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Geologic controls on bedrock channel width in large, slowly-eroding catchments: Case study of the New River in eastern North America

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ABSTRACT

We have investigated the geologic controls on hydraulic geometry of bedrock rivers using a single large catchment, the New River, from a stable tectonic setting with variable, resistant lithology but spatially stable climate. Our survey of channel width at 0.5 km spacing along 572 km of the river shows major variation that only roughly fits the expected scaling relationships between width, drainage area, and slope. Considerable variations in width, including steps in trends and large spikes, relate to physiogeologic boundaries that the river passes through. A large fraction (15%) of the river's length classifies as bedrock reach, showing that it behaves more like a bedrock river than an alluvial river. Unlike established trends, the channel is wider in bedrock than in alluvium. Field observations show that aspect ratio (width to depth) is not constant, but fluctuates systematically with width from wide, shallow reaches to narrower, deeper reaches. Our observations of bedrock properties suggest that susceptibility to fluvial plucking versus abrasion may control this anomalous channel morphology. One end member form with aspect ratio as high as 500, which we term the *incision plain*, is associated with very closely spaced discontinuities (~10 cm) in otherwise hard rock. We propose that the closely spaced discontinuities enable efficient plucking that leads to widening by lateral erosion. This morphology locally occurs in other passive margin rivers and may be a fundamental fluvial form that is similar to, but the inverse of, slot canyons. The other end member, which we term *channel neck*, is narrower and deeper with complex flow paths through blocky bedrock. This form occurs where discontinuity spacing is longer (>0.5 m) and erosion is abrasion dominated. These results imply that changes in channel width do not necessarily reflect variations in uplift rate, but instead may result from complex response to bedrock properties.

1. Introduction

The hydraulic geometry of rivers has been the subject of intense geomorphologic study over the past half century and is considered fundamental to landscape evolution and the interpretation of erosional history from topography (cf. Whipple, 2004). The primary elements that comprise a channel's hydraulic geometry include gradient, roughness, and cross-sectional geometry. Channel width (W) and aspect ratio (W divided by mean depth, D) are particularly important for understanding fluvial processes, as they control how stream power (and therefore boundary shear stress) is distributed across a channel. Width is an adjustable parameter that combines with the dominant factors of drainage area and slope to dictate how rivers erode their beds. As a result, understanding what controls W in bedrock channels is fundamental to understanding landscape scale processes, including the response of landscapes to changing climate and active tectonism (Whipple, 2004; Finnegan et al., 2005; Wobus et al., 2006; Craddock et al., 2007; Attal et al., 2008; Yanites et al., 2010).

Although considerable attention has been paid to channel form, it is still not fully understood what controls W and W/D, particularly in bedrock rivers (Montgomery and Gran, 2001; Whipple, 2004; Amos and Burbank, 2007; Whittaker et al., 2007a; Wohl and David, 2008; Yanites and Tucker, 2010). Most of the work on this problem over the past decade has focused on small to moderate rivers in areas of active tectonic uplift, with only limited exception (Finnegan et al., 2005; Wohl and David, 2008; Yanites and Tucker, 2010). How scaling relations between W, A, and S hold at large drainage areas ($>1000\ \text{km}^2$) in areas of slow erosion is not well understood. Important signals of how boundary conditions, such as rock erodibility, control channel form may also be masked in areas of active tectonic uplift, given how uplift rate, sediment supply, orographic precipitation, and landscape transience all influence channel geometry (Craddock et al., 2007; Yanites and Tucker, 2010; Kirby and Ouimet, 2011).

To better understand how bedrock erodibility influences channel form, we have empirically investigated a large river with extensive bedrock reaches in an area of slow rock uplift and low sediment supply. The New River on the passive margin of eastern North America (Fig. 1)

