Late Cenozoic stream incision in the Appalachian region

Scott Miller (MIT; srmiller@mit.edu), Eric Kirby (Penn State; ekirby@psu.edu), Peter Sak (Dickinson; sakp@dickinson.edu), & Claudio Berti (Lehigh; clb208@lehigh.edu)

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The persistence of topography along the ancient Appalachian orogen remains one of the outstanding questions in landscape evolution. In particular, it is unknown whether Appalachian topography is in a state of quasi-equilibrium (e.g., *1, 2*), is decaying slowly over geologic time (e.g., *3*), or whether it has been rejuvenated during Neogene time (e.g., *4, 5, 6*). Pursuit of these hypotheses over the past century has led to numerous contributions to the discipline of geomorphology, but the fundamental question about why Appalachian topography still exists remains largely unanswered. In this white paper, we make the case that advances in our understanding of how to interpret topographic signatures of long-term landscape change (e.g., *7*), in our ability to measure erosion rates (e.g., *2*), and in our ability to model the influence of mantle flow on surface topography (e.g., *8*) allow us to re-evaluate the problem of Appalachian topography. The landscapes of eastern North America (ENAM) present a research opportunity that is both intellectually rich, in the interplay between deep earth and surface processes, and timely, in that both the EarthScope facility and GeoPRISMS community are beginning to focus on this region.

Perhaps the strongest line of evidence in support of steady, long-term lowering of Appalachian topography, modulated by isostatic rebound (*9*), is the broad coincidence between rates of erosion over Cenozoic timescales inferred from thermochronology, and rates of erosion measured over late Quaternary timescales with cosmogenic isotopes (*2*). Departures from this condition, in the form of rapid stream incision (*10*) and pulsed sediment delivery offshore (*6*), have been variously attributed to climate change (*5, 10, 11*), drainage divide migration and stream capture (*12, 13*), or tectonically driven rock uplift (*6, 14*).

The advent of mantle flow models raise the striking possibility that dynamic topography on the East Coast has contributed to as much as 200–300 m of surface uplift since ~30 Ma (*8*). To date, most of the geologic evidence for dynamic topography in ENAM consists of anomalous New Jersey sea-level curves (*15*) and deformed shorelines south of New Jersey (*16*). Eroding, upland landscapes inboard of these shorelines, however, typically do not preserve markers of subtle warping (cf. *17*) and therefore make it a challenge to determine spatial patterns of deformation. Moreover, late Cenozoic exhumation is sufficiently limited such that even very low-temperature thermochronologic systems are not particularly sensitive. In such settings, however, information may be extracted from the topography itself; stream profile analyses coupled with erosion rate data provide a potential tool for deciphering long-term landscape evolution. Here we present some preliminary results that motivate us to look more closely at the fluvial record as a means for testing hypotheses about Cenozoic landscape evolution in ENAM.

Preliminary analysis of that knickpoints in the Susquehanna River basin (Fig. 1) suggests that these features represent a fundamental boundary between faster incision downstream and slower incision upstream (*18*), consistent with models of transient erosion and local evidence for relict topography such as residual soils as old as Miocene (*19*). Analysis of streams draining upland plateaus revealed transient profiles, characterized by steep reaches incised into narrow, steep-sided valleys below knickpoints that are not associated with lithologic contacts or contrasts in rock strength (Fig. 2). When normalized for drainage area, channel gradients correlate with watershed-averaged erosion rates from cosmogenic ^{10}Be in detrital quartz (Fig. 3), indicating that steeper channels are eroding at rates two to three times greater than those atop the plateau.

Similar relationships between erosion rates and stream profile form have been observed in more tectonically active regions (e.g., *20*), and suggest that the techniques developed to interpret the history of tectonic forcing of landscapes of those regions (e.g., *21*) may be applicable here as well. Thus, we believe that we are able to begin to resolve rates of transient erosional responses and use increasingly sophisticated models of fluvial incision to constrain the timing (and perhaps magnitudes) of forcing. Reconstruction of relict channel profiles in the Susquehanna study area suggests that higher rates of incision are a response to ~200 m of relative base level fall. Stream profile models calibrated with erosion rate data suggest base level fall began in the range of 10–20 Ma. Although still somewhat imprecise, this combination of geomorphic and geochronological approaches allows one to establish 1) whether knickpoints are migratory (transient) or anchored to features of the drainage network (steady-state) and 2) to place constraints on the rate of knickpoint migration (and thus the timescales associated with transient incision). It also provides a framework for comparing observations against models to assess whether transient incision is tectonically or climatically driven (*22*). Such a combination of stream profile analyses, erosion rate measurements, and stream profile models may be applied over a larger part of the Appalachians.

These results draw attention to outstanding methodological and theoretical questions. Current methods for inverting rock uplift history from stream profiles make simplifying assumptions about erosion processes (e.g., *23*), but do the inverse solutions adequately state their uncertainties? Also, how best do we account for complex geology, and what is the quantitative relationship between lithology and erosion? How are transient erosion signals transmitted through fluvio-karst terrains? How can we separate and quantify the relative contributions of multiple factors that may each be driving transient erosion in a single basin (e.g., climate, tectonics, and stream capture)?

The results above also bring a number of regional research problems into focus. Volumes of Miocene and younger sediment in the Baltimore Canyon Trough indicate ~1 km of spatially averaged denudation across the northern and central US ENAM margