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Neogene rejuvenation of central Appalachian topography: Evidence for differential rock uplift from stream profiles and erosion rates

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ABSTRACT

The persistence of topography within ancient orogens remains one of the outstanding questions in landscape evolution. In the eastern North American Appalachians, this question is manifest in the outstanding problem of whether topographic relief is in a quasi-equilibrium state, decaying slowly over many millennia, or whether relief has increased during the late Cenozoic. Here we present quantitative geomorphic data from the nonglaciated portion of the Susquehanna River drainage basin that provide insight into these end-member models. Analysis of channel profiles draining upland catchments in the northern Valley and Ridge, Appalachian Plateau, Blue Ridge, and Piedmont provinces reveals that a large number of streams have well defined knickpoints clustered at 300–600 m elevation but not systematically associated with transitions from weak to resistant substrate. Cosmogenic ^{10}Be inventories of modern stream sediment indicate that erosion rates are spatially variable, ranging from ~5–30 m/Myr above knickpoints to ~50–100 m/Myr below knickpoints. Overall, channel gradients, normalized for drainage area, scale linearly with catchment-averaged erosion rates. Collectively, regionally consistent spatial relationships among erosion rate, channel steepness, and knickpoints reveal an ongoing wave of transient channel adjustment to a change in relative base level. Reconstructions of relict channel profiles above knickpoints suggest that higher rates of incision are associated with ~100–150 m of relative base level fall that accompanied epierogenic rock uplift rather than a change to a more erosive climate or drainage reorganization. Channel response timescales imply that the onset of relative base level change predates ~3.5 Ma and may have begun as early as ~15 Ma. We suggest that adjustment of the channel network was likely driven by changes in mantle dynamics along the eastern seaboard of North America during the Neogene.

1. Introduction

Despite significant progress in understanding the coupling among topography, climate, and tectonics within active orogens (Whipple, 2009), the persistence of topography observed along many passive margins remains enigmatic (Baldwin et al., 2003; Bishop and Goldrick, 2010; Scharf et al., 2013). As an example, the eastern seaboard of North America has been a passive continental margin for ~180 Myr (Faill, 1998); yet, the Appalachian Mountains retain significant topographic relief, with the highest elevations reaching just over 2000 m above sea level (Fig. 1A). The history of this topography has long been a topic of study (Davis, 1889), and a continuing debate centers on whether Appalachian topography is in a state of quasi-equilibrium (e.g., Hack, 1960; Matmon et al., 2003), maintained isostatically but decaying slowly over geologic time (e.g., Baldwin et al., 2003), or whether it has been rejuvenated during the late Cenozoic (e.g., Davis, 1889; Hack, 1982; Poag and Sevon, 1989; Hancock and Kirwan, 2007; Gallen et al., 2013; Portenga et al., 2013; Prince and Spotila, in press).

Recent geomorphic studies in the Appalachians have revealed fluctuations in channel incision during late Cenozoic time (Poag and Sevon, 1989; Pazzaglia and Gardner, 1993; Sasowsky et al., 1995; Granger et al., 1997; Springer et al., 1997; Reusser et al., 2004; Ward et al., 2005), that stand in apparent contradiction to the conventional wisdom that slow degradation of topography has been sustained for >100 Myr (Matmon et al., 2003; Spotila et al., 2004). Potential drivers of erosion rate variability, however, remain a point of debate, with workers alternatively favoring climate change (Boettcher and Milliken, 1994; Reusser et al., 2004; Ward et al., 2005; Hancock and Kirwan, 2007; Westaway,

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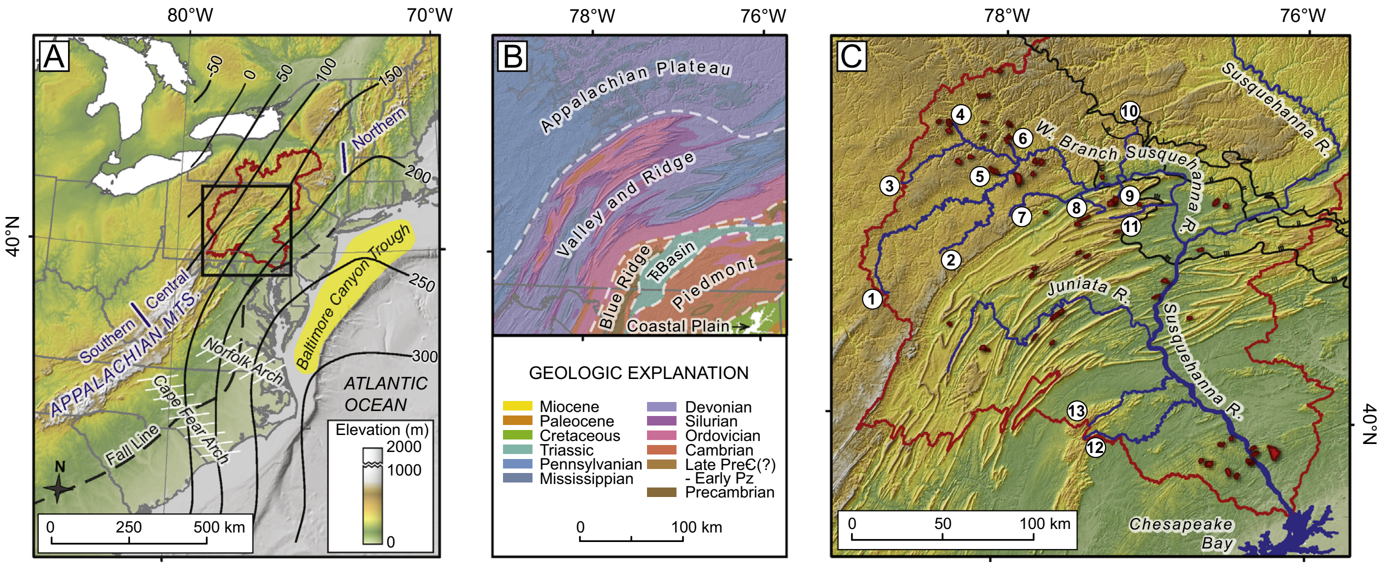

Fig. 1. Maps of study area. (A) Digital elevation model (DEM) of the eastern USA showing the Appalachian Mountains, Susquehanna River catchment (red), and Baltimore Canyon Trough (yellow). Black contours show change in dynamic topography since 30 Ma, in meters (modified from Moucha et al. (2008)). Dashed line is the Fall Line. Location of panels B and C outlined in black. (B) Geologic map draped over shaded relief DEM of study area. Geologic province boundaries shown with white dashed lines. (C) Red polygons mark individual catchments used in erosion rate and stream profile analyses. Black lines mark southern margins of major glacial advances from Fullerton et al. (2003)) (one tic: late Wisconsin; two tics: Illinoian; three tics: pre-Illinoian). Thick blue lines mark streams referred to in text and other figures (1: W. Branch Susquehanna R.; 2: Moshannon Ck.; 3: Bennett Branch Sinnemahoning Ck.; 4: E. Branch Hicks Run; 5: Little Birch Island Run; 6: Lebo Branch Cooks Run; 7: N. Fork Beech Ck.; 8: Long Run; 9: Gottshall Run; 10: Larrys Ck.; 11: White Deer Ck.; 12: W. Conewago Ck.; 13: Mountain Ck.). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

2007), drainage reorganization and stream capture (Harbor et al., 2005; Pazzaglia et al., 2006; Gunnell and Harbor, 2010; Prince et al., 2010, 2011; Prince and Spotila, in press), or changes in the tectonic rock uplift rate (Poag and Sevon, 1989; Pazzaglia and Brandon, 1996; Gallen et al., 2013).

Lately, studies of density-driven flow in the mantle (Moucha et al., 2008; Spasojević et al., 2008) have renewed interest in dynamically supported topography along the eastern North American margin (Vogt, 1991; Pazzaglia and Brandon, 1996; King, 2007), perhaps associated with intraplate seismicity in the region (Wolin et al., 2012). Although important differences among models and their predictions exist (Flament et al., 2013), such models provide reasonable explanations for anomalous sea-level curves determined from the Atlantic passive margin (Spasojević et al., 2008) and deformed shorelines across the Cape Fear and Norfolk Arches (Rowley et al., 2011). Moreover, some model realizations (Moucha et al., 2008) raise the possibility that changes in mantle circulation since ~30 Ma have driven surface uplift of ~100–200 m inboard of the coastal margin (Fig. 1A). Although such changes should, in principle, be measurable, the scarcity of geomorphic markers with which to gauge subtle, long-wavelength deformation in the eroding upland landscapes of the Appalachians, and thus test dynamic topography models, makes this challenging.

River profiles are increasingly exploited as gauges of tectonic and climate change (Wobus et al., 2010; Kirby and Whipple, 2012; Schildgen et al., 2012). Interpretations of profile shape are complicated where rivers cross substrates with contrasting erodibilities because equilibrium channel gradients depend on rock mass quality and resistance to erosion (e.g., Duvall et al., 2004). Such complications are present in the Appalachians, where the Paleozoic fold and thrust belt structure is clearly displayed in the topography (Hack, 1960; Mills, 2003). Consequently, it has been difficult in the Appalachians to show whether knickpoints in river profiles—traditional geomorphic fingerprints of perturbations in incision rate (e.g., Bishop et al., 2005)—are migratory, reflecting changes in external forcing, or whether these are stable, anchored by spatial variations in substrate erodibility (Hickok, 1933; Morisawa, 1962; Harbor et al., 2005; Frankel et al., 2007; Gallen et al., 2011, 2013; Prince et al., 2011; Prince and Spotila, in press). Central to this problem, it remains to be shown in the Appalachians that knickpoints thought to be migratory (e.g., Gallen et al., 2013; Prince and Spotila, in press) correspond to along-stream variations in incision rate.

In this paper, we examine whether the topography in the Susquehanna River drainage basin (Fig. 1), part of the central Appalachian Mountains, can be considered in a steady state or whether it records the imprint of transient channel incision. Because this region is largely upstream of relict fluvial terraces (Pazzaglia and Gardner, 1993), we combine quantitative analyses of channel longitudinal profiles (Wobus et al., 2006a; Kirby and Whipple, 2012) with existing determinations of erosion rate from in-situ cosmogenic ^{10}Be inventories in fluvial sediment (Reuter, 2005; Portenga and Bierman, 2011). The results demonstrate that regional channel gradients and erosion rates are adjusting to 100–150 m of base level fall that most likely began in the Neogene. Finally, we explore the implications of our results for geodynamic predictions of mantle-driven late Cenozoic surface uplift. Our results demonstrate that stream profile analyses coupled with basin-averaged erosion rate data provide a powerful tool for detecting and quantifying transient erosion in a lithologically diverse, ancient orogen.

2. Study area

The 71,200 km^2 catchment of the Susquehanna River is the largest draining the eastern slope of the Appalachians. Our study focuses on the part of that catchment that is south of the limit of Quaternary glaciation and mostly within the state of Pennsylvania, USA (Fig. 1). Elevations range from sea level to 957 m. This region encompasses a part of the Paleozoic Appalachian orogen that was rifted locally during the Triassic and has subsequently become the North American passive margin (Faill, 1998, 2003). Today, the area comprises six geologic and physiographic provinces (Fig. 1B) with