
Low 179 m
New River
P
P'
A
B
C
D
E
F
G
H
I
i
ii
iii
1
2
3
4
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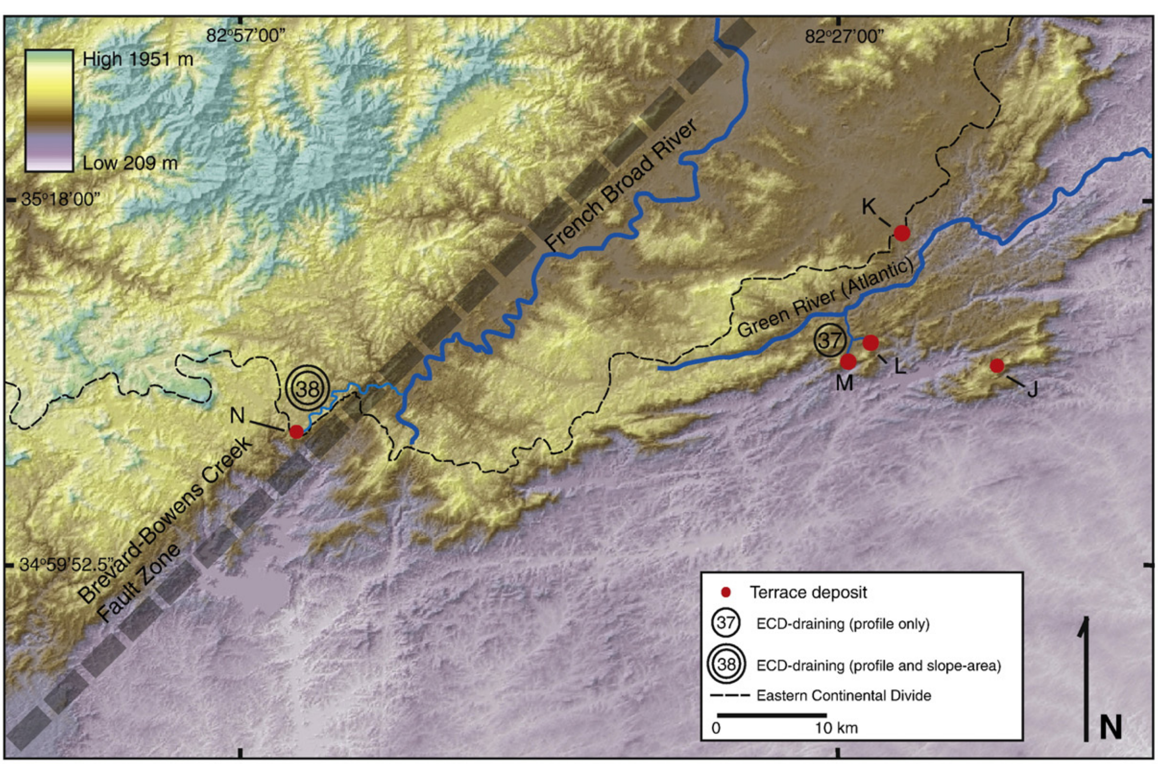
34
35
36
Brevard-Bowens Creek Fault Zone
Terrace deposit
25 Upland control (profile only)
28 ECD-draining (profile only)
14 Upland control (profile and slope-area)
22 ECD-draining (profile and slope-area)
Eastern Continental Divide
0
15 km
N

(B)


82°57'00"
82°27'00"
35°18'00"
34°59'52.5"
High 1951 m
Low 209 m
French Broad River
Green River (Atlantic)
Brevard-Bowens Creek Fault Zone
K
L
M
J
N
37
38
Terrace deposit
37 ECD-draining (profile only)
38 ECD-draining (profile and slope-area)
Eastern Continental Divide
0
10 km
N

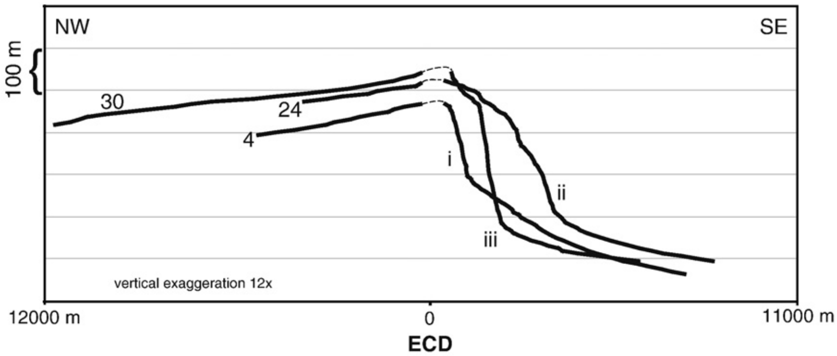


Fig. 4. Long profiles of three pairs of Upland and Atlantic basin streams (Fig. 3A) illustrating the asymmetry of the Eastern Continental Divide. The overall convex profile of the Ararat River (ii) indicates a large zone of active incision that may result from a recent capture event that stranded terrace E (Fig. 3A).

River of Virginia (stream 19, Fig. 3A), whose headwaters meander across the Upland before turning 90° and dropping over 600 m to the Piedmont (Dietrich, 1957; Hack, 1973). Apparent redistribution of fish species of the New River basin into streams comprising the headwaters of the Atlantic-draining Roanoke River basin (streams 19, i and ii of Fig. 3) provides further qualitative evidence of the capture of westward-flowing drainages (for a review, see Jenkins et al., 1971). These topographic and biological data provide anecdotal evidence of stream capture and episodic divide and BRE retreat.

The BRE has long been viewed as a feature shaped by erosional retreat related to the asymmetry of the divide (Davis, 1903; Wright, 1927; White, 1950; Dietrich, 1957, 1959; Harbor, 1996) but has seldom been regarded as a great escarpment produced by rift-flank uplift (e.g., Ollier, 1984; Tucker and Slingerland, 1994). Pazzaglia and Gardner (2000) suggested that the BRE is a great escarpment that was excavated from a fixed inland divide after Mesozoic rifting and base level drop. Other hypotheses for its origin have favored active tectonic or geodynamic origins. White (1950) proposed that normal-sense reactivation of the nearby Brevard/Bowens Creek fault zone produced the escarpment. Numerous workers have cited isostatic rebound related to thickened Appalachian crust or flexural response to offshore sediment loading as drivers of BRE formation and evolution (Wright, 1927; Pratt et al., 1988; Battiau-Queney, 1989; Hubbard et al., 1991; Pazzaglia and Brandon, 1996; Pazzaglia and Gardner, 2000). Spotila et al. (2004) presented thermochronological constraints on BRE evolution. Cooling histories of the Upland and Piedmont are distinct, suggesting that they do not represent a single offset "surface." These data also showed no difference in cooling ages across the Brevard/Bowens Creek fault zone, suggesting that reactivation of the structure did not form the BRE. The greater exhumation that has occurred on the Piedmont during the past 100 Ma is consistent with the erosional removal of a topographic bulge seaward of the present escarpment and, hence, long-lived retreat. While these data argue against local faulting or uplift as the origin of the BRE, they do not distinguish between escarpment formation through differential erosion by parallel retreat or downwearing from a preexisting or fixed inland divide. Thermochronology also fails to indicate distance and timing of retreat or association with an initiating structure in the present Piedmont. Verifying the mechanism of erosional retreat and constraining the kinematics of retreat are essential to testing the varied hypotheses of BRE origin.

