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Evidence of transient topographic disequilibrium in a landward passive margin river system: knickpoints and paleo-landscapes of the New River basin, southern Appalachians

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ABSTRACT: The upper New River basin of the southern Appalachian Mountains, a major tributary of the modern Ohio River, represents the unglaciated headwaters of the Tertiary Teays River system of eastern North America. Dating of relict fluvial gravels have suggested that New River incision may be outpacing lowering of the surrounding uplands, but physical evidence of transient topographic disequilibrium has yet to be identified. We use focused topographic analysis of the upper New River basin to delineate a perched, low-relief paleo-landscape that is experiencing transgressive dissection due to incision by the New River and its tributaries. Accelerated incision has decoupled hillslopes from the drainage network, generating knickpoints which represent the boundary between remnants of the paleo-landscape and actively adjusting topography downstream. Steepening of hillslopes downstream of knickpoints suggests dynamic headward migration which, along with knickpoint occurrence throughout the drainage network, is inconsistent with the development of fixed stream profile convexities atop strike-extensive geologic contacts. In the absence of tectonic forcing, we favor a climatically-forced drop in external base level as driver of the incision pattern we observe. Plio-Pleistocene glacial damming and diversion of the Teays River to form the modern Ohio River lowered regional base level for the study area, potentially forcing the paleo-landscape developed during the Teays era to adjust to the modern drainage pattern. The upper New River may therefore represent the potential for glacially-driven drainage rearrangement to drive transient topographic evolution hundreds of kilometers away from the ice margin, long after the disappearance of ice sheets. Copyright © 2013 John Wiley & Sons, Ltd.

KEYWORDS: Appalachians; transient incision; knickpoint; relict landscape; passive margin topography

Introduction

Despite increased study during the last decade, the mechanisms of Cenozoic topographic evolution in the ancient Appalachian orogen remain poorly understood. At the orogen scale, apparent adjustment of topography and stream gradient to bedrock resistance (Hack, 1960, 1973) suggests a steady-state landscape, where erosion is spatially uniform at rates governed largely by slow, steady exhumation of a thickened crustal root. This hypothesis has been supported by a number of quantitative studies of Appalachian erosion and exhumation, which indicate consistent rates of 20 to 40 m/Myr over million-year timescales (Hack, 1965; Pavich *et al.*, 1985; Roden, 1991; Pazzaglia and Gardner, 1994; Matmon *et al.*, 2003; Spotila *et al.*, 2004). The general tectonic quiescence of the Appalachians during the last ~200 Myr (Oyarzun *et al.*, 1997), along with their insulation from eustatic fluctuation (Ward *et al.*, 2005), seem to preclude major perturbation to existing boundary conditions, further supporting topographic steady-state. Climatic conditions, however, have not been consistent over time, late Cenozoic climatic fluctuations may have occurred too rapidly for even a mature passive margin landscape to maintain topographic equilibrium (Peizhen *et al.*, 2001; Whipple, 2001; Molnar, 2004; Norton *et al.*, 2008). While the topographic consequences of Cenozoic climate change have been considered in active orogenic landscapes (e.g. Molnar, 2004; Schoenbohm *et al.*, 2004; Clark *et al.*, 2005; Crosby and Whipple, 2006), the magnitude of response to tectonic forcing in such settings may obscure the impacts of climatic fluctuation. Given that the Appalachians have been tectonically inactive for at least 200 Ma (Oyarzun *et al.*, 1997; Spotila *et al.*, 2004), and a zone of negative dynamic topography is thought to exist beneath eastern North America (Steinberger, 2007; Braun, 2010; Forte *et al.*, 2010), transient incision resulting from climate change should not be overshadowed by response to tectonic process. The slow background evolution of Appalachian river systems may thus represent an excellent venue to examine the topographic impact of changing global climate.

Response to climatic fluctuation by major Appalachian rivers may be reflected in widespread fluvial terraces, which indicate variations in trunk stream incision rates throughout the late Cenozoic (Houser, 1981; Colman, 1983; Bartholomew and Mills, 1991; Howard *et al.*, 1995; Mills, 2000; Granger *et al.*, 2001;

Ward *et al.*, 2005). While some of these terraces are cut-and-fill and appear to represent variable sediment supply, strath terraces also exist (Granger *et al.*, 2001; Ward *et al.*, 2005; Anthony and Granger, 2007) and indicate episodes of accelerated bedrock incision. Dating of these terraces suggests they may be the result of climatic forcing, but studies to date have been limited to trunk streams and are yet to address the potential topographic impact on the landscape at large. As tributary and headwater streams represent the means by which a landscape will be adjusted to a new base level, their response to trunk stream incision must also be characterized (Sugai and Ohmori, 1999; Clark *et al.*, 2005, 2006; Crosby and Whipple, 2006). In active tectonic settings, where base level drop is rapid and significant, bedrock incision in trunk streams outpaces tributary adjustment to induce a transient state where 'relict' topography, evolving under pre-incision boundary conditions, may persist in headwaters areas until the incision signal migrates through the entire drainage network (e.g. Schoenbohm *et al.*, 2004; Clark *et al.*, 2006; Crosby and Whipple, 2006). During this transient phase, erosional processes in adjusting streams will not reflect evolution of the entire basin until adjustment is complete. Has accelerated incision in Appalachian trunk streams led to a similar decoupling of lower-order tributaries and the rest of the landscape, or have perturbations been sufficiently minor that the entirety of the drainage network has kept pace with master streams (Norton *et al.*, 2008)? If incision of stream valleys is increasing relief, do these changes reflect bedrock incision or cut/fill processes associated with climatically-driven changes in sediment supply (Ward *et al.*, 2005)? To fully understand the response of slowly-eroding, mature landscapes to Cenozoic climate change, these questions must be addressed.

Transient incision is rarely associated with passive margin settings due to their lack of tectonically-forced base level perturbation. Stream capture along asymmetric passive margin drainage divides is known to cause basin-scale transient events (Gunnell and Harbor, 2010; Prince *et al.*, 2010, 2011), but this mechanism does not affect large, landward-draining river systems still connected to continental interior base level. However, evidence for transient incision within Appalalachian rivers flowing towards the continental interior does exist. Berylium-10 (^{10}Be) and aluminum-26 (^{26}Al) data have indicated Pleistocene fluvial incision rates of 30 to 100 m/Myr (Springer *et al.*, 1997; Granger *et al.*, 2001; Clifton and Granger, 2005; Ward *et al.*, 2005), which outpace slow lowering (< 10 m/Myr) of sandstone- and conglomerate-capped uplands surfaces within the region (Granger *et al.*, 2001; Hancock and Kirwan, 2007). Due to the absence of local stream captures or tectonic uplift, these data suggest climatic fluctuation may cause sufficiently rapid base level drop to force regionally-extensive disequilbrium in passive margin fluvial systems.

If transient incision is affecting landward-draining Appalachian rivers, a characteristic topographic signature of steep-walled gorges developed into a lower-relief upland, with knickpoints at gorgeheads, should result. This signature can be effectively identified through focused topographic analyses, with emphasis on the distribution of low-slope relict uplands, knickpoints, and steepened hillslopes resulting from knickpoint migration (e.g. Schoenbohm *et al.*, 2004; Clark *et al.*, 2006; Crosby and Whipple, 2006; Norton *et al.*, 2008). These methods of topographic characterization have yet to be applied to passive margin river systems in which ^{10}Be data suggest trunk stream incision outpaces upland lowering. In this paper, we combine analysis of digital elevation model (DEM) topography and longitudinal profiles with extensive fieldwork to test for the signature of transient incision throughout the upper New River basin of southwest Virginia.

The New River

The New River drains ~19 500 km^2 of the southern Appalachian Highlands north and west to the Ohio River, ultimately to the Gulf

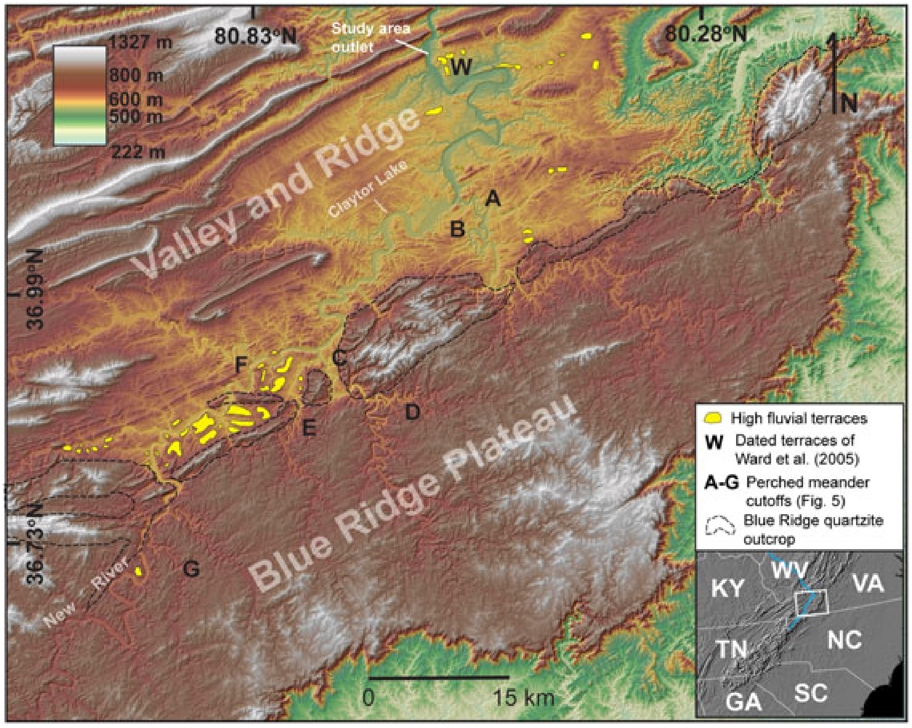

Figure 1. Shaded relief map of the studied portion of the New River basin. Map is generated from a 10-m resolution DEM. Inset shows the regional setting of the study area within the southern Appalachian Mountains. Isolated, discontinuous fluvial terraces in the northern half of the map have been described by Houser (1981); Mills (1986); Bartholomew and Mills (1991), and Ward *et al.* (2005). Terraces in the southern half were documented by Stose and Stose (1957). Terraces are almost certainly more extensive, and the reported occurrences only reflect mapping completed to date. Location of the New River Gorge and position of the New River within the Ohio River system is shown in Figure 10. This figure is available in colour online at wileyonlinelibrary.com/journal/espl

of Mexico. Rising on the western slope of the Eastern Continental Divide in North Carolina, the river follows a northerly course through the Blue Ridge Plateau, Valley and Ridge, and Allegheny Plateau physiogeologic provinces (Figure 1). Though its uppermost reaches are characterized by a low-gradient, alluvial channel, the river steepens markedly and becomes increasingly bedrock-floored prior to exiting the Blue Ridge Plateau (Ward *et al.*, 2005). Alternating bedrock and alluvial reaches occur through the Valley and Ridge and much of the Appalachian Plateau (Hack, 1957, 1973; Ward *et al.*, 2005), collectively producing an upwardly convex longitudinal profile until the river flattens in central West Virginia (Hack, 1973; Ward *et al.*, 2005).

Throughout its length, the transverse course of the New River shows little obvious control by geologic structure or lithology. This course is widely considered to have been superimposed on the landscape, and is regarded as evidence of the antiquity of the New River system within the Appalachian orogen (Dietrich, 1959). Observation of the New River channel in the study area suggests some reaches are actively incising into bedrock, with numerous falls or rapids separating slower-moving, sediment-floored reaches. The overall downstream steepening of the river's profile culminates in the notable rapids of the 300 m-deep New River Gorge, below which gradient decreases. 18 km downstream of the gorge, the river becomes navigable and sediment-floored for ~100 km to its confluence with the Ohio River (Ward *et al.*, 2005) (see Figure 1 caption).

The structural and lithologic framework of the study area is reflected in its varied topography. Widespread exposure of non-resistant Cambrian-Ordovician carbonates and shales in the eastern Valley and Ridge and Neo-Proterozoic schists in the Blue Ridge plateau have formed extensive tracts of low-relief topography, which contrast sharply with narrow ridges developed on folded units of resistant sandstone and quartzite. The low-relief carbonate/shale landscape of the eastern Valley and Ridge is separated from the schist and gneiss landscape of the Blue Ridge Plateau by a narrow quartzite ridge exposed in the hanging wall of the Paleozoic Blue Ridge Thrust. This Alleghanian structure emplaced crystalline units atop sedimentary strata of the Laurentian margin, producing the structural framework which has been eroded to generate the modern landscape. The quartzite ridge has been described as a 'base level prop' (Hack, 1973) for the Blue Ridge Plateau, which maintains a higher elevation than the adjacent eastern Valley and Ridge despite being drained to the same regional base level set by the New River (Figure 1). This morphology has been regarded as consistent with a landscape approaching topographic equilibrium, where streams follow steepened channels across resistant rock to match erosion rates of weaker substrates, thereby producing the elevation step from Blue Ridge to Valley and Ridge (Hack, 1960, 1973).

Although topographic adjustment appears extensive when the New River landscape is viewed at the large scale, the results of previous studies suggest Cenozoic incision of the New River itself may have outpaced lowering of surrounding uplands to produce an overall increase in local relief. Widespread deposits of fluvial gravel persist tens of meters above, and occasionally kilometers away from, the modern New River channel (Stose and Stose, 1957; Dietrich, 1959; Houser, 1981; Mills and Wagner, 1985; Mills, 1986; Bartholomew and Mills, 1991; Ward *et al.*, 2005) (Figure 1). All of these studies noted the great height of some gravels (over 100 m) above the active channel, the extent of gravel preservation, and the presence of several terrace levels between the uppermost deposits and the modern river surface. The persistence of these gravels suggests uplands have remained relatively stable while the New River and its tributaries incise into the landscape. ^{10}Be dating of New River terraces by Ward *et al.* (2005) yielded a loosely-constrained ~2 m/Myr erosion rate from an ancient upland terrace and a long-term New River incision rate of 43 m/Myr, suggesting a state of topographic disequilibrium in which the New River is increasing relief in the eastern Valley and Ridge. This finding echoes evidence of incision rates exceeding upland lowering in other landward Appalachian drainages of the Ohio River system (Granger *et al.*, 2001; Anthony and Granger, 2007; Hancock and Kirwan, 2007), which has been interpreted as a result of Plio-Pleistocene climatic fluctuation.

The present-day New River basin represents the unglaciated headwaters of the Tertiary Teays River system, which was the dominant landward drainage of eastern North America prior to Plio-Pleistocene ice sheet advance (Gray, 1991). Gray (1991) suggested the late Tertiary Teays may have flowed to the North Atlantic, and was captured into the continental interior prior to, or as an early result of, initial encroachment of ice sheets during the Pliocene. Continued ice advance repeatedly forced the Teays into new courses along the ice margin, with the maximum Pleistocene glacial advance at 1.5 Ma damming the Teays near present-day Chillicothe, Ohio to form glacial Lake Tight (Tight, 1903; Gray, 1991; Granger *et al.*, 2001). Breaching of the south-western margin of the lake ultimately formed the modern Ohio River course along the ice margin (Tight, 1903; cf. Ray, 1974; Melhorn and Kempton, 1991). Ultimately, the glacially-altered drainage pattern shortened the distance between unglaciated headwaters and the Gulf of Mexico base level, which along with glacial outwash would have increased stream power to drive rapid entrenching of the Ohio channel into bedrock, as much as 60 m below its aggraded modern channel (Miotke and Palmer, 1972; Granger *et al.*, 2001). The base level drops associated with progressive Teays rearrangement forced episodes of bedrock incision apparent in cave passage and terrace development in lower Ohio River tributaries (Teller, 1973; Granger and Smith, 2000; Granger *et al.*, 2001; Anthony and Granger, 2007). These events correlate with a glacial meltwater spike in the Gulf of Mexico and sedimentation increase on the Mississippi fan at *c.* 2 Ma (Joyce *et al.*, 1993, adjusted to the timescale of Shackleton *et al.*, 1990), followed by another major pulse of sediment at 1·4–1·5 Ma (Joyce *et al.*, 1993; Pullham, 1993). These incision events were punctuated by periods of base level stability and aggradation, producing a complex series of both strath and fill terraces (Granger *et al.*, 2001; Anthony and Granger, 2007).

Base level drop resulting from Teays rearrangement could be expected to spread headwardly from diversion points, possibly as far as the study area. Ward *et al.* (2005) estimated an age of at least 1 Ma, and possibly as much as 3 Ma, for the uppermost (~110 m) terrace near the study area outlet (Figure 1) by applying an average incision rate of 43 m/Myr determined from ^{10}Be dating of a series of younger terraces at the same location. These terraces collectively record a complex history of incision and aggradation, which Ward *et al.* (2005) suggested might be attributable to variations in sediment supply during glacial–inter-glacial cycling. However, Ward *et al.* (2005) acknowledged that uncertainties in ^{10}Be terrace ages complicated associating base level change with specific climatic fluctuations, and suggested the possibility of a link between New River terrace development and glacially-forced drainage rearrangement of the Teays. The development of comparable terraces due to bedrock incision in the lower Ohio basin (Granger *et al.*, 2001; Anthony and Granger, 2007), along with the chronology of the Ward *et al.* (2005) terraces, may suggest that acceleration in New River incision rate is a response to Teays rearrangement. Further evidence of the topographic disequilibrium identified by Ward *et al.* (2005) may therefore be present throughout the New River drainage network in the form of transgressive knickpoints introducing new boundary conditions into the elevated, low-relief paleo-landscape which reflects the former Teays drainage pattern.

Methods

The primary goal of this study is to test for a transient response of the drainage network to the late Cenozoic increase in New River incision rate measured by Ward *et al.* (2005). If tributary streams cannot keep pace with incision by the New River itself, the resulting disequilibrium should be apparent in the morphologic contrast between actively adjusting areas of the basin and relict areas which are yet to respond to the incision signal (e.g. Clark *et al.*, 2006; Berlin and Anderson, 2009). Relict topography should be elevated above the modern drainage network and retain gentle hillslopes and low-gradient alluvial channels, while steepened, actively adjusting areas should appear to follow in the 'wake' (Gallen *et al.*, 2011) of bedrock knickpoints advancing into the relict landscape (Schoenbohm *et al.*, 2004; Harkins *et al.*, 2007; Reinhardt *et al.*, 2007). Bedrock knickpoints should represent a boundary between relict and adjusting channel reaches, reflecting the spread of the incision signal through the drainage network as opposed to development along strike-extensive resistant lithologies (e.g. Crosby and Whipple, 2006). This topographic regime should be clearly distinguishable from the effects of a contemporaneous, spatially-uniform response, where the character of topography, regardless of the degree to which it might steepen, would remain generally uniform throughout the basin. By testing for the presence of relict topography yet to be effected by a headwardly-mobile incision signal, we can effectively determine whether the upper New River basin exists in a transient state of disequilibrium following an increase in trunk stream incision rate. Identification and correlation of relict topography separated from the modern base level will simultaneously confirm the transient condition of New River basin topography and offer a reference horizon for the progress and magnitude of incision into the paleo-landscape (Schoenbohm *et al.*, 2004; Clark *et al.*, 2006; Reinhardt *et al.*, 2007).

Our study is focused on the gently rolling landscape of the eastern Valley and Ridge and Blue Ridge Plateau of the southern Appalachians (Figure 1). The respective Cambro-Ordovician carbonate/shale landscape of the eastern Valley and Ridge and the Proterozoic schist/gneiss landscape of the Blue Ridge Plateau represent widespread outcrop of mechanically-similar, weak lithologies (Hack, 1973) which develop muted, rolling topography (Figure 1). This low-relief topographic 'background' should contrast with steepened slopes resulting from active incision, allowing effective delineation of relict and adjusting areas through topographic inspection and fieldwork. Knickpoints identified within single, non-resistant lithologies (away from contacts juxtaposing resistant and weak units) will also offer evidence of forced steepening unrelated to lithologic contrast. We apply DEM analysis, direct topographic inspection, and fieldwork to delineate zones of relict and actively adjusting topography relative to knickpoints, constraining the spatial distribution of erosional processes within the study area to determine how much of the landscape is likely to be evolving under the conditions active in the New River itself.

Relict landscape identification

We define relict topography as portions of the landscape which continue to erode slowly under pre-incision boundary conditions at an elevation consistent with a former, higher base level. Relict topography should occur at high elevation relative to the modern New River channel and maintain low slope and relief, alluvial channels, and extensive weathering and soil development in response to characteristically slow 'background' Appalachian erosion (<10 m/Myr; Pavich *et al.*, 1985; Granger *et al.*, 2001; Hancock and Kirwan, 2007). We analyzed 10-m resolution DEM topography with associated slope data to delineate low-slope domains elevated above the modern drainage network. Slope and elevation distribution were also referenced against bedrock geology to assess any potential lithologic and structural control on topography discernible at the mapping resolution. Extensive field observation of potential relict topography was conducted to test for evidence of extensive *in situ* weathering and soil/saprolite development, the prevalence of alluvial channels, and the predominance of creep and diffusive processes on hillslopes, all of which would indicate slow erosion in which hillslopes remain coupled to the drainage network. This morphology contrasts with the appearance of adjusting areas where increased stream power has scoured away *in situ* soil and saprolite, developing steepened bedrock slopes to force an increase in the rate of sediment delivery to the channel (see Results section).

To evaluate the spatial continuity between potential areas of relict topography, a series of topographic profiles trending orthogonal to general flow direction were constructed throughout the study area. Topographic profiles can effectively capture 'patch-to-patch' continuity (Clark *et al.*, 2006) between remnants of a dissected relict landscape, allowing re-construction of the pre-incision low-relief landscape as a reference datum for the progress of adjustment. To illustrate the trend of the relict surface across the study area, we constructed 12 profiles (6–16 km) across the trend of the New River and three longer profiles (85–110 km) roughly orthogonal to drainage trend across the Blue Ridge Plateau. Areas on the profiles showing comparable elevation above the modern New River channel, low slope, and field evidence of extensive weathering were correlated by visual inspection to establish the relict surface trend. Relict surface elevation ranges at each of the points where the 12 profiles crossed the New River were superimposed on the New River profile to provide a frame of reference for incision into the relict topography. By superimposing the position and elevation of areas of relict surface on stream profile plots, we simultaneously represent the general elevation and downstream slope of the relict surface along with the channels and knickpoints which ultimately control the elevation of the landscape.

Knickpoint identification

The definition of 'knickpoint' varies slightly throughout the literature, but generally refers to a discrete convexity in longitudinal profile that disrupts an otherwise concave-up shape. Knickpoints frequently present a step-like appearance in stream profiles, although the mechanical properties of the substrate, as well as the mechanism of knickpoint retreat, may affect knickpoint shape (Gardner, 1983; Miller, 1991; Frankel *et al.*, 2007). The kinematic implication of knickpoints is also variable; knickpoints may occur as fixed convexities associated with lithologic variation, or they may be headwardly-mobile transient features indicative of a change in boundary conditions. We apply the term to refer to a discrete convex-up portion of a longitudinal profile, which coincides with a shift from a largely alluvial to a bedrock streambed and shows evidence of headward migration in hillsope steepening downstream (Gallen *et al.*, 2011). We only consider knickpoints occurring at least 4 km downstream from a drainage divide to focus on channel steepening related to fluvial process and not debris flows (Gallen *et al.*, 2011). Using locally-derived Hack's Law (Hack, 1960) coefficients and exponents of Prince *et al.* (2010), this distance corresponds to a drainage area of ~6·5 km^2 and channels of at least third order (Strahler, 1957). While somewhat arbitrary, this minimum channel length should exclude headwater morphologies controlled by hillslope processes (Crosby and Whipple, 2006; Gallen *et al.*, 2011). Due to the recognized tendency of knickpoints to leak incision and broaden over time (Frankel *et al.*, 2007; Berlin and Anderson, 2009), we avoid assigning a minimum gradient and drop in channel elevation to define a knickpoint and focus instead on disruption of upward concavity accompanied by a change in streambed character and downstream steepening o hillslopes.

A fundamental aspect of using knickpoints to constrain the progress of an incision signal is the exclusion of stationary profile convexities related to lithologic contrast. This type of convex-up reach should, in theory, be present where streams exit the Blue Ridge Plateau, as the passage from a quartzite to carbonate or shale substrate should produce a fixed convexity in the profile. These convexities may be amplified, however, as they slow the retreat of transient knickpoints (Miller *et al.*, 2010), whose passage from downstream should be discernible in hillslope steepening and gorge development. Accordingly, we consider the lithologic context of all convexities identified through profile analysis. If no topographic evidence, such as abandoned terraces or downstream hillslope steepening, occurred downstream of a lithologic contact convexity, the convexity was filtered from the data set. We thus focus on features that are indicative of the upstream migration of a mobile incision front.

Longitudinal profiles were developed from 1:24 000-scale topographic maps with 20 ft (6·1 m) contour interval. Map inspection permits evaluation of topography downstream of profile convexities, allowing identification of potential relationships between convexities, hillslope steepening, and dissection of the relict surface. While this resolution of profile analysis will exclude some very small convexities less than the contour interval in size, it provides an efficient means of assessing profiles over a very large study area where > 100 m of trunk stream incision is known to have occurred (Ward *et al.*, 2005). Locations of profile convexities were then compared to the distribution of relict and adjusted topography based on slope and elevation data from a 10-m resolution DEM. Profiles were integrated into the profile of the New River, allowing the location of knickpoints to be assessed in the context of channel distance from the study area outlet. This method of profile representation emphasizes the headward migration and resulting spatial distribution of knickpoints, whose significance would be obscured if profiles were examined individually.

Results

Relict landscape

Topographic analyses reveal extensive areas of elevated, low-slope topography separated from the active drainage network by knickpoints and oversteepened hillslopes (Figures 1 and 2). This relict landscape contrasts sharply with the steepened gorge walls and extensive bedrock outcrop in areas responding to knickpoint passage. Steepening of hillslopes appears to spread from the New River through its tributaries into the relict landscape, consistent with progressive transient adjustment to the new base level. This topographic signature is particularly strong in large Blue Ridge Plateau streams, where hillslope steepening can be seen to extend from their mouths at the New River as far as their uppermost knickpoints (Figure 2). The distribution of steepened hillslopes appears to relate to knickpoint position, with soil-mantled, low-slope relict topography only persisting upstream of knickpoints (Figure 2).

Topographic profiles reveal elevation accordance of relict surfaces separated by steep-walled stream gorges (Figures 3 and 4). Elevation and location relict topography allow reconstruction of a paleo-landscape with gentle slope towards the New River and an overall slope towards the study area outlet. The Blue Ridge Plateau paleo-landscape is consistently higher than that of the Valley and Ridge, potentially as a result of the 'base level prop' effect suggested by Hack (1960) (Figures 3

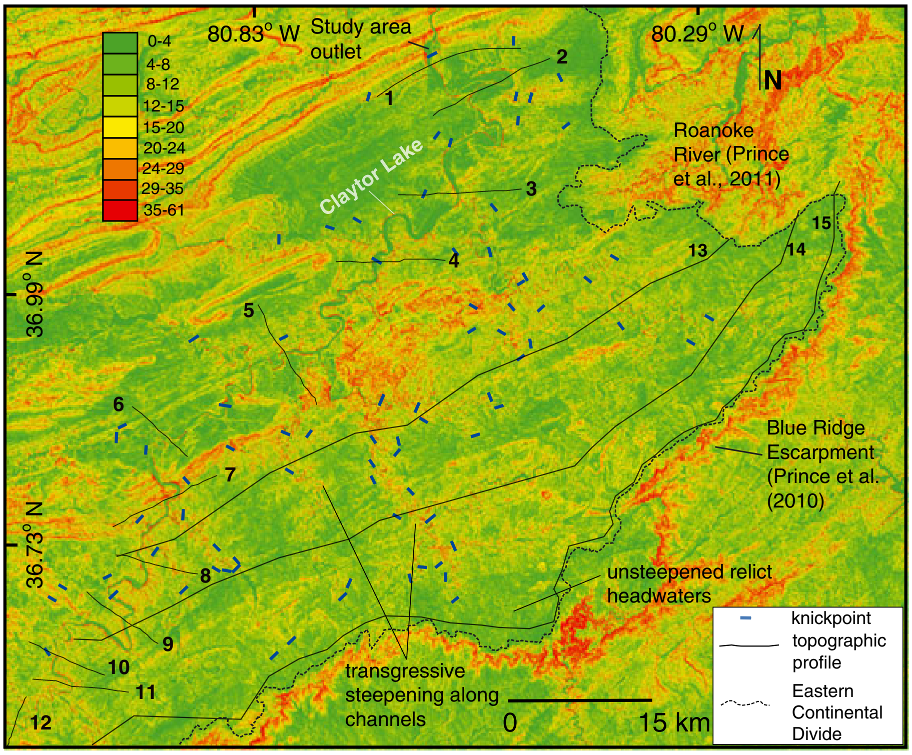

Figure 2. Slope map of the study area derived from 10-m DEM topography. Numbered topographic profiles are plotted graphically in Figures 3 and 4. Hash marks indicate the locations of knickpoints; note the tendency of knickpoints to occur at the upper limit of steepened topography (slope ≥ 16°) along larger channels. High slopes along the margins of the Blue Ridge Plateau result from incision due to repeated capture of New River tributary headwaters into Atlantic slope drainages (Prince *et al.*, 2010, 2011). This figure is available in colour online at wileyonlinelibrary.com/journal/espl

