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Lithologic controls on landscape dynamics and aquatic species evolution in post-orogenic mountains

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ABSTRACT

Determining factors that modify Earth's topography is essential for understanding continental mass and nutrient fluxes, and the evolution and diversity of species. Contrary to the paradigm of slow, steady topographic decay after orogenesis ceases, nearly all ancient mountain belts exhibit evidence of unsteady landscape evolution at large spatial scales. External forcing from uplift from dynamic mantle processes or climate change is commonly invoked to explain the unexpected dynamics of dead orogens, yet direct evidence supporting such inferences is generally lacking. Here I use quantitative analysis of fluvial topography in the southern Appalachian Mountains to show that the exhumation of rocks of variable erosional resistance exerts a fundamental, autogenic control on the evolution of post-orogenic landscapes that continually reshapes river networks. I characterize the spatial pattern of erodibility associated with individual rock-types, and use inverse modeling of river profiles to document a ~150 m base level fall event at 9 ± 3 Ma in the Upper Tennessee drainage basin. This analysis, combined with existing geological and biological data, demonstrates that base level fall was triggered by capture of the Upper Tennessee River basin by the Lower Tennessee River basin in the Late Miocene. I demonstrate that rock-type triggered changes in river network topology gave rise to the modern Tennessee River system and enhanced erosion rates, changed sediment flux and dispersal patterns, and altered bio-evolutionary pathways in the southeastern U.S.A., a biodiversity hotspot. These findings suggest that variability observed in the stratigraphic, geomorphic, and biologic archives of tectonically quiescent regions does not require external drivers, such as geodynamic or climate forcing, as is typically the interpretation. Rather, my findings lead to a new model of inherently unsteady evolution of ancient mountain landscapes due to the geologic legacy of plate tectonics.

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1. Introduction

The development of topography on Earth influences the flux and routing of surface water, sediment, and organic matter to the world's oceans (Milliman and Syvitski, 1992; Summerfield and Hulton, 1994; France-Lanord and Derry, 1997; Battin et al., 2008), affects feedbacks between the solid Earth and atmosphere (Molnar and England, 1990; Raymo and Ruddiman, 1992), and alters the evolution and diversity of plant and animal species (Mayden, 1988; Waters et al., 2001; Hoorn et al., 2010). While the dominant mechanisms that drive topographic change in tectonically active settings, such as rock uplift and climate (Molnar and England, 1990), are clear, those that govern landscape evolution in tectonically quiescent mountains remain ambiguous. The conventional view of post-orogenic landscape evolution is one of slow, steady reduction in mean elevation, erosion rate, and topographic relief (Davis, 1899). However, most dead orogens preserve evidence of variable sediment flux and erosion rate and periods of topographic rejuvenation long after tectonics ends (Pazzaglia and Brandon, 1996; Hancock and Kirwan, 2007; Galloway et al., 2011; Gallen et al., 2013; Miller et al., 2013; Tucker and van der Beek, 2013). Most researchers now agree that topographic evolution in dead orogens is unsteady, although the underlying driving mechanisms remain poorly understood.

With the availability of high-resolution tomographic imaging of the Earth's mantle and global mantle convection models, uplift via dynamic topography or removal of lithospheric material has emerged as a process commonly invoked to explain topographic changes in tectonically inactive settings (Pazzaglia and Brandon, 1996; Gallen et al., 2013; Miller et al., 2013; Rowley et al., 2013; Liu, 2014; Biryol et al., 2016). Alternatively, climate change is often called upon to explain enigmatic evidence of landscape change under the assumption that a transition to a Quaternary-like climate ~3–4 Ma enhanced erosional efficiency on a global scale

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(Molnar and England, 1990; Hancock and Kirwan, 2007). The majority of studies rely on conceptual arguments and approximate spatial and temporal coincidence of landscape change with seismic wave velocity anomalies in the mantle or shifts in climate proxy data, whereas others use more sophisticated geodynamic of climate models to support a favored interpretation. However, in most cases such arguments are circumstantial, and do not provide particularly compelling support for either mechanism.

Landscapes in all dead orogens evolve on complex and spatially variable, but predictable geology. Links between topographic form and rock-type have long been observed (Hack, 1960; Mills, 2003), and spatially variable bedrock erodibility has been invoked as an attempt to explain changes in the retreat rate of passive margin escarpments (Gunnell and Harbor, 2010; Naeser et al., 2016). However, only recently have modeling studies shown that landscape evolution is surprisingly dynamic when rivers incise through rocks of variable erosional resistance (Forte et al., 2016) and that spatial variations of rock-types common in ancient mountain belts may play a role in post-orogenic topographic change (Tucker and van der Beek, 2013). Nevertheless, the potentially important role of rock-type as an autogenic driver of transient landscape evolution and river network reorganization, which modifies sediment dispersal patterns and fragments aquatic ecosystems, enriching biodiversity (Mayden, 1988; Waters et al., 2001; Near and Keck, 2005; Kozak et al., 2006; Rahel, 2007; Hoorn et al., 2010), remains largely unexplored in natural settings.