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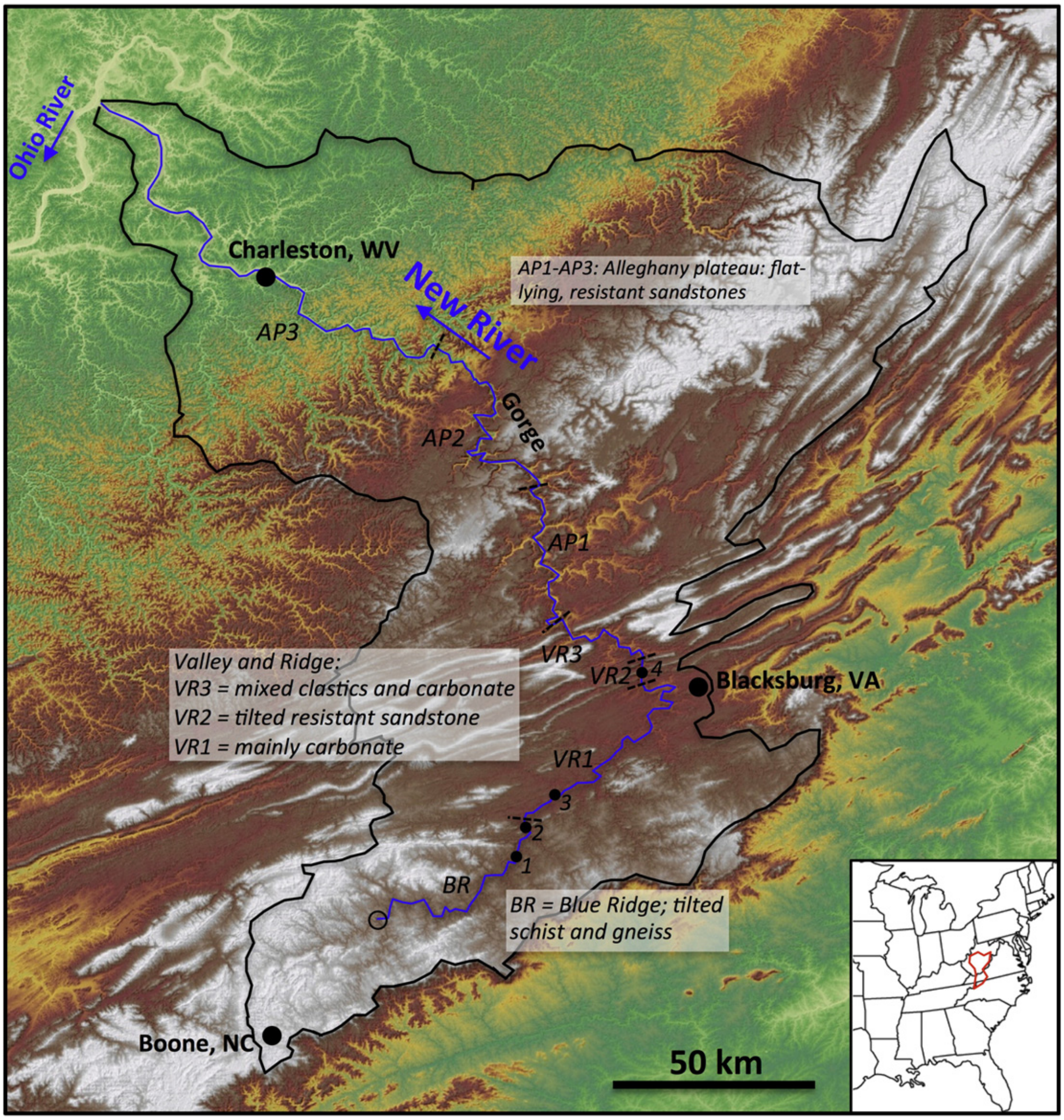

Fig. 1. Map of the New River basin in the central Appalachian Mountains of eastern North America. Mapbase is comprised of a color coded, 3-arc second digital elevation model. The study length of the river is highlighted in blue, from the confluence of the North and South Forks in the south (denoted by open circle) and the confluence of the Kanawha and Ohio Rivers in the north. Segments of the river used in analysis below are shown (BR = Blue Ridge, VR = Valley and Ridge, AP = Alleghany Plateau). Locations of paired field sites (Figs. 2, 9, and 10) are shown as follows: 1 = Fries, 2 = Buck-Ivanhoe, 3 = Foster Fall, 4 = Parrot–McCoy–Spruce Run.

is an ideal setting for this problem, not only because of the low rates of background rock uplift, but also because the legacy of prior tectonics imparts high variation in material properties of exposed bedrock (e.g., exhumed foreland basins) that could exert major control on bedrock channel geometry. Focusing on only one drainage basin also helps elucidate controls on geometry that relate to rock properties where other parameters (incision rate, sediment supply, climate) are effectively invariant. We hypothesize that the lack of apparent relationships between channel geometry and erodibility in syntheses of rivers in areas of active uplift (Wohl and David, 2008; Yanites et al., 2010) results from multiparameter variation that masks underlying effects of bedrock. By investigating one river system that transgresses zones of highly variable erodibility, we have identified important signals for the controls on channel geometry that are undetectable in more complex settings.

2. Controls on channel geometry

In alluvial rivers, *W* scales as a power-law function of discharge, *Q* (and therefore drainage area, *A*) with an exponent of ~0.5 (Leopold and Maddock, 1953; Parker, 1979). This empirical scaling relationship is robust across a range of conditions and drainage areas from headwater streams to the very large rivers (e.g., the Mississippi). Fluctuations to this rule may occur, however, such as where alluvial rivers are underpowered to erode their substrate (Wohl, 2004) or where feedbacks develop between hydraulic geometry and aggradation (Pelletier and DeLong, 2004). Alluvial rivers also narrow in response to differential rock uplift, in some cases enabling incision rates to match rock uplift rates without an increase in channel gradient (Amos and Burbank, 2007).

The controls on *W* in bedrock rivers are less well known (Montgomery and Gran, 2001; Finnegan et al., 2005; Wobus et al., 2006). Whipple's (2004) and Wohl and David's (2008) syntheses of previous work concluded that bedrock rivers of mainly small *A* (<1000 km^2) follow basically the same scaling rule as alluvial rivers, although with more local variation: $W \sim A^{0.3–0.5}$. The local variation has been attributed to lithologic contrasts of substrate or variations in incision rate. Systematic narrowing as channels progress from more erodible to more resistant lithology has been observed in several specific cases (Wohl and Ikeda, 1998; Montgomery and Gran, 2001). Substrate characteristics