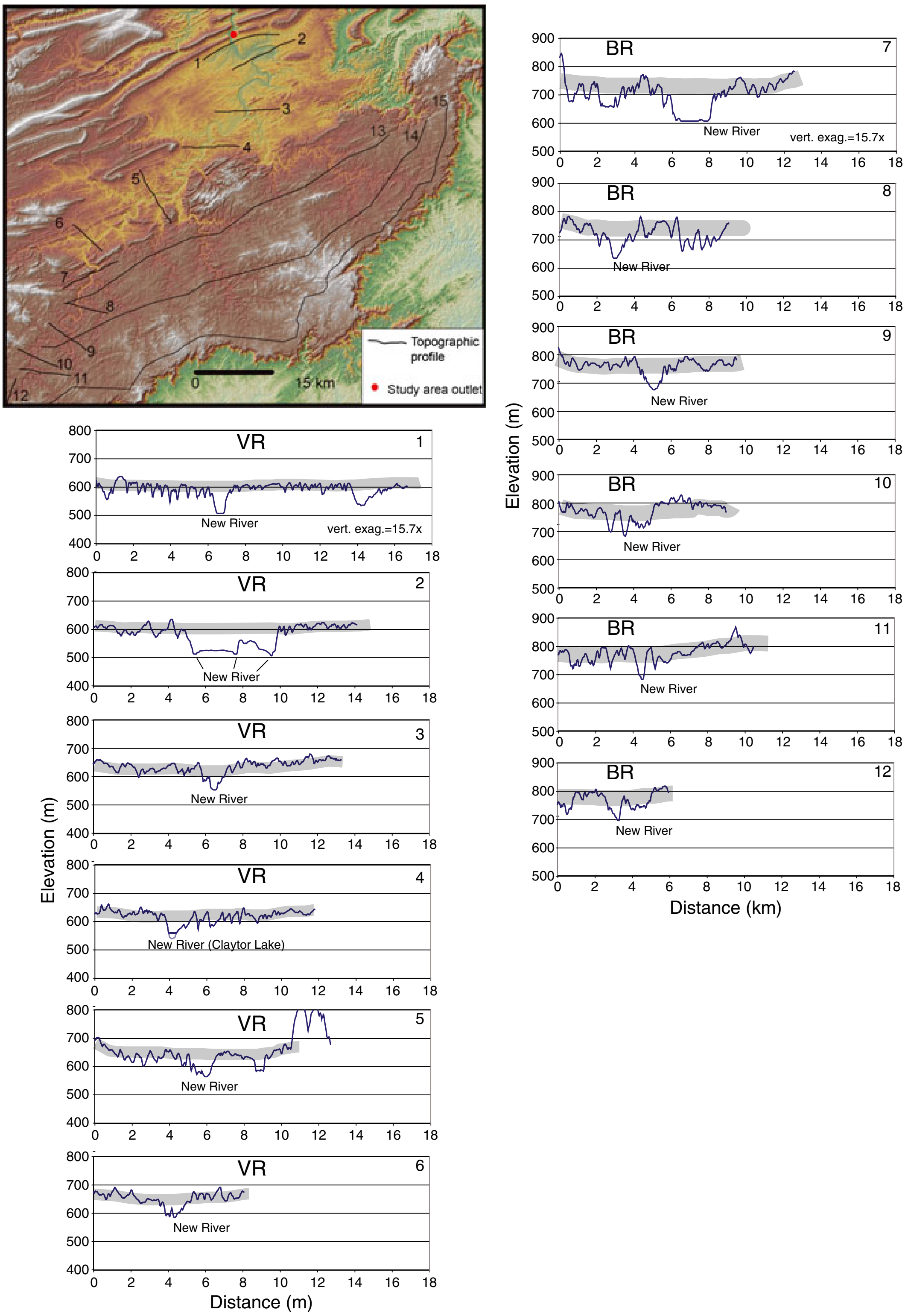

Figure 3. Topographic profiles across the study area. Thin line represents actual topography; thick shaded fields represent inferred elevation and total relief of the pre-incision paleo-landscape that is now locally preserved as relict surfaces. Delineation of paleo-landscape is based on inspection of slope and elevation distribution (after Clark *et al.*, 2006) of relict surfaces relative to stream channels combined with field observations of weathering and soil/saprolite development. This figure is available in colour online at wileyonlinelibrary.com/journal/espl

and 4). The 'patch-to-patch' continuity (Clark *et al.*, 2006) between areas of relict topography separated by steep-walled gorges is consistent with physical similarities (e.g. development of thick, highly oxidized soils and saprolite) revealed by field inspection. Topographic profiles indicate relief in relict areas of the Valley and Ridge is ~30 m, with relict areas of the Blue Ridge Plateau showing ~50–75 m of relief. These values exclude relief developed by isolated, steeply-sloping topographic highs supported by resistant bedrock (Figure 2).

Knickpoints appear to frame the large tracts of relict topography persisting between major New River tributaries (Figure 2). These large relict areas are particularly extensive on interfluves between major drainages and in the headwaters of Blue Ridge Plateau streams (Figure 2). Both the Valley and Ridge and Blue Ridge Plateau relict landscapes become increasingly dissected towards the study area outlet. Incision depth, defined as the vertical distance between the modern New River and the base of relict topography, decreases from ~90 m immediately

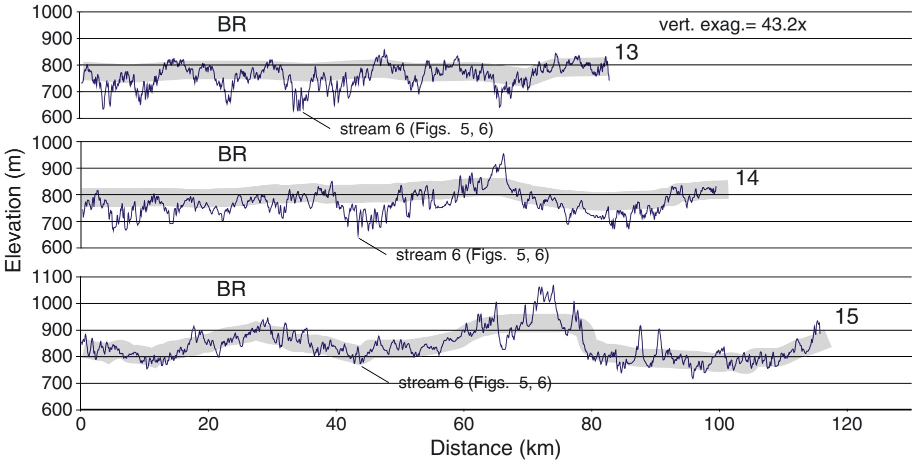

Figure 4. Long (85–100 km) topographic profiles trending northeast along the Blue Ridge Plateau (see Figures 2 and 3 for profile location). Note change in length scale relative to Figure 3. Actual topography, along with reconstruction of the trend of the paleo-landscape, are presented using the same process and symbols as in Figure 3. This figure is available in colour online at wileyonlinelibrary.com/journal/espl

upstream of the study area outlet to ~20 m at the upstream edge of the Valley and Ridge; incision depth in the Blue Ridge Plateau decreases from ~100 m where the New River exits the Plateau to ~30 m at the upper end of the study area (Figure 5). The offset between incision depth in the Valley and Ridge and Blue Ridge likely relates to the 'base level prop' effect described earlier (Hack, 1973), but the progressive upstream decrease in incision depth is present within each physiogeologic province. The same trend is apparent in the larger Blue Ridge Plateau topographic profiles, in which gorge depth of high-order New River tributaries decrease from ~100 m

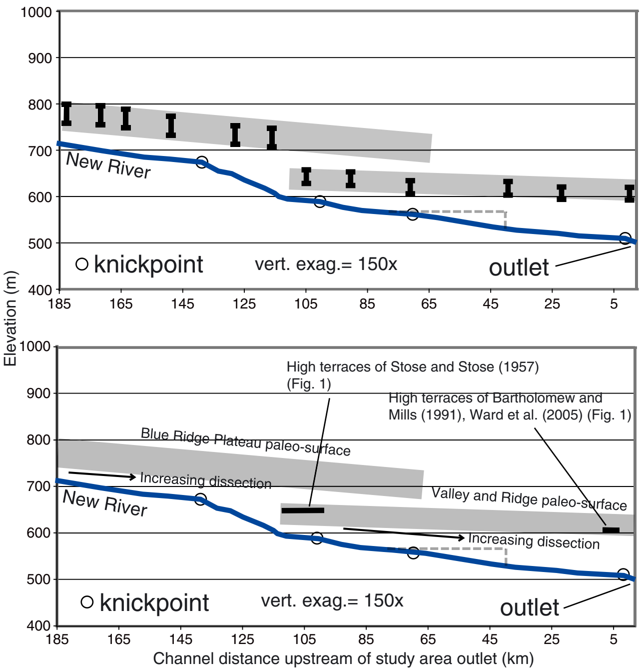

Figure 5. Projection of reconstructed relict landscapes of the Blue Ridge Plateau and Valley and Ridge by channel distance to study area outlet. Black bars indicate elevation range and position of relict topography where topographic profiles of Figure 3 cross the New River. (Top) Reconstructed relict landscapes (gray areas) plotted against the longitudinal profile of the New River. (Bottom) Knickpoint position relative to study area outlet plotted against the reconstructed relict landscapes. Knickpoints identified in the New River channel (Figures 2 and 6) are indicated by open circles. Dashed gray line indicates the position and relative height of Claytor Lake above modern river level. This figure is available in colour online at wileyonlinelibrary.com/journal/espl

nearest the New River (profile 13) to a small amount that cannot be clearly distinguished in headwaters reaches (profile 15) (Figures 2 and 4). Patches of relict topography are thus perched at increasing elevation above the modern drainage network towards the study area outlet.