Here, I perform a quantitative geomorphology study of the southern Appalachian Mountains, where the last phase of tectonic activity ended >200 Ma (Hatcher, 1989), to elucidate the role of variable erodibility associated with different rock units on unsteady landscape evolution and drainage basin dynamics in post-orogenic regions. In this study, first, I quantify the impact of rock-type on topographic form and landscape response times, and use a formal linear inversion of river profiles to extract the history of transient landscape evolution; second, I use rock-type as a proxy for the spatial distribution of erodibility to elucidate the mechanisms driving transient landscape evolution and drainage basin dynamics in post-orogenic settings. I focus my study on the >105,000 km^2 Tennessee River Basin that flows westward from the eastern continental divide over rock-types common to all ancient mountain settings, and hosts the most diverse freshwater fish fauna in North America (Etnier and Starnes, 1993), making it an ideal setting to study the processes that shape post-orogenic topography and give rise to elevated biodiversity (Fig. 1).

2. Description of the study area

The Appalachians were built during a series of collisional episodes during the Paleozoic that ended with closure of the Iapetus Ocean during the Alleghany Orogeny (Hatcher, 1989). The former mountain range was rifted in the Late Triassic during opening of the North Atlantic and has since been tectonically inactive (Hatcher, 1989). The legacy of Paleozoic mountain building, Mesozoic rifting, and the subsequent passive margin history of eastern North America is strongly expressed in the modern landscape, and forms the basis for the classification of distinct physiographic provinces (Reed et al., 2005) (Fig. 1). Mesozoic to Cenozoic marine and terrestrial sediments of the Coastal Plain record the rifting and passive margin history. High-to-mid grade metamorphic rocks of the low-relief Piedmont and high-relief Blue Ridge represent the former hinterland of the Alleghany Orogen. Sedimentary units of the Alleghany fold-thrust belt and foreland basin define the Valley and Ridge province, and Appalachian and Interior Low Plateau provinces, respectively (Fig. 1a).

The Tennessee River basin spans the Blue Ridge, Valley and Ridge, and Appalachian and Interior Low Plateaus, and is divided into the Upper and Lower Tennessee basins that are connected by the Tennessee River Gorge near the city of Chattanooga, TN (Fig. 1). The axis of the main valley of the Upper Tennessee River basin is oriented roughly south-southwest before taking an abrupt westward turn as it enters the Tennessee River Gorge (Fig. 1). The river then flows westward through the Lower Tennessee basin, turns north joining the Ohio and Mississippi rivers before flowing southward and ultimately discharging into the Gulf of Mexico, nearly 3000 river kilometers from its headwaters (Fig. 1a).

For more than a century, geologists, physical geographers, and biologists have pondered the curious, long westward course of the Tennessee River, debating whether the Lower Tennessee River captured a paleo-Upper Tennessee River, known as the Appalachian River, diverting it from a more direct southerly route to the Gulf of Mexico via the Mobile basin (Hayes and Campbell, 1894; Simpson, 1900; Johnson, 1905) (Fig. 1a, b). Geologic studies remain ambiguous with evidence cited both for and against major shifts in flow direction of the Tennessee River (Hayes and Campbell, 1894; Johnson, 1905; Mills and Kaye, 2001; Mills, 2005). Phylogenetic studies in the southeastern U.S.A. indicate that freshwater faunal vicariance and dispersal events have been common during the late Cenozoic, implying reorganization of river networks; however, without conclusive corroborating geologic evidence, the timing and mechanisms that facilitated drainage rearrangement are debated (Mayden, 1988; Near and Keck, 2005; Kozak et al., 2006). Resolution of this controversy demands compelling evidence for or against capture of the Upper Tennessee basin, and if such evidence exists, determining that timing of capture and the mechanism(s) capable of reshaping of river networks in the absence of tectonic forcing. The Tennessee River controversy, thus, represents a microcosm of the broader questions regarding the drivers of dynamic landscape evolution in post-orogenic settings.

3. Fluvial geomorphology of the Upper Tennessee River basin

Capture of the hypothesized Appalachian river should leave a signal of discrete base level fall on the upstream fluvial network (the Upper Tennessee drainage basin), provided the response time of the river system is longer than the time since capture. Therefore to evaluate the Appalachian River hypothesis, I perform a quantitative analysis of fluvial topography in the Upper Tennessee basin to determine if it preserves a signature of base level fall consistent with river capture at its present-day outlet. For this analysis, I use 1-arc second (~30 m) Shuttle Radar Topography Mission (SRTM) digital topography. River networks are extracted based on a threshold drainage area of 5 km^2 and analyzed using TopoToolbox version 2.1 (see details below) (Schwanghart and Scherler, 2014). In this section, I first characterize the basic river profile morphology using standard river profile analysis; I then quantify the spatial variability in rock-type related erodibility in the drainage basin; finally, after controlling for the influence of spatially variable erodibility, I test for the signature of river capture in the Upper Tennessee River basin using a formal linear inversion of fluvial topography that allows for characterization of the base level fall history.

3.1. River profile analysis

River incision, E, into bedrock is typically modeled as a function of upstream contributing drainage area and channel gradient and, assuming detachment-limited conditions, can be expressed as (Howard, 1994):

$$E = KA^m S^n, \tag{1}$$

where A is the upstream drainage area, S is local channel slope (dz/dx), K is a dimensional erodibility coefficient, and m and n are

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