Sparse field evidence of parallel retreat, in the form of well-rounded alluvium preserved near the BRE and divide and the character of beheaded streams, has previously been reported (Wright, 1927; Dietrich, 1957, 1959; Bank, 2001). Rounded cobbles and boulders scattered in dry valleys or on hilltops near the divide are believed to have been stranded by a reduction in drainage basin area and competence of westward-flowing Upland streams through landward escarpment and divide migration (Dietrich, 1957, 1959). This proposed origin of the alluvium is consistent with qualitative observations suggesting drainage basin reduction in westward-flowing Upland streams that now originate at the ECD. Many Upland streams begin to meander very close to their headwaters at the escarpment lip, while Piedmont streams of similar size show no meanders (Spotila et al., 2004). Wide, flat valleys and swamps are common at headwaters in close proximity to the divide, atypical of the headwaters of other streams atop the Upland surface. Quantitative study of fluvial profiles and slope–drainage area relationships of these streams may aid in verifying basin reduction as a product of divide and escarpment retreat. Establishing the provenance of escarpment-crest alluvium should further enhance understanding of retreat kinematics. The use of field-based proxies for escarpment evolution has proved somewhat useful in other locations, such as localized deposits preserved seaward of the Western Ghats escarpment (Widdowson and Gunnell, 1999; Harbor and Gunnell, 2007), weathering surfaces and duricrusts of the South African upland (Partridge and Maud, 1987), and the offshore stratigraphic record of erosion along the BRE (Poag and Sevon, 1989; Naeser et al., 2006) and southwestern Africa (Rust and Summerfield, 1990). Alluvium preserved at the escarpment crest and evidence of drainage basin reduction may thus directly reflect the history of divide retreat and provide concrete physical constraints on the evolution of the BRE.

3. Methods

To obtain empirical constraints on the kinematics of BRE retreat, we have investigated the morphology of beheaded streams on the Upland and characterized associated relict alluvium preserved atop the divide. Both of these sources of data should reflect any loss of basin area from parallel retreat of the divide and escarpment. Progressive encroachment of the divide into established Upland basins may have

Fig. 3. (A) Shaded relief map of Virginia study area showing streams (numbers) and terrace deposits (letters) used. Larger numbers indicate large streams whose profiles are presented in Fig. 5B. P and P′ are endpoints along a topographic profile of the ECD (Fig. 8). ECD and Brevard fault zone (BFZ) are indicated. Map is based on 10-m resolution DEM. Streams are labeled as follows: 1 = Little River, 2 = Payne Creek, 3 = Silverleaf Branch, 4 = Meadow Creek, 5 = Thomas Grove Church tributary to Dodd Creek, 6 = W. Fork Dodd Creek, 7 = Oldfield Creek, 8 = W. Fork Little River, 9 = Spurlock Creek, 10 = Big Indian Creek, 11 = Rock Creek, 12 = Greasy Creek, 13 = Burks Fork tributary, 14 = Burks Fork, 15 = Adams Branch, 16 = Chisholm Creek, 17 = Laurel Fork, 18 = Bear Creek, 19 = Dan River (Atlantic basin), 20 = Stone Mountain Branch, 21 = Big Reed Island Creek headwaters, 22 = Pine Creek, 23 = Puckett Church Branch, 24 = Pipestem Branch, 25 = Sulphur Springs Branch, 26 = Grassy Creek, 27 = Grassy Creek tributary, 28 = Pine Creek Ward's Gap, 29 = Little Snake Creek, 30 = Big Reed Island Creek, 31 = S. Prong Buckhorn Creek, 32 = Little Reed Island Creek, 33 = E. Fork Crooked Creek, 34 = Crooked Creek, 35 = Chestnut Creek, 38 = Brush Creek, i = Rennett Bag Creek, ii = Ararat River headwaters, iii = Waterfall Branch. (B) Shaded relief map of North Carolina study area showing streams and terrace deposits used. Map is based on 10-m resolution DEM. 37 = Terry Creek, 38 = Flat Creek. Terraces J, L, and M and Terry Creek are drained to the Atlantic Ocean by the Green River, a stream analogous to the Dan River (19) of the Virginia study area.

removed steep headwater reaches of fluvial profiles, leaving behind the lower gradient of downstream morphologies. By comparing these potentially beheaded drainage profiles to unaltered streams atop the Upland, estimating the magnitude of basin area or stream length lost may be possible. Alluvium of obvious fluvial origin preserved at the headwaters of beheaded streams may exceed the competence of the host stream given present relief and discharge and be excessively rounded for present channel length. Qualitative comparison of clast roundness to an established relationship to transport distance may provide an estimate of the magnitude of divide and escarpment migration. Together, these data may confirm the mechanism of BRE retreat and permit a generalized restoration of the BRE through paleobasin reconstruction.

Graphical and quantitative methods can be applied to the description of stream channel and basin geometry. A smooth, concave-up longitudinal profile is regarded as an indicator of steady-state equilibrium in a fluvial system (Hack, 1957, 1973; Snyder et al., 2000; Roe et al., 2002; Whipple, 2004; Bowman et al., 2007; Goldrick and Bishop, 2007; LaRue, 2008), with disruptions in smooth concave-up shape indicating disequilibrium, such as that produced by faulting or basin capture. The loss of headwaters to divide migration could be manifest as linear profiles whose steepened headwaters, and thus concave-up shape, have been lost to headward erosion of Atlantic drainages. Longitudinal profiles provide a qualitative basis of comparison, whereas the slope–drainage area relationships of streams can be quantitatively compared. Local channel slope and drainage area are related by the power law

$$S = kA^{-\theta} \quad (1)$$

where S is local slope, k is the steepness index, A is drainage area upstream of the point of the slope measurement, and θ is the concavity index (Flint, 1974). Values of θ should be generally consistent within tectonically and lithologically similar regions (Kirby and Whipple, 2001; Whipple, 2004). Beheaded streams lacking a concave-up profile shape should present less negative θ values and lower slope at a given drainage area (or stream length) than unaltered Upland streams of comparable size.

We constructed longitudinal profiles and slope–area relationships based on 1:24,000-scale USGS topographic maps for 20 westward-flowing streams with headwaters at the ECD (the ECD-draining streams) and 18 westward-flowing control streams from the Upland interior (the Upland control streams). ECD-draining profiles were first compared to Upland control profiles to identify characteristics consistent with divide migration and basin loss, such as low-gradient headwaters and overall linear (not concave-up) shape. Average Upland control and ECD-draining profiles were produced by averaging slopes from all streams in each population in 1000-m increments. The qualitative data gathered from profile analysis was then used to guide our selection of streams for slope–area analysis. When the effects of divide and escarpment retreat on the drainage pattern of the study area are considered, it is apparent that not every stream rising at the divide and flowing west would have been beheaded. During landward migration, the major regional divide would occasionally "overtake" preexisting subordinate divides once located in the Upland interior. Headwaters of streams rising at these subordinate divides would then rise at the ECD and escarpment crest, but would not have been affected by beheading. A random selection of ECD-draining streams would mix these equilibrium streams with beheaded streams, potentially obscuring evidence of divide and escarpment retreat. Accordingly, we applied an intentional bias to focus attention on ECD-draining streams that have most likely been beheaded. We chose the five most linear and apparently anomalous streams draining the ECD westward to estimate stream length lost through comparison to streams draining the same surface but rising landward of the ECD. Ten Upland control streams whose profiles showed smooth, well-developed concave-up shape were selected to quantify an Upland control stream slope–area relationship describing streams unaffected by divide retreat. This slope–area relationship was combined with the average length–area power law relationship from the same ten streams to obtain an expression for length (L) as a function of slope (S):

$$L = (S/0.0335)^{-1.68} \quad (2)$$

This expression describes the relationship between increasing channel length and decreasing local slope of Upland control streams unaffected by divide retreat. Slopes at or near the headwaters of many ECD-draining streams are anomalously low and more consistent with slopes observed well downstream of typical Upland stream headwaters. We substituted the unusually low initial slope values (defined by the length of the first contour interval in the stream) of the five most linear streams draining the asymmetric divide for S in Eq. (2) to estimate channel length lost to divide and BRE retreat.