The spatial progression of lowering base level and accelerated erosion rates through the drainage network is further illustrated by unique perched meander cutoff 'loops,' analogous to the 'The Loop' of the Green River (Utah) described by Leopold and Bull (1979) (Figures 1 and 6). All loops are perched above the modern drainage network, reflecting continued incision of the active stream since their abandonment. The loops remain sufficiently intact to be apparent in DEM and satellite image analysis. Loops that still carry a small active tributary are more extensively adjusted to modern base level than their 'dry' counterparts. These features occur at higher elevation above modern base level in the lower reaches of the study area, but the timing or order of their abandonment is unknown. Considerable incision has occurred within the preservation lifetime of the loops; loops A and B (perched above stream 3; Figure 6), developed into carbonate bedrock, are preserved ~40 m (Figure 6A) and ~60 m (Figure 6B) above the active channel. These features offer a unique physical constraint on the progressive base level drop in the New River basin as well as the mechanism by which adjustment spreads into relict topography through active channels.

Knickpoints

We identified a total of 80 knickpoints (four in the New River channel) in the study area through inspection of longitudinal profiles and DEM topography and subsequent analysis of satellite imagery and field reconnaissance (Figures 2 and 7). The steep-walled gorges developed by knickpoint retreat are apparent in DEM topography and hillslope data, and effectively aid in the identification of apparently transient knickpoints despite modest maximum relief (< 150 m) in the study area. Due to the resolution of our analyses, the knickpoints we identify range from hundreds of meters to several kilometers in length and accommodate a minimum of 6·1 m (20 ft) of elevation change to be detected. Most knickpoints accomplish 15–20 m of channel elevation drop, which occurs as a series of bedrock ledges separated by pools (Figure 8). Vertical waterfalls greater than 1 m in height are rare, but occasionally occur where a gorgehead coincides with a particularly resistant substrate (Figure 8C). Several of the knickpoints we identify

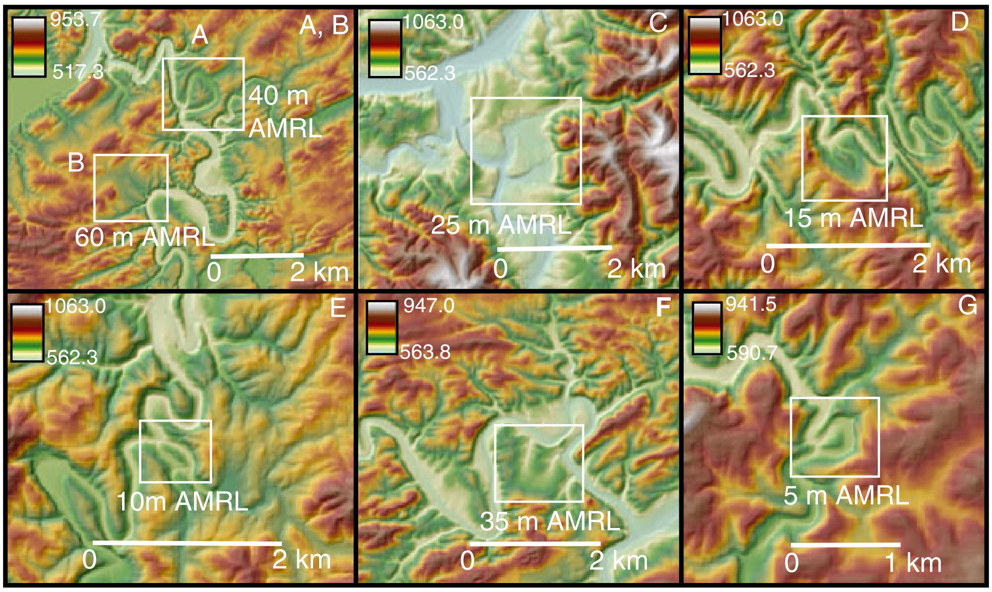

Figure 6. Perched meander cutoffs [‘loops’ after Leopold and Bull (1979)] identified in the study area. Elevation ranges differ within each panel; colored elevation fields are intended to enhance contrast to highlight loops relative to modern stream courses and do not provide a uniform elevation standard. Perch height for each loop is indicated. Active streams are labeled by numbers as in Figure 7. This figure is available in colour online at wileyonlinelibrary.com/journal/espl

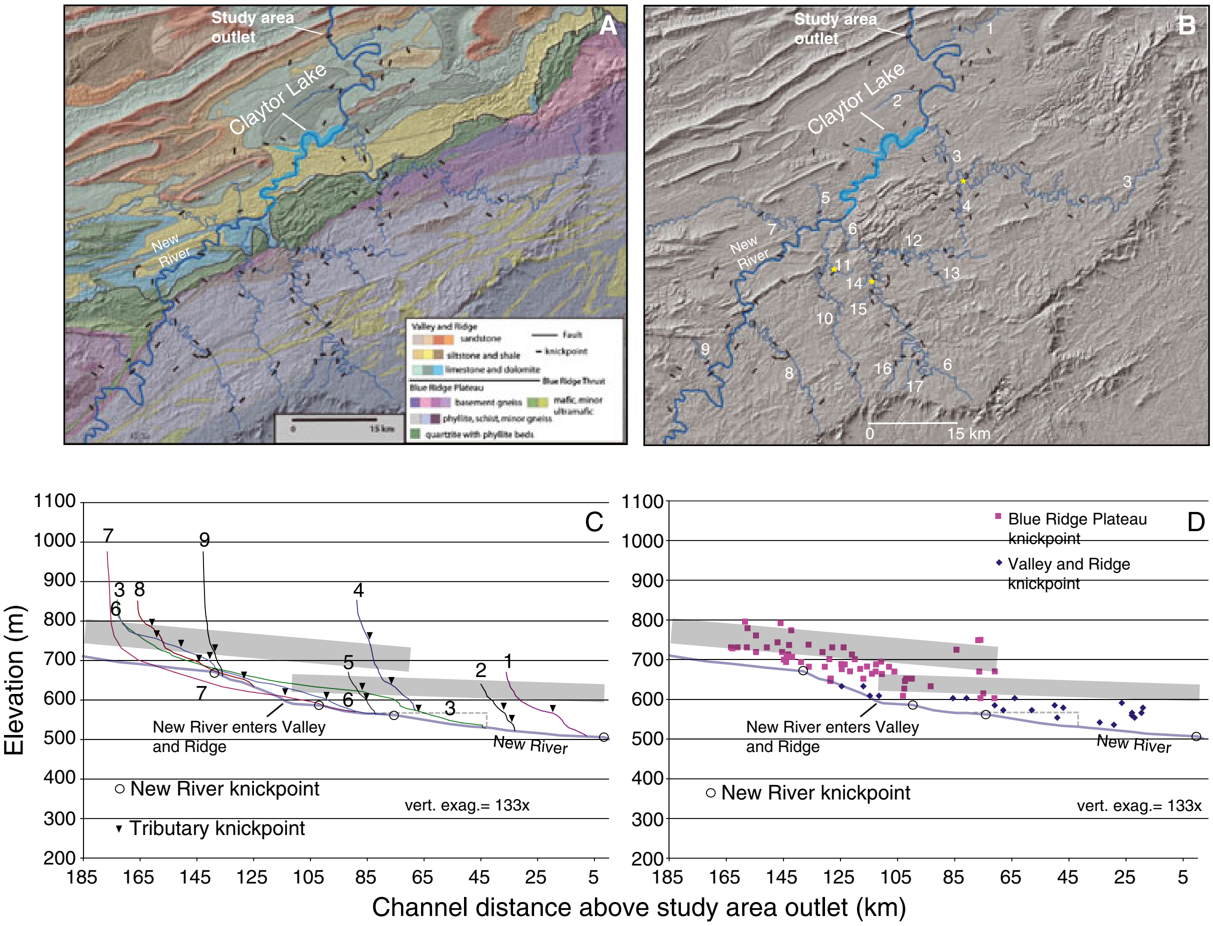

Figure 7. (A) Knickpoint locations plotted relative to mapped bedrock geology (Virginia Division of Mineral Resources, 1993). (B) Knickpoints plotted on hillshade topography; numbered drainages correspond to profiles in C and D and Figure 8. Stars indicate locations of photographs in Figures 8 and 10. (C) Longitudinal profiles of selected New River tributaries plotted against the profile of the New River and the trend of the reconstructed paleo-landscape. (D) Elevation of knickpoints plotted relative to the profile of the New River. This figure is available in colour online at wileyonlinelibrary.com/journal/espl

are very broad and present a step-like appearance within the overall convexity (for example, lower knickpoint of stream 4; Figure 7C). Due to the scale of our study, we are unable to resolve a topographic effect of each smaller convexity and therefore do not identify each as a knickpoint. Their combined effect on the fluvial profile and topography at large is, however, accounted for as they combine to produce the larger-scale convexity which correlates with evidence of steepening and headward retreat.

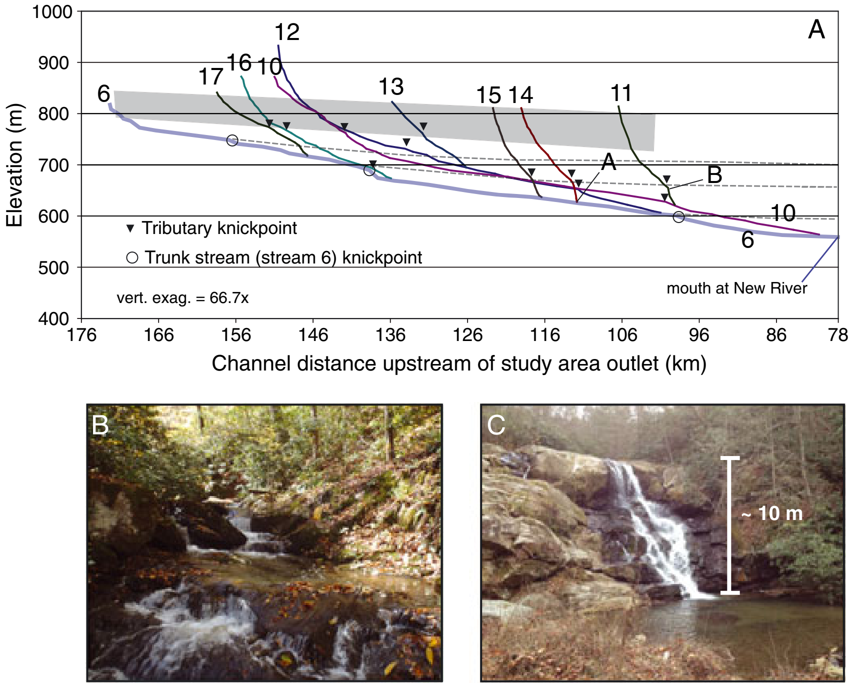

Figure 8. (A) Longitudinal profiles of stream 6 (Big Reed Island Creek) and selected tributaries. Dotted lines indicate hypothetical paleo-profiles of stream 6 projected from knickpoint lips. Shaded field indicates trend of Blue Ridge Plateau paleo-surface inferred from long topographic profiles (Figure 4). (B) Bedrock channel of stream 14 near its confluence with stream 6. Extensive pothole drilling occurs within the schists and mica-rich gneisses in the streambed. (C) Eagle Falls, a ~10 m waterfall at the upper end of the stream 11 knickpoint. This is the largest single drop within any knickpoint in the study area, and appears to be the result of incision waves stalling atop a resistant gneiss horizon. Photograph by Llyn Sharp, Virginia Tech Museum of Geosciences. This figure is available in colour online at wileyonlinelibrary.com/journal/espl

Knickpoints are distributed throughout the study area on a variety of lithologies (Figure 7A), and do not cluster along strike-extensive contacts between weak and resistant lithologies. We do not filter any profile convexities from the data set as products of lithologic control only, as all profile convexities which occur atop a lithologic contact show evidence of headward retreat to their present location. Knickpoints occur in every reach crossing the quartzite units of the north-western margin of the Blue Ridge Plateau (Figure 7A), the most resistant lithology in the study area, but downstream topography (Figure 2) shows evidence of headward migration prior to their arrival atop the resistant strata. Knickpoints are presently located at a range of drainage areas (inferred from knickpoint distance below drainage divide; Figure 9A), and are not limited to a low threshold drainage area beyond which migration would be extremely slow (Crosby and Whipple, 2006). Knickpoint retreat distance does not show a strong correlation with total stream drainage area; some knickpoints in high-order channels have experienced comparatively little retreat compared to those in smaller streams (Figure 9B).

We identify four knickpoints within the New River itself, based on combined analysis of its longitudinal profile and the locations of increases in incision depth apparent in topographic profiles (Figures 2, 5, and 7). The uppermost knickpoint occurs ~135 km above the study area outlet and begins in schists of the Blue Ridge Plateau. This broad knickpoint stretches across ~30 km of the New River, and gives a step-like appearance as it crosses alternating quartzites and slates along the north-western margin of the Blue Ridge. The steepest reach of the New River within the entire study area occurs at the downstream end of this knickpoint, where the river passes from steeply-dipping Blue Ridge quartzite to carbonates of the Valley and Ridge province. A significant knickpoint occurs ~100 km above the study area outlet, beginning in folded dolomite and extending across a klippe of quartzite. This knickpoint, expressed as a series of ledges and shoals, corresponds to a ~15 m increase

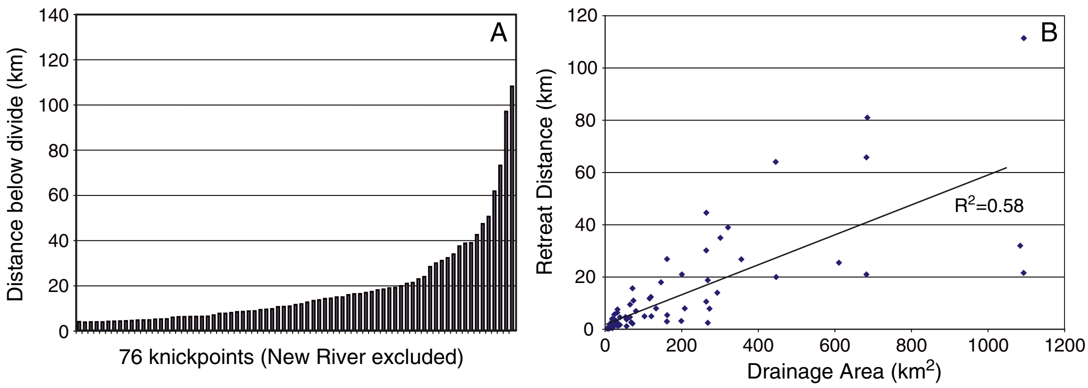

Figure 9. (A) Stream channel distances of knickpoints (excluding knickpoints in New River channel) below channel headwaters at a drainage divide. (B) Knickpoint retreat distance from stream mouth plotted against total stream drainage area (excluding knickpoints in New River channel).

in incision depth into the New River Valley surface (Figure 5). A major knickpoint in the Valley and Ridge is obscured by Claytor Lake, a reservoir constructed in 1939. While the exact position and steepness of this knickpoint cannot be determined due to a lack of detailed pre-reservoir mapping, the drop in channel elevation between reservoir headwaters and the base of the dam requires that a significant profile convexity be present within the flooded reach. This knickpoint was a well-known obstacle to river navigation prior to dam construction (Trout, 2003). The lowermost New River knickpoint identified occurs just above the study area outlet.

Knickpoint form varies throughout the study area (Figures 7, 8, and 10). Some knickpoints maintain an abrupt 'lip' and appear to mark a discrete boundary between old and new base level (stream 11; Figure 8A); others develop a broadly convex lip which implies 'leaking' of incision as described by Berlin and Anderson (2009) (i.e. stream 7; Figure 7C). Larger streams more commonly have broadly convex knickpoints. Satellite and field observation indicate that the upper portions of the convex reach are characterized by increased presence of bedrock in the streambed and along hillslopes, which grades into an almost entirely bedrock-floored 'core,' below which gradient rapidly decays and the streambed regains alluvial cover. In all lithologies, headward retreat of the knickpoint is apparent in bedrock cliffs which line the channel within the knickpoint zone; decay of these features by mass wasting is apparent, representing an increased rate of sediment production to match increased stream power (Norton *et al.*, 2008). Inspection of the slope map indicates that hillslope maxima in the Valley and Ridge and Blue Ridge are comparable in areas immediately downstream of knickpoints. The study area contains numerous gorges cut into non-resistant carbonate strata as well as into weak chlorite-rich phyllites and slates of the Blue Ridge (Figure 10C).

Knickpoint distribution appears consistent with the model of a headwardly-mobile response to external base level drop. The distribution of knickpoints near the mouths of low-order streams, particularly on the Blue Ridge Plateau, suggests formation in the 'wake' (Gallen *et al.*, 2011) of knickpoints migrating up their master stream (Figures 2, 7, and 8). Knickpoints and the associated steepest topography of the study area still occur at low elevations within the landscape, generating 'negative topography' in which elevation in inversely proportional to slope and relief (Liu-Zeng *et al.*, 2008). We interpret this pattern to be a result of incomplete knickpoint progress through the drainage network. This pattern is particularly well-illustrated in the basin of Big Reed Island Creek (stream 6; Figures 7 and 8). The uppermost knickpoint of stream 6 occurs ~75 km from its mouth and 21 km downstream of headwaters. Downstream of this uppermost knickpoint, tributaries cross knickpoints as they drop into the steep-walled gorge of stream 6 (Figure 8). Beyond the uppermost knickpoint of stream 6, however, hillslopes remain gentle (generally $< 10°$; Figure 2) and tributaries do not host knickpoints.

The majority of knickpoints occur along the base of the relict surfaces or at elevations below the relict surfaces, producing a downstream increase in maximum knickpoint height above the New River within the respective physiogeologic provinces (Figure 7D). Streams in the lower reaches of the study more commonly contain multiple knickpoints. A noticeable change in the pattern of knickpoint distribution as well as maximum knickpoint elevation above the modern New River base level occurs between the mouths of stream 3 and stream 6, along the reach of the New River now obscured by Claytor Lake (Figure 10). Stream 3 is ~80 m incised into the carbonate rocks of the Valley and Ridge landscape at its mouth, and hosts a major knickpoint where it exits the Blue Ridge Plateau. In contrast, stream 6 is < 60 m incised and hosts a comparatively modest knickpoint where it exits the Blue Ridge Plateau across an intact and very resistant section of quartzite. Addtionally, stream 3 crosses knickpoints developed in carbonate strata in its Valley and Ridge reach; knickpoints are absent from the concave-up Valley and Ridge reach of stream 6. We interpret this distribution of knickpoints and incision to be the result of a headwardly-mobile incision signal which is yet to reach the mouth of stream 6 and beyond, where earlier incision waves have already passed (Figure 10).