To constrain retreat using relict alluvium preserved at the escarpment crest, we first completed a systematic search for terrace deposits at the headwaters of ECD-draining streams that appear truncated by the divide. We focused on streams originating in broad gaps or low-relief areas at the escarpment crest. The gentle gradient of these headwaters areas, characteristic of downstream reaches of Upland control streams landward of the escarpment and divide, presented qualitative evidence of basin loss and offered the greatest potential to preserve relict alluvium at the surface. Field reconnaissance was conducted at the headwaters of all ECD-draining streams whose morphologies indicated beheading to locate physical evidence of basin loss from divide retreat, such as mature alluvium preserved in wind gaps very near or atop the ECD. Four of the headwaters terraces that hosted the most abundant and best-preserved rounded clasts were selected for transport distance estimates based on clast roundness.

Clast roundness is known to increase with progressive fluvial transport such that the shape of clasts in alluvium preserved at the divide may be inverted to obtain the magnitude of channel length lost to BRE and divide retreat (Mills, 1979; Lindsey et al., 2007). Sadler and Reeder (1983) offered an empirical and field-expedient method for relating the roundness of quartzite clasts to transport distance. Their regression was produced in the San Bernardino Mountains, California, using clasts of clearly discernible provenance, permitting a direct "outcrop-to-basin" determination of transport distance that could be related to roundness. We chose the method and regression of Sadler and Reeder (1983) because it was developed for a similar lithology and was produced empirically using clasts of known origin and transport distance. Their results showed good agreement with a quartzite clast flume experiment of Kuenen (1956) as well as other empirical studies (Tricart and Schaeffer, 1950; Hovermann and Poser, 1951; Hollerman, 1971; Goede, 1975). Clast shape is expressed quantitatively by the Cailleux Roundness Index, or CRI (Cailleux, 1947), defined as

$$CRI = \{(2^*R_c)/L\}^*1000 \quad (3)$$

where R_c is the radius of curvature of the sharpest corner and L is the length of the long axis. To avoid low estimates for thinly bedded quartzites or tabular veins, R_c is measured in the orientation of maximum projection (parallel to short axis, orthogonal to long and intermediate axes). After Sadler and Reeder (1983), we only measured clasts with long axes ranging from 4 to 10 cm to avoid transport over-estimates related to the greater ease of rounding of very large clasts. We measured CRI for ~30–60 of the most rounded unbroken clasts present in each terrace to obtain a maximum estimate of transport distance (i.e., using an intentional bias).

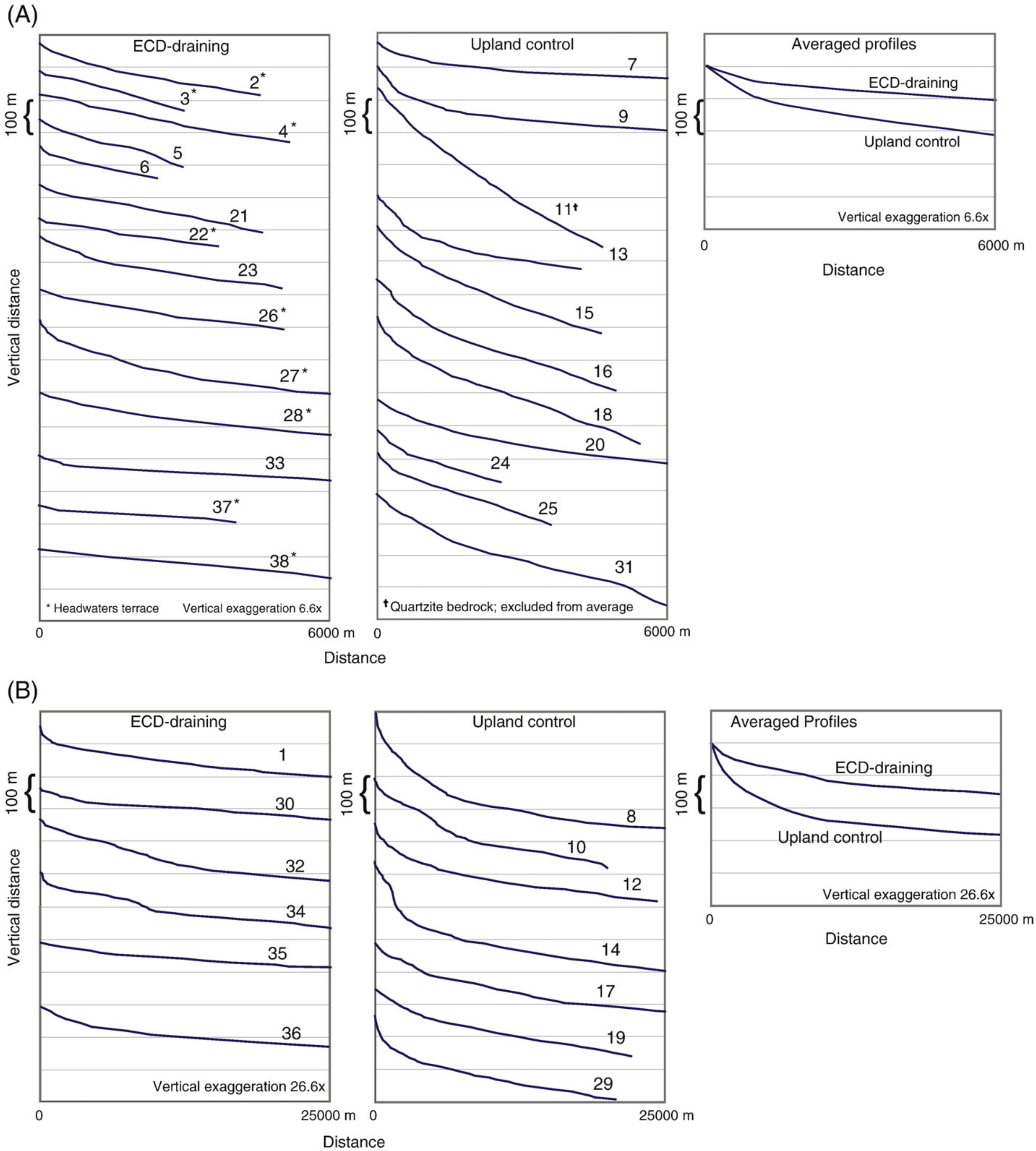


Fig. 5. (A) Long profiles of short (≤6 km) ECD-draining streams (left) and Upland control streams (right) (Fig. 3A, B). Average profiles were developed by averaging slope values over 1000 m intervals for every stream within each of the four groups. Locations shown in Fig. 3. Asterisks denote streams with terrace deposits at their headwaters. (B) Long profiles of ~25-km-long ECD-draining streams (left) and Upland control streams (right) (Fig. 3). Little Snake Creek (29; right) drains a high elevation, high-relief area that was likely a local divide within the Upland, and is therefore treated as an Upland control stream despite its present proximity to the ECD. Average profiles constructed in the same manner as A.

4. Results

Longitudinal profiles indicate morphological contrasts between ECD-draining and Upland control streams. A number of ECD-draining profiles are nearly linear and lack the steep headwater reaches that produce the concave-up shape of Upland control profiles (Fig. 5). The more pronounced concave-up shape of the average Upland control profile implies fluvial equilibrium with lithology and regional base level, whereas the comparatively linear shape of the average ECD-draining profile suggests the loss of headwaters to fluvial beheading. This trend in profile shape is apparent in both short (~6 km) and long (~25 km) streams (Fig. 5).

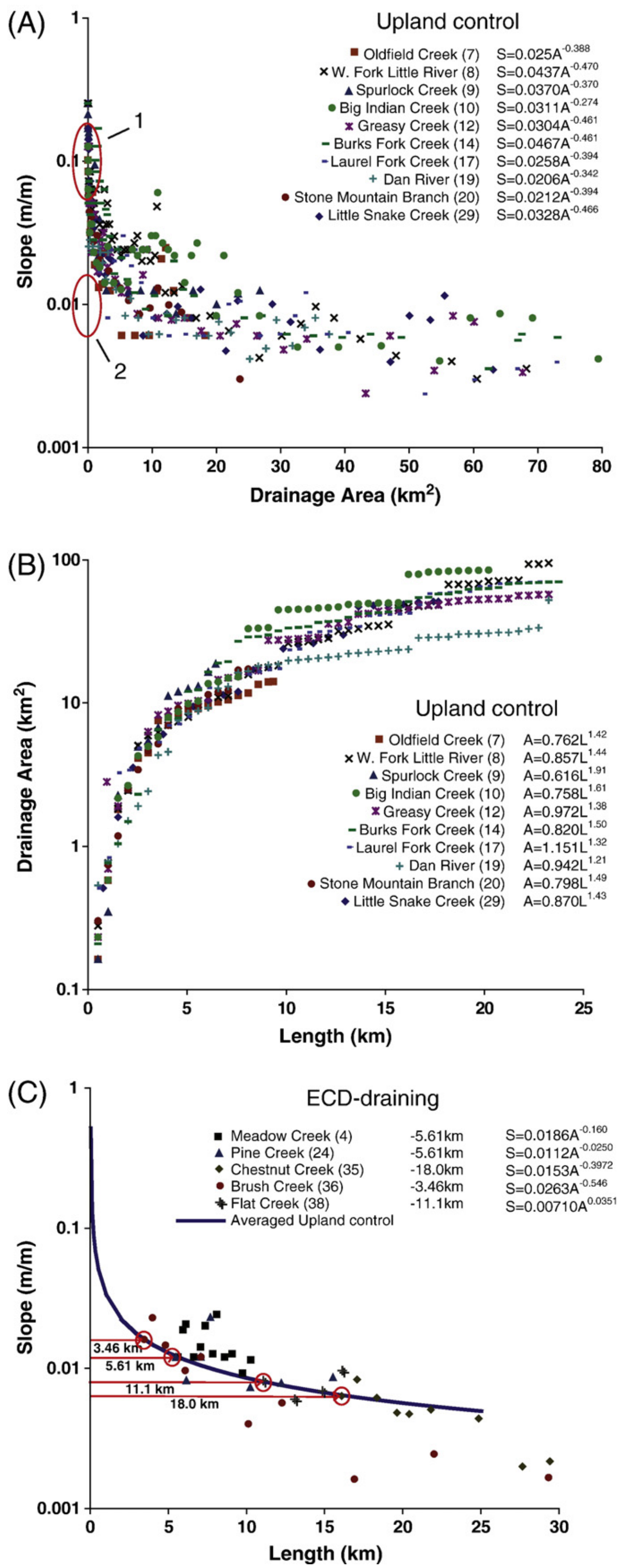


Fig. 6. (A) Slope–drainage area relationships of ten Upland control streams showing plotted raw data and best-fit power law expressions. Average Upland control slope–area relationship is described by the power law $S = 0.0314A^{-0.403}$. Ellipse 1 indicates the range of Upland control stream headwater slopes; ellipse 2 indicates range of headwater slopes of beheaded ECD-draining streams (C). (B) Drainage area-channel length relationships of the ten Upland control streams from A. Average relationship is described by the power law $A = 0.855L^{1.47}$. Average slope–area (A) and area–length (B) power laws were combined to obtain the average Upland control slope–length power law ($L = (S/0.0335)^{-1.68}$) plotted in C. (C) Headwater slope values of five beheaded ECD-draining streams shifted to fit the average Upland control slope–length power law curve. ECD-draining headwater slopes are anomalously low and consistent with slopes encountered kilometers downstream from Upland control stream headwaters. Red arrows indicate the magnitude of the required shift and thus the Upland control channel length necessary to obtain the low headwater slopes of the ECD-draining streams.

Knickpoints, or local convexities, occur along profiles of both populations (e.g., streams 10 and 31 of the control group; 5 and 34 of ECD-draining streams), but do not alter the overall shape of profiles (Fig. 5). These may represent active rejuvenation of a relict westward-flowing drainage network by intermittent lowering of the landward base level. Slight contrasts in lithologic resistance may also produce the isolated convexities, but the effects are localized and are not mapped (Virginia Division of Mineral Resources, 2003). The unusually steep profile of stream 11 likely results from the resistant Precambrian–Cambrian quartzites underlying its basin; it was excluded from average Upland profile calculation (Fig. 5). Several ECD-draining streams show concave-up profiles or exhibit slightly steepened headwater reaches (3, 6, 23, 33) (Fig. 5). These profiles may represent preexisting equilibrium streams of the Upland interior that were "overtaken" in place by landward divide migration and thus have not lost drainage area. Alternatively, this morphology may be the result of an earlier pulse of New River incision which migrated headwardly through the drainage network and rejuvenated the basins to their headwaters at the ECD. Aside from these variations, however, a clear distinction between the two stream populations is evident in the individual and averaged profile shapes (Fig. 5).

A comparison of the steepness and concavity indices of streams draining the asymmetric divide to the Upland control streams further delineates morphological distinctions between the two groups and provides an estimate of channel length lost to divide retreat. We focused our analysis on five streams rising at the divide that presented particularly linear profiles and low headwater slopes: 4, 22, 35, 36, and 38 (Figs. 3, 5). ECD-draining streams show a more gradual downstream decay of channel gradient, resulting in less negative concavity index (θ) values. Average concavity index (θ) for the ECD-draining streams is -0.219, compared to -0.401 for the ten Upland control streams analyzed. Morphological distinctions between the two stream populations are also apparent in steepness index (k; Eq. (2)) values; average steepness index (k) for ECD-draining streams is 0.157, while the steeper headwater reaches of the Upland control streams yield an average (k) value of 0.401. These slope–area data reflect the trend observed in the longitudinal profiles and are consistent with basin loss resulting from divide and escarpment retreat. Substituting the low headwater slopes of the five ECD-draining streams into Eq. (2) provides a loose estimate of stream length lost to divide retreat. Estimated channel loss results are presented in Fig. 6. Average estimated channel loss from BRE and divide retreat is ~8 km (Fig. 6). Chestnut Creek (35) and Flat Creek (38) suggest the largest channel losses (18.0 and 11.1 km, respectively). While loose estimates, these analyses of channel concavity appear to reflect significant channel loss and are thus consistent with divide retreat and sufficient stability of the Upland to preserve the relict basin morphology.

Combined analysis of longitudinal profiles, slope–area relationships, and 1:24,000-scale topography led to the identification of 14 individual fluvial terrace deposits in wind gaps and low-relief areas atop or near the ECD (Fig. 3). These terraces are physical evidence of both parallel retreat of the assymetric divide and stability of the Upland surface. The terraces are characterized by accumulations of rounded to well-rounded vein quartz or quartzite clasts up to ~25 cm long (Fig. 7). No polymineralic (lithic) clasts were observed in any of the terrace deposits. Fine matrix material typically is sandy clay; but some deposits, particularly site N (Figs. 3B, 7), contain a matrix dominated by quartz sand and refractory minerals. Clay content and redness appear to be proportional to the extent of clast weathering. The effects of floroturbation (i.e., tree throw) and agricultural disturbance are apparent (Fig. 7). Terrace I (Fig. 3A) may contain primary depositional features indicated by roughly parallel lines of cobbles ~1 m below the surface in a roadcut (Fig. 7), but the extensive weathering of the deposit complicates this interpretation. Clasts are very abundant in the deposits, a number of which approach a clast-supported structure. All clasts show signs of weathering, but the extent of weathering is variable between deposits located in close proximity to one another. For example, site E contains numerous clasts showing little evidence of chemical weathering; but site I, located ~15 km away (Fig. 3A), contains only extensively weathered and pitted cobbles, most of which are broken. The absence of a trend between clast weathering or soil development and terrace location suggests ongoing, but episodic, asymmetric divide retreat.