Discussion

The upper New River basin displays a pattern of transient topographic disequilibrium typically associated with significant, rapid base level drop in active tectonic settings. The

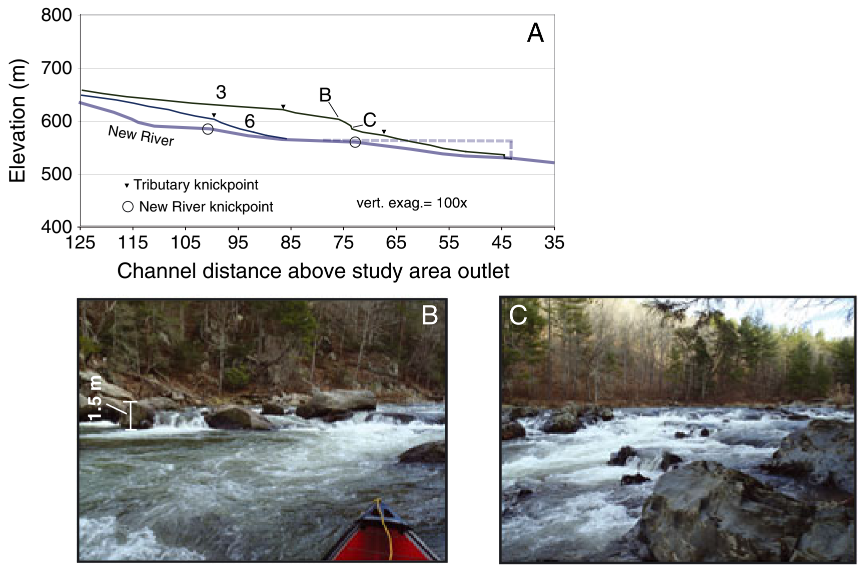

Figure 10. (A) Longitudinal profiles of lower reaches of stream 3 and stream 6 near their confluences with the New River (Figure 7). Dashed line indicates location and elevation of Claytor Lake. (B) Falls developed on quartz-rich mylonitized gneiss within the broad middle knickpoint of stream 3 at the margin of the Blue Ridge Plateau. (C) Falls developed in chlorite-rich slates/phyllites ~1 · 5 km downstream of B. This figure is available in colour online at wileyonlinelibrary.com/journal/espl

development of bedrock knickpoints at the boundary between the relict landscape and the headwardly-mobile new base level suggests that stream incision has accelerated sufficiently to decouple topography from the drainage network, steepening hillslopes to induce accelerated delivery of sediment to channels. Upstream of knickpoints, topography continues to evolve under pre-incision conditions and does not adjust to base level drop until reached by knickpoints. Rates of knickpoint retreat and base level drop are unknown, but must be sufficiently rapid to maintain disequilibrium by outpacing the capacity of hillslopes to provide sediment to the energized drainage network (Crosby and Whipple, 2006; Norton *et al*., 2008). As the fluvial and topographic responses we observe appear to spread headward away from the study area outlet, we favor climatically-driven lowering of external base level against fixed surface elevation as the driver for transient incision in this otherwise stable passive margin landscape.

While it is mechanistically analogous to topographic response following large tectonic base level fluctuation, the lower magnitude of incision in the transient response we observe is more subtle and less apparent in the field or in traditional topographic mapping. Bedrock gorges in the study area do not approach the depths reached in high-elevation, high-relief transient landscapes such as the Tibetan Plateau (Schoenbohm *et al*., 2004; Clark *et al*., 2006; Harkins *et al*., 2007; Stroeven *et al*., 2009), but they are still rugged, and are characterized by bedrock cliffs and mass wasting events. The morphological contrasts between relict and adjusting topography control land-use in the study area. Adjusting areas are too rugged and lacking in soil cover to permit agriculture (Schoenbohm *et al*., 2004), which is limited to the gentler topography of elevated relict surfaces (Figure 11). Farming along stream valleys is rare except in the upper reaches of New River tributaries, where knickpoints and hillslope steepening have yet to migrate. The slow evolution of these relict domains, evident in their soil cappings, produces sharp contrast with the oversteepened slopes of adjusting areas despite the lack of extreme relief encountered in active tectonic transient landscapes.

The spatial and temporal pattern of relict landscape response appears to reflect differing rates of knickpoint retreat as well as continued migration of knickpoints through the New River itself. As the New River is the means through which external

Figure 11. Inclined Google Earth satellite image looking north along stream 6. Agricultural development in this area is limited to low-relief relict surfaces perched above stream 6; arable floodplain along the channel is absent. Hillslopes steepened by incision of stream 6 and its tributaries are forested and undeveloped due to their steep slope. A portion of topographic profile 13 (Figures 2 and 4) is visible near the top of the image. Image ©Google Earth 2012©Google. This figure is available in colour online at wileyonlinelibrary.com/journal/espl

base level is introduced to the study area, tributaries entering the New River near one another can be expected to develop knickpoints at their mouths at essentially the same time. Variable knickpoint retreat distance (in terms of map distance from stream mouth) in tributaries which enter the New River very close to one another may thus be attributable to the dependence of knickpoint retreat rate on stream power, with knickpoints migrating most rapidly up the channels of large streams (compare streams 5 and 6; Figure 7). Knickpoint retreat is likely slower in smaller, less powerful streams, although their steeper initial gradient allows knickpoints to 'climb' vertically into the relict landscape at a comparable rate to large, lower-gradient streams (i.e. tributaries to stream 6; Figure 8). As migration through the entire channel to headwaters is ultimately essential for complete adjustment of relict topography, slow knickpoint retreat in small channels is probably the rate-limiting process in the response of the study area landscape (Crosby and Whipple, 2006). As a result, areas drained by separate first-order streams, such as interfluves separating major New River tributaries or bluffs along the New River itself, may be the last areas to completely adjust to base level drop. Knickpoint distribution in the New River, however, suggests base level drop is ongoing (i.e. yet to fully effect the entire studied reach of New River). The upper reaches of the study area may only be reached by the leading edge of base level forcing well after it has affected tributaries further downstream, producing a 'snapshot' image of adjustment in which knickpoints recently formed at the mouths of large tributaries have not yet had time to migrate headward. This model may explain the limited correlation between stream size and present knickpoint position (Figure 9), offering an interesting contrast to knickpoint occurrence at a threshold drainage area as documented by Crosby and Whipple (2006). Response to base level forcing may therefore depend on the position of a point with respect to high-order streams as well as the overall channel distance between the point and the origin of the external base level drop.

The extent to which lithologic factors may control longitudinal profile shape remains unclear. Existing geologic mapping indicates that the majority of knickpoints occur in single, non-resistant lithologies (Figure 7A); however, local compositional or structural characteristics (i.e. folding, joint spacing) could be expected to cause variation in the mechanical behavior of a single unit exposed to base level drop (Miller *et al*., 1990). Fluctuations in dip due to folding could cause knickpoints to decay vertically and leak incision upstream as they migrate through very steeply dipping strata (Frankel *et al*., 2007; Berlin and Anderson, 2009), only to reform on a differently-oriented horizon within the same lithologic unit. Quartz veins are ubiquitous in the Blue Ridge Plateau, and dense veining or very thick veins might also impact local lithologic resistance. Accordingly, rock strength analyses considering a wide range of variables such as compressive strength, joint spacing, and vein density would have to be conducted along the entire length of a stream channel to decisively relate knickpoint position to lithologic characteristics. While this level of analysis is impossible due to the size of the study area, we do observe trends which suggest active migration is a significant control on knickpoint position. Knickpoint elevations describe a gentle upstream increase across the study area, consistent with knickpoint lips are migrating along the trend of a pre-existing relict landscape base level (D, Figures 7D and 8). The complex deformation of the study area offers further evidence against widespread lithologic control, as breaching northwest-vergent folding and thrust faulting has produced nearly ubiquitous southeast dip of strata and contacts and should preclude the widespread occurrence of a resistant horizon at a fixed or gently northeast-sloping elevation.

While we do observe evidence of dynamic knickpoint migration, current knickpoint elevations do not show a clear relationship with physical indicators of temporary base level such as terraces or perched loops. Terraces studied by Ward *et al*. (2005) near the study area outlet suggest an episodic late Cenozoic incision history, but the numerous knickpoints in the New River itself do not clearly match the terraces of Ward *et al*. (2005). The number of New River knickpoints may suggest that base level drop has been episodic, but could also be the result of complex response to continual base level drop whose overall effect is apparent in the downstream increase in incision depth. This is further complicated by the possibility that a single incision event will have a varied topographic expression due to localized bedrock characteristics that are not immediately apparent during field mapping (Miller, 1991; Miller *et al*., 2010). Such complexity emphasizes the importance of considering the spatial relationships between knickpoints and topographic characteristics, such as slope distribution, when evaluating the effects of transient incision, as well as the great difficulty inherent to developing well-constrained model inputs for a system of this size and structural architecture.

Origin of incision

The origin of the incision pulses migrating through the upper New River basin is uncertain. Given the unlikelihood of tectonic forcing (Oyarzun *et al*., 1997; Spotila *et al*., 2004; Steinberger, 2007; Braun, 2010; Forte *et al*., 2010), Ward *et al*. (2005) favored a climatic explanation for New River terrace development, citing similarities between the age of terraces and the δ^{18}O record of glacial–inter-glacial cycling. Hancock and Kirwan (2007) suggested a similar forcing for disequilibrium documented in the Cheat River headwaters (Figure 12), and cycles of increased sediment supply during glaciation coupled with rapid incision during melting episodes has been suggested as a driver of terrace formation throughout western North America (Bull, 1991; Hancock *et al*., 1999; Maddy *et al*., 2001; Hancock and Anderson, 2002; Wegmann and Pazzaglia, 2002). Given the effect of glacial–inter-glacial climate on vegetation, freeze–thaw processes, and enhanced storm intensity beyond the ice margin, this sediment supply- and discharge-controlled process could induce disequilibrium in unglaciated basins apparently out of reach of eustatic fluctuation. An important aspect of this model is that incision is forced by processes affecting the entire basin at once, and does not require lowering of the external base level.

While fluctuating late Neogene climatic variables (i.e. temperature, precipitation) almost certainly had some sort of effect on the studied landscape, the pattern of transient adjustment we observe suggests the drainage network is incising in response to a drop in external base level beyond the study area. The downstream increase in incision depth, the preservation of intact relict surfaces, and the lack of threshold drainage area control over knickpoint position suggests transient incision has migrated into the study area from downstream of the study area outlet. This origin of incision is consistent with continued upstream migration of transient adjustment documented in streams of the lower Ohio River basin by Granger *et al*. (2001) and Anthony and Granger (2007), and would also explain the disequilibrium apparent in the Cheat River basin, another major tributary of the Ohio River (Springer *et al*., 1997; Hancock and Kirwan, 2007) (Figure 12). If progressive Teays River integration is, in fact, the principal driver of New River incision, then the elevation and morphology of the relict topography we observe is a product of the latest Tertiary Teays River and its course to ultimate base level in the Gulf of Mexico. The drop in continental interior regional base level produced by progressive integration of the Teays River would have forced incision signals to propagate through the New River system to initiate its adjustment to the new location and ultimately the elevation of the Ohio River channel (Figure 12). The transient incision we observe may thus result from the accelerated release of topographic potential energy preserved in the Appalachian Highlands. Similar to the erosional response following stream capture along the Blue Ridge Escarpment (Prince *et al*., 2010, 2011), upper New River basin incision may be another example of how drainage rearrangement can force episodes of transient incision in the absence of tectonic uplift. The upper New River basin, along with other Ohio River basin examples (Springer *et al*., 1997; Granger *et al*., 2001; Anthony and Granger, 2007; Hancock and Kirwan, 2007), may therefore present a unique glimpse into the wide range of impacts climatic fluctuation may have on fluvial systems. Our study area is located ~250 km (straight line distance) from the ice margin, and continued headward advance of the incision process we document will impact the landscape up to 400 km south of the southernmost advance of ice sheets at 1·5 Ma (Gray, 1991). While these landscapes may not have experienced substantial topographic change during the Pliocene and Pleistocene, they

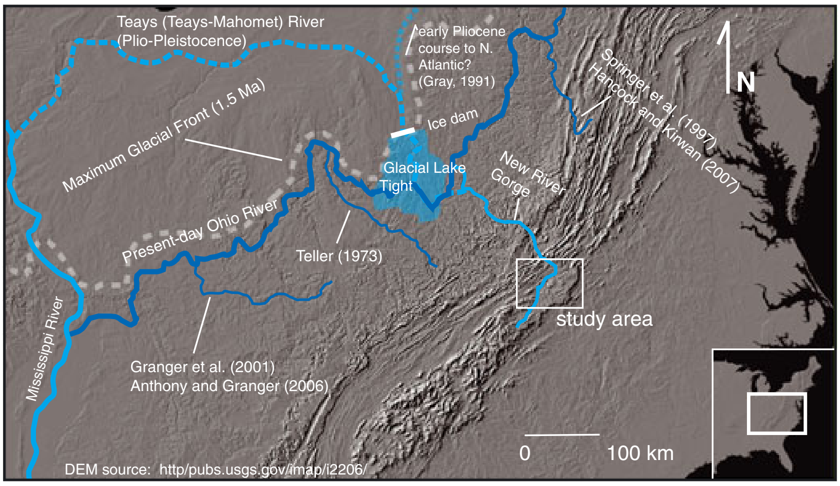

Figure 12. Location of the study area in the pre-glacial (Teays) and modern Ohio River drainage networks. Approximate pre-glaciation Teays-Mahomet course is based on the work of Gray (1991). Other Ohio River tributary basins whose Plio-Pleistocene incision histories have been studied are indicated. The glacial Lake Tight indicated (Tight, 1903; Gray, 1991) is one of many lakes formed along the ice margin; glacial lakes and pre-glacial courses other than the main stem of the Teays are not shown. This figure is available in colour online at wileyonlinelibrary.com/journal/espl

should eventually respond to the base level signal resulting from progressive rearrangement of the Teays River system which continues to migrate headwardly through the modern New River system (Gray, 1991).

If the incision we observe is the result of progressive Teays rearrangement, which may have begun in the mid-Pliocene (Gray, 1991), the distance of migration of incision signals requires that the wave of adjustment travel at > 100 km/Myr through the New River channel itself, with rates of advance through smaller tributaries being one or two orders of magnitude lower. Noteworthy is that these values describe the transit rate of an climatically-forced incision signal of finite size and duration through the channel, generating an episode of response distinct from the ongoing forcing associated with active tectonic settings. Accordingly, studies of terrace abandonment, such as Ward *et al.* (2005), capture a rate of vertical incision that is limited by the size of overall base level drop and will not reflect the rate of migration of the incision signal. Combining the age of terraces with the distance the incision signal that abandoned them has traveled would thus provide a useful commentary on the pace of landscape adjustment in settings where transient response is the result of punctuated forcing as opposed to continued tectonism.

The uppermost terrace of Ward *et al.* (2005) (Figure 1), with a loosely-constrained age of 2 · 5 Ma, can be used to demonstrate how the rate of headward migration of an incision signal of finite size might be determined. Assuming this highest terrace correlates with the pre-incision relict surface, the abandonment signal has migrated at least 125 km up the New River. This yields a signal migration rate of 50 km/Myr through the New River channel and ~5 km/Myr in stream 1, which enters the New River near the dated terrace. These rates of upstream migration of the incision front, which are distinct from vertical incision rates (~40 m/Myr; Ward *et al.*, 2005), are plausible in the context of other studies of fluvial response to finite late Pleistocene base level fluctuation (e.g. Crosby and Whipple, 2006; Norton *et al.*, 2008). These rates, however, are highly speculative, and attempts at constraining transit rates are hampered by the challenges of dating terraces and correlating them with knickpoints. Dating of sediments stored in loops (Figure 6) would offer a useful chronological constraint on paleo-base level, and might further enhance understanding of the timing of adjustment.

Although the origin of incision remains speculative, it is reasonable to expect the transient response to continue until the upper New River basin achieves better adjustment to modern Ohio River base level. Eventual adjustment will lower elevations of the study area by at least 100 m, potentially generating a ridge along the Eastern Continental Divide and altering the large-scale appearance of a large portion of the Valley and Ridge and Blue Ridge Plateau provinces. Should other Ohio River tributaries experience similar incision in response to Teays rearrangement, the appearance of the majority of the unglaciated Appalachian Highlands will eventually be altered by response to glacially-forced drainage rearrangement in the continental interior. The bedrock incision through which adjustment is accomplished should continue to deliver increased sediment volume to the Gulf of Mexico, where evidence of the Pleistocene arrival of glacial meltwater and associated sediment has already been documented. Drainage rearrangement along ice sheet margins may represent a significant driver of incision pulses in basins throughout the world, and representing a mechanism through which climate change can impact topography long after the onset of a given climatic forcing event.

Conclusions

Knickpoint and relict landscape distribution in the studied portion of the New River basin are consistent with a state of transient topographic disequilibrium not typically associated with passive margin settings. Relict surface preservation, along with a downstream increase in incision depth, suggest waves of fluvial incision are spreading through the study area in response to a drop in external base level as opposed to a climatically-driven change in sediment supply. Knickpoints mark the leading edge of these incision waves and represent the headwardly-mobile boundary between relict and adjusting topography. The progress of knickpoint retreat is apparent in oversteepened hillslopes left in their 'wake' (Gallen *et al.*, 2011), which contrasts sharply with the low slope and relief of relict topography yet to be reached by knickpoints. This pattern allows the progress of transient adjustment to be effectively delineated by comparing hillslope and elevation data to knickpoint location. While the maximum incision depth (~110 m) is comparatively modest, the topographic and fluvial patterns we observe are consistent with those of tectonically-forced river systems and can be identified using the same methods of topographic study. It is possible that climatically-forced transient incision events are more common in passive margins than previously thought, and refined methods of topographic characterization may permit their identification.

In the absence of tectonic forcing or obvious local drainage rearrangement, we favor glacially-forced drop in landward base level as the driver for New River incision. While the study area itself remained unglaciated, the modern base level for the New River, the Ohio River, is the ultimate product of progressive southerly drainage integration of the Teays River system along the margin of advancing late Pliocene and Pleistocene ice sheets. The rapidity with which glacial advance and breaching of ice-dammed lakes altered drainage patterns in the North American continental interior may have been sufficient to force episodes of rapid fluvial incision in present-day Ohio River tributaries hundreds of kilometers south of the ice margin. While the onset of incision and adjustment to Teays rearrangement has been sufficiently rapid to maintain disequilibrium, migration of knickpoints through smaller channels is sufficiently slow that adjustment to the initial climatic forcing continues long after ice sheets retreat. Ultimate adjustment of the entire New River basin to the modern Ohio River base level will significantly reduce the elevation of the Blue Ridge Highlands, altering the region-scale appearance of the central and southern Appalachians and reducing asymmetry along the migrating eastern continental divide (Prince *et al.*, 2010, 2011). Our results indicate the potential for glacial advance to impact landscape development in areas well beyond the ice margin and out of reach of eustatic fluctuation by forcing major drainage rearrangements over relatively short timescales. Distant glacial impact on regional base level, in addition to altered precipitation patterns and sediment supply, should therefore be considered as a potential driver of large-scale topographic response to global climate change.

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