The locations of the terrace deposits are related to the local topography. Deposits concentrate in wind gaps and low-relief areas

Fig. 7. Selected images of terraces showing typical field characteristics. All photos are taken within ~100 m of the ECD. Locations of terraces are shown in Fig. 3. Scale card arrow is 10 cm long. (A) Large, well-rounded clasts in sandy clay matrix from terrace E. (B) Unweathered vein quartz clasts in quartz sand matrix from terrace N. (C) Rounded to well-rounded clasts exposed by floroturbation (tree throw) from terrace B. (D) Small boulder from terrace E. (E) Cobble lines exposed by roadcut from terrace I. (F) Selected clasts from terrace E. Note rounding at all clast sizes.

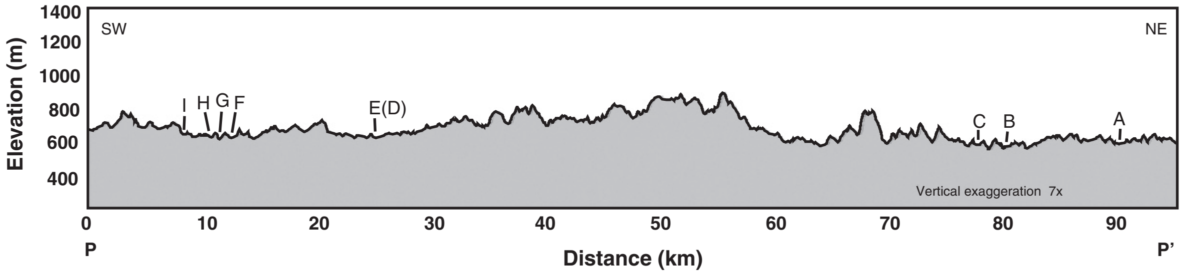


Fig. 8. Profile along the ECD from P to P′ (Fig. 3A) showing terrace locations. Terraces cluster in low-elevation, low-relief areas along the ECD.

within broad, region-scale sags along the divide (Fig. 8). In the Virginia study area (Fig. 3A), these sags cluster at 825 m (~2700 ft) and 760 m (~2500 ft) elevation. Many terraces occur just at or above the headwaters of streams whose profiles show little or no concave-up shape, low headwater gradient, and a lack of rejuvenation from landward base level drop (Fig. 5). Preserved unconsolidated alluvium is not, however, found at the headwaters of all such streams or in all sags along the asymmetric divide. Several preserved terraces are located seaward of the divide (e.g., D, J, L, M; Fig. 3). These terraces share the same elevations and topographic features as other sites on the Upland margin and seem to be perched on topographic remnants of a once-continuous Upland surface. For example, terrace D appears to align with stream 24 and is preserved at the same elevation as terrace E, possibly reflecting divide retreat through two distinct episodes of stream capture (the headwaters of stream 30 were captured to form stream 19, followed by additional capture of stream 30 headwaters by stream ii; Fig. 3). The preservation of unconsolidated alluvium atop these small Upland remnants separated by deep, narrow gorges suggests that sudden, rapid base level drop resulting from stream capture can produce strongly differential erosion in mature landscapes. The apparent stability of these Upland remnants adjacent to active gorge development invites comparison to the contrast in Upland and stream valley erosion rates at Dolly Sods, West Virginia, described by Hancock and Kirwan (2007).

Roundness of the clasts preserved in remnant terraces at the crest of the BRE imply significant transport and hence considerable loss of stream length by divide and BRE retreat. We measured clast roundness for ~30–60 clasts from four terraces (N, E, B, A) (Fig. 9). Roundness was converted to an estimate of transport distance using the relationship of Sadler and Reeder (1983). Terraces N and E show the highest roundness and estimated transport distances for individual clasts, with a maximum value of ~270 km (clast shown in Fig. 7F). Average transport distance and filtered average (excluding highest and lowest 10% of values) are lower, but all suggest stream length loss of >10 km (Fig. 9). Given that not all clasts within a terrace would have been transported the same distance, the average roundness values of the top 10%, ranging between 47–185 km, may be more useful metrics. Some of the variation between terraces may relate to "paleoorder" or paleoflow direction of the streams that deposited the terraces. The two terraces with lower average transport values (A, B) occur in tributaries of the same master stream, the Little River (Figs. 3A, 9). In contrast, the more rounded clasts of terraces E and N occur in valleys that are directly contiguous with escarpment-orthogonal trunk streams.

5. Discussion

Anomalous drainage basin morphologies and fluvial terraces provide strong qualitative evidence for ongoing divide and escarpment retreat resulting from the repeated capture and dissection of Upland drainage basins. These data suggest a model of escarpment evolution that differs from the recent preexisting, or fixed, inland divide plateau degradation model derived from cosmogenic, thermochronologic, and numerical

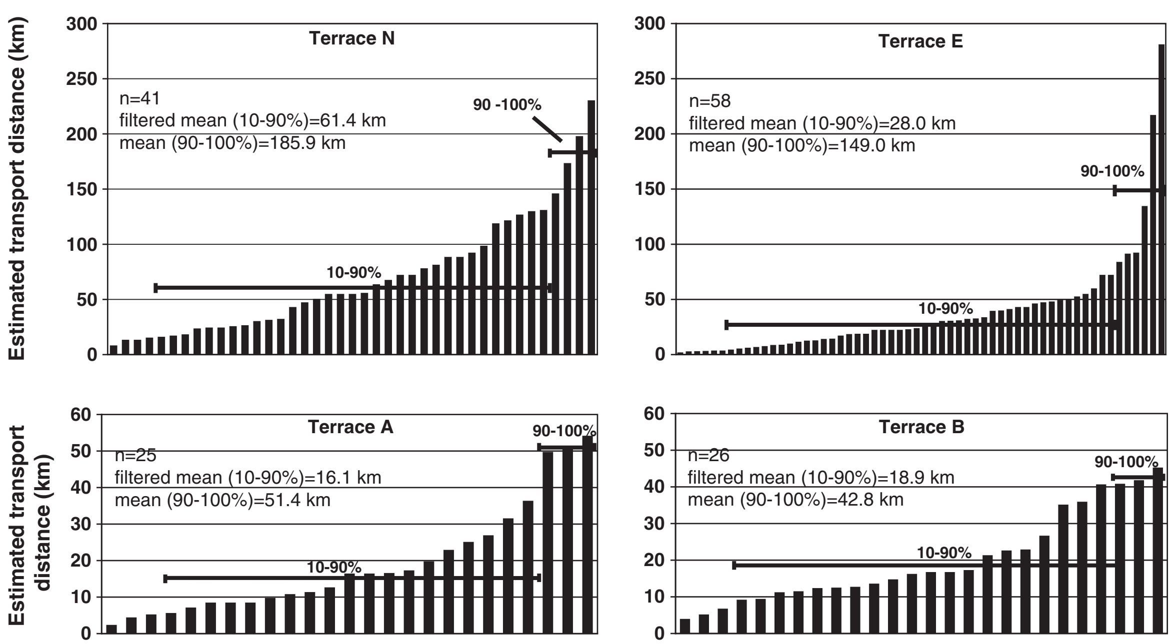


Fig. 9. Distribution of estimated clast transport distances from terraces N, E, B, and A (Fig. 3).
Transport estimates are based on measured values of Cailleux Roundness Index from each clast (Cailleux, 1947) after Sadler and Reeder (1983).

modeling studies of other escarpments (Moore et al., 1986; Gilchrist et al., 1994; Bishop and Goldrick, 2000; Cockburn et al., 2000; Matmon et al., 2002; Persano et al., 2002; van der Beek et al., 2002; Braun and van der Beek, 2004). The morphology of Upland drainages rising at the divide is consistent with a state of transient adjustment between the Upland and BRE (Dietrich, 1957; Hack, 1973; Gasparini et al., 2007). Examples of topographic disequilibrium observed cannot be rectified with a near-stationary BRE that stopped retreating significantly long ago (Sullivan et al., 2007). We instead propose a BRE history similar to the structurally and fluvially controlled retreat model suggested for the Western Ghats escarpment by Harbor and Gunnell (2007) and Gunnell and Harbor (2008). We view BRE evolution as an episodic, yet ongoing, process where significant long-term parallel retreat is accomplished through the repeated capture and rapid dissection of Upland drainage basins.

While the overall distance of escarpment migration remains uncertain, altered basin morphologies and clast roundness allow for loose estimates of recent (10^6 years) retreat. The vein quartz clasts measured here certainly equal, and likely exceed, the resistance to rounding of the quartzite clasts of Sadler and Reeder (1983), suggesting that our transport estimates (i.e. ~50–100 km based on maximum roundness) are probably conservative. Structural control of drainage immediately southeast of the BRE by northwest–southeast trending fractures or joints suggests that tens of kilometers of transport could have been orthogonal to the escarpment, suggesting transport distance could provide a reasonable basis for a loose retreat estimate. Headwater gradient of channels truncated by the divide suggests ~10–20 km of channel loss, reasonably consistent with averaged clast transport estimates. Flow direction and meander interval are, however, significant unconstrained variables; and the escarpment-parallel flow and high degree of sinuosity present in streams of the study areas would contribute to an overestimate of retreat. Clast transport distance will thus remain a rough estimate of retreat magnitude until sediment provenance is clearly established.

The systematic preservation of terrace deposits at low-gradient headwaters supports the conclusion that apparent channel loss is the result of divide and escarpment retreat. The persistence of surficial alluvial deposits and anomalously low headwater slopes at the escarpment crest suggests Upland denudation is outpaced by landward retreat of the divide and escarpment. Although the terraces are not dated, clast weathering is similar to Upland-sourced vein quartz clasts from >1 Ma New River terraces preserved under the same climate conditions in the nearby Valley and Ridge (Ward et al., 2005). While a potential age of more than 1 Ma for our deposits suggests great stability of the surface on which they are preserved, Upland denudation rates of ~10 m/Myr based on thermochronometry (Spotila et al., 2004) and cosmogenic dating (e.g., Sullivan et al., 2007) suggest a limited lifetime of surficial deposits atop the Upland. If the terraces are several million years old and were stranded by the capture of escarpment-orthogonal drainages (terraces D and E; Fig. 3A) tens of kilometers in length, local capture-driven retreat rates of 1–10 km/Ma are plausible. This implies that local divide and BRE retreat rates may, in the case of major capture events, outpace Upland lowering by as much as three orders of magnitude. These speculative retreat rates would, however, only result from the occasional capture of large Upland drainage basins with discharges capable of producing very rapid erosion upon capture. Indeed, smaller but more frequent captures producing comparatively modest local retreat rates probably account for considerable retreat over the long term. In either case, BRE and divide retreat rates exceeding Upland lowering by an order of magnitude or more would be limited to captured basins undergoing dissection and not be applicable to the entire BRE at any given time.

When considered in the context of the present Upland drainage network, the respective location, roundness, and freshness of terrace alluvium may offer some insight into the paleodrainage network and its role in escarpment retreat. Terraces A and B have lower average roundness values and are drained by the BRE-parallel local trunk stream, the Little River (stream 1; Fig. 3A), and may thus be the remnants of short, lower order tributary streams only truncated by the last few kilometers of asymmetric divide retreat. Terrace E is drained by a stream directionally and topographically continuous with the local trunk stream, Big Reed Island Creek (stream 30; Fig. 3A), which flows roughly orthogonal to the BRE. The greater roundness of terrace E clasts may reflect longer transport in the larger basin of a paleo-trunk stream. Clasts from terrace N, which is also drained by a stream showing general continuity with the French Broad River (Fig. 3B), provided the highest overall transport estimates from all terraces studied. Terraces N and E, which host the most rounded alluvium, also showed the least amount of weathering, suggesting relatively recent stranding and thus rapid erosional destruction of their depositing basin upon its capture. This comparatively fresh alluvium may be viewed as additional qualitative evidence of the rapid dissection and local divide and escarpment retreat associated with large capture events.

We propose a conceptual model of BRE evolution that highlights the role of stream capture in producing escarpment retreat through prolonged, but punctuated, retreat of the ECD (Fig. 10). Headwardly eroding Atlantic basin streams of the steep divide flank (Fig. 10, panel 1) can tap the potential energy of westward-flowing Upland drainages through stream capture (panel 2). The capture process may initiate with diversion of Upland groundwater before the westward-flowing surface channel is physically diverted to the Atlantic basin. Connection to the seaward base level, which is hundreds of meters lower, greatly steepens and energizes the captured stream, and rapid incision propagates headwardly through the basin as it equilibrates to the new base level (panel 2). Structural weaknesses (faults and fractures/joints) controlling flow directions will facilitate rapid dissection of the captured basin and allow headward erosion to encroach upon neighboring Upland basins, eventually producing additional captures along strike (panel 3). Adjustment of captured streams to the seaward base level rapidly dissects the detached Upland remnants and moves the locus of topography landward in response to the new location of the divide. Continued headward erosion along structural weaknesses sets up future landward captures and re-starts the retreat process (panel 4). In order for this retreat model to continue in the long term, capture and retreat must occur more rapidly than lowering of the Upland (landward) base level to maintain divide asymmetry and the energetic potential of Upland streams relative to the seaward base level. Minor (tens of meters) episodic incision of Upland streams due to landward base level drop could potentially propagate headwardly through the entire drainage network and ultimately steepen the headwaters of westward-flowing Upland streams, increasing symmetry of the divide. A topographic ridge may form along the ECD, acting as a physical impediment to future capture events. Over the long term, the combined effects of repeated Upland base level drops will reduce contrast in landward and seaward base levels and thus reduce the potential energy of Upland streams available for capture (bottom of panel 4). Divide asymmetry and retreat thus form a positive feedback loop; asymmetry facilitates rapid retreat, which in turn maintains the divide morphology and the energetic potential for continued capture and retreat. A sufficiently stable landward Upland base level is thus equally vital to preserving retreat potential in the long term and allowing the process to continue after lengthy intervals between localized captures.

While we view BRE evolution as a long-lived and ongoing process, the local, basin-scale retreat rates of ~1–10 km/Ma proposed are certainly not applicable to the whole feature for the entirety of its inferred ~200 Ma lifetime. Cosmogenic dating indicates the BRE is no longer experiencing significant retreat along much of its length (e.g., Sullivan et al., 2007). This suggests rate-controlling events must be

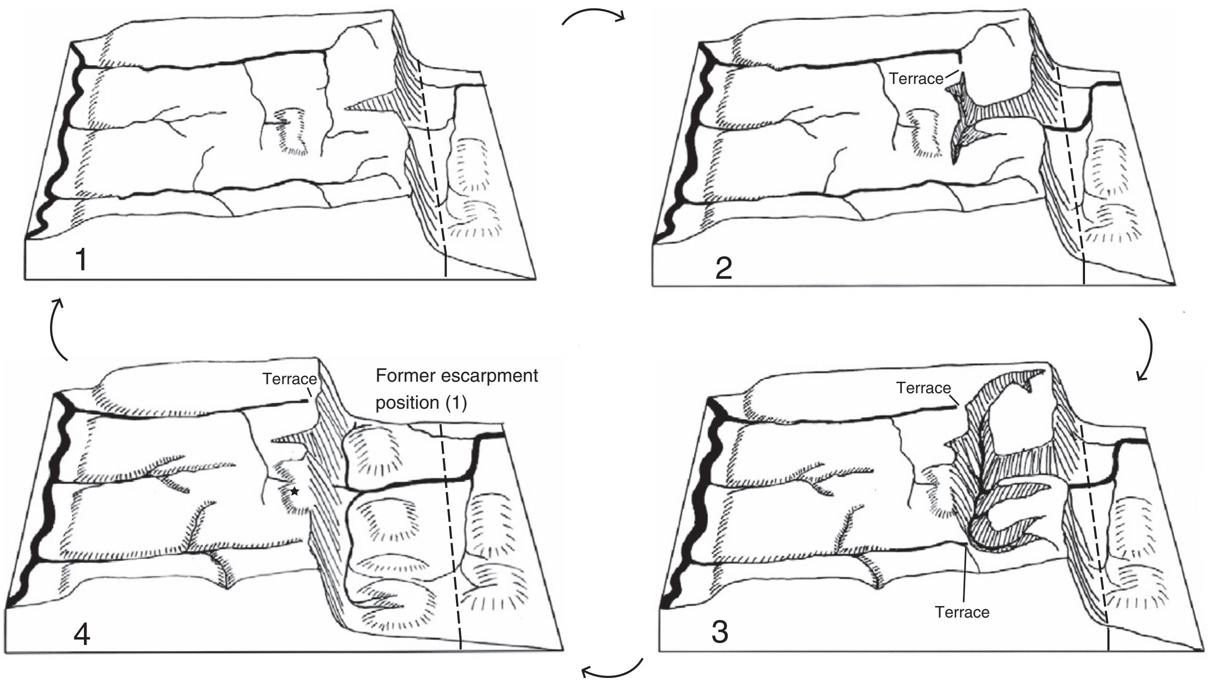


Fig. 10. Illustration of the conceptual model of parallel divide and escarpment retreat driven by high order stream capture. The dashed line, indicating position of the escarpment in Frame 1, remains fixed throughout as a reference point. (panel 1) Headward erosion progresses rapidly along an escarpment-orthogonal weakness (e.g., fracture) and approaches an initial capture point. (panel 2) Capture and reversal of escarpment-parallel drainage leads to rapid dissection and the progression of headward erosion along drainage-controlling weaknesses. Because of the rectilinear drainage network and low Upland relief, two additional captures are now imminent. A terrace may have been preserved by the beheading of the preexisting drainage. (panel 3) Capture of two more escarpment-orthogonal streams leads to rapid dissection of the entire basin affected by capture thus far. Rapid incision by the reenergized drainages isolates portions of the Upland and strands two new remnant terraces. (panel 4) Complete dissection of the captured basin leads to parallel escarpment and divide retreat. A terrace deposit remains at the now underfed headwaters of the far drainage. The near drainage, though beheaded, has been rejuvenated by an Upland base level drop that has locally steepened the terrain and scoured away any residual alluvium. The small ridge now located at the escarpment crest was once a local divide within the Upland interior, and the stream draining it (starred) has not been affected by divide migration although it now drains the main regional divide. Stream 29 may be representative of the ECD "overtaking" a subordinate, landward divide (Figs. 3, 5). Capture is not favored across this ridge or the more symmetric divide at the bottom of Frame 4, and this portion of the escarpment will enter a phase of stability. Headward erosion could proceed along another escarpment-orthogonal lineament to initiate a new cycle of capture and punctuated retreat of the far portion of the escarpment.

spatially isolated but occur in enough locations with sufficient regularity to produce an overall parallel retreat over the lifetime of the BRE. The long-term BRE retreat rate may therefore best be viewed as a "weighted average" of local and short-lived rapid retreat events interrupting long periods of quiescence where escarpment evolution is negligible. When these rare, localized but extremely rapid retreat rates are considered over the length of the feature, possibly for ~200 Ma, a more reasonable "lifetime" parallel retreat rate is suggested.

Our proposed retreat model is heavily dependent on a preexisting rectilinear drainage network on the Upland surface. Lineament analysis of areas of the escarpment in which alluvium is fresh and divide asymmetry most pronounced indicate the role of orthogonal drainage-controlling weaknesses in sustaining the retreat process (Figs. 10, 11). Streams in the Appalachian Blue Ridge and Piedmont generally trend along two orientations: orogenic (and BRE) strike-parallel, controlled by weak lithologies or structures (e.g., Brevard fault zone), and orogenic strike-orthogonal, controlled by fractures and joints (Fig. 11). The enhanced erodibility of these drainage-controlling features is fundamental to BRE evolution. Orthogonal flow directions allow for more frequent captures at high order points along Upland streams that facilitate a large increase in stream power and rapid dissection of the captured basin as illustrated by our conceptual model (Fig. 10). Where flow directions are essentially opposite across the divide, headward erosion captures insignificant Upland area and does not energize the capturing drainage, producing minimal slow retreat. Terrace I (Fig. 3A), preserved in such an area, contains clasts showing considerable pitting, breakage, and deep staining, all indicative of more extensive weathering than that experienced by the other terraces. In contrast, orthogonal flow directions increase the potential for capture of high order channels and rapid adjustment of topography to the new divide location. Orthogonal drainages also facilitate capture across low-relief subordinate divides of the Upland (Fig. 10, panel 3), allowing basin-by-basin capture to propagate along BRE strike. The impact of orthogonal flow directions and weak drainage-controlling structures on retreat rate is clearly seen where fluvial evidence of retreat is best preserved, such as in terraces E and N (Fig. 3A, B). Easily eroded fractures and lithologies permit rapid basin dissection and speed the landward progression of headward erosion, the source of subsequent captures further inland.

Considering the potential for repeated episodes of local but rapid retreat combined with extremely slow Upland lowering, interpretation of the BRE as the final remnant of a Mesozoic rift-flank feature may be reasonable. The initial BRE topography almost certainly formed well seaward of its present location, and quartz mylonite clasts in terraces B and E (Fig. 3A) indicate the Brevard/Bowens Creek fault zone was a drainage-controlling feature atop the Upland and did not reactivate to initiate the BRE as suggested by White (1950). This idea is further supported by fluvial evidence of retreat atop the ECD and BRE where it is located well seaward of the Brevard Zone in western North Carolina (Fig. 3B). While the clasts we examined represent only the most recent captures and retreat, they still suggest sufficient transport to restore parts of the escarpment near Triassic basin border faults 70 km southeast. Whether the BRE initiated at these structures or further southeast remains unknown. The present Piedmont drainage network suggests that the mechanism indicated

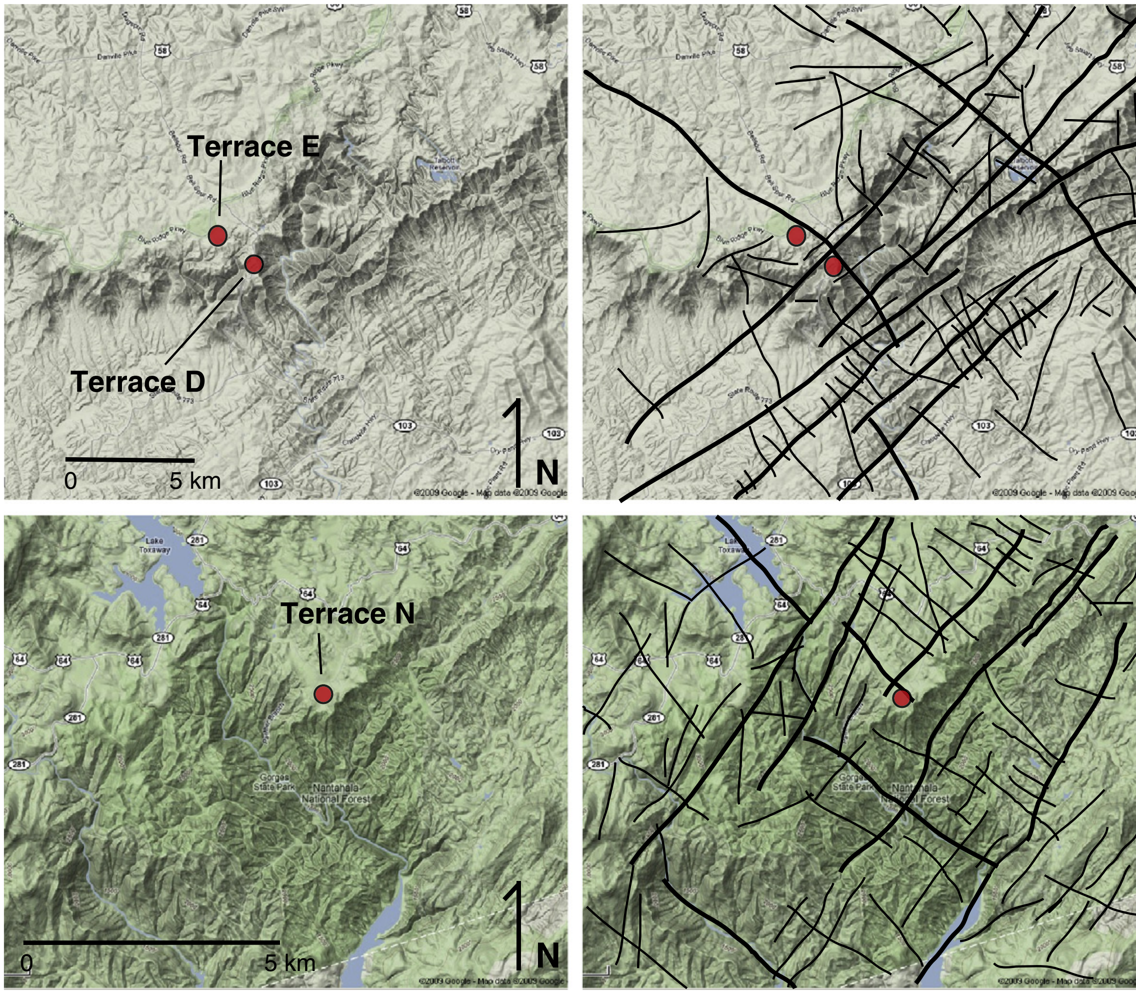


Fig. 11. Shaded relief maps of two areas, each shown with and without interpreted lineaments, showing the roughly orthogonal lineament trends prevalent in areas of the BRE that host well-rounded and fresh terrace alluvium (see Fig. 3 for location). The thickness of the interpreted lineament trends is a proxy for influence over the drainage network. Northeast-trending lineaments are associated with thrust faults and weak, sheared lithologies of the Brevard/Bowens Creek fault zone. Northwest-trending lineaments are joints and fractures that pass uninterrupted across the Brevard fault zone, suggesting post-Paleozoic origin. The rectilinear drainage network resulting from the interaction of these weak features facilitates repeated large capture events as well as rapid dissection of the captured basin (Fig. 10). Shaded relief images are captured from Google Maps, based on 10-m resolution topography.

by our study could have supported continued BRE retreat from an initial location over 100 km to the southeast. Persistence of divide asymmetry related to Upland stability (Sullivan et al., 2007) combines with active incision along the escarpment front (e.g., streams 19 and ii; Fig. 3A) to suggest that the landform will continue to evolve and maintain its topographic youth despite an ~200 Ma erosional history.

Field evidence of the role of structurally controlled stream capture and punctuated retreat of the BRE complements studies of other passive margin escarpments. Our results illustrate the value of applying more traditional methods of geologic study to constrain passive margin escarpment history. Alluvium has not yet been used as a proxy for retreat of the Western Ghats, but the combination of appropriate structure, variation in lithology, and apparent capture frequency (Harbor and Gunnell, 2007) suggests the likelihood of terraces preserved at or near its crest. The low relief, low erosion rates, preservation of soils, and rectilinear drainage network of the Sri Lankan Upland (von Blanckenburg et al., 2004; Vanacker et al., 2007), qualitatively similar to features of the Blue Ridge Upland, may have preserved evidence of parallel escarpment retreat driven by stream capture. The episodic retreat model highlights the importance of divide location and preexisting drainage network as controls over escarpment evolution (van der Beek et al., 2002). Our data also indicate the importance of careful selection of cosmogenic erosion rate sample locations. As the high order capture events that ultimately drive retreat are spatially isolated and transient because of the rapid dissection of captured basins, escarpments may appear (and likely are) stable along most of their length at any given time (Fleming et al., 1999; Cockburn et al., 2000; Sullivan et al., 2007; Vanacker et al., 2007). The active process may be difficult to observe unless cosmogenic samples are taken in the immediate vicinity of a large knickpoint formed by a recent capture event. Cosmogenic dating of captured basins undergoing dissection, such as the Dan River Gorge (stream 19 of Fig. 3A), will be an important way of testing the episodic retreat model and assessing its potential applicability to sinuous escarpments, such as southeast Australia, where gorge incision is known to outpace upland lowering (Nott et al., 1996).

6. Conclusions

Fluvial terraces and beheaded stream valleys preserved atop the ECD at the BRE crest provide clear evidence of significant escarpment retreat associated with landward divide migration during the Cenozoic. Stream morphology and terrace location suggest this ongoing retreat process is driven by the episodic capture of large Upland drainages by steep streams flowing east to the Atlantic Ocean. The structurally controlled rectilinear drainage network and low relief of the Upland facilitate repeated captures, which produce rapid dissection of the captured basin and localized landward migration of the zone of maximum relief. When considered along the entire strike length of the BRE, the combined effect of these local, but rapid, retreat events may lead to parallel divide and escarpment retreat over the long term. While the roundness of terrace clasts suggests many tens of kilometers of transport, uncertain provenance and paleodrainage networks preclude the use of this data in establishing a total retreat distance or point of origin for the BRE. Nevertheless, the size and roundness of alluvium preserved at the BRE crest suggest extensive Upland drainage basins have been destroyed by escarpment and divide retreat.

In contrast to recent numerical modeling and cosmogenic studies, our results indicate that landward migration of the drainage divide produced by stream capture events can produce continued significant retreat of mature passive margin escarpments. The persistence of the retreat process long after the demise of initial rift topography may be related to a combination of extremely slow Upland denudation and comparatively rapid escarpment retreat. The freshness of terrace alluvium and intact preservation of relict stream gradients suggest that local retreat rates resulting from large captures may outpace Upland lowering by three orders of magnitude. This differential erosion maintains maximum divide asymmetry and the potential energy of Upland streams relative to the Atlantic base level, preserving the energetic driver of the retreat process. This model of episodic retreat is consistent with areas of slow retreat along the BRE and other escarpments indicated by cosmogenic dating, but it also predicts that very localized retreat rates in other areas could be at least three orders of magnitude higher. Additional cosmogenic dating along the BRE will be necessary to validate our model, and its relevance to other passive margin escarpments is presently unclear. A single paradigm of passive margin escarpment evolution may not exist, and these features may evolve through a range of mechanisms governed by drainage networks, divide location and asymmetry, structure, and lithology. In either case, the physical evidence of the role of divide migration in BRE retreat provides a useful additional constraint on the evolution of this feature and may suggest a new source of data regarding the retreat mechanism of other passive margin escarpments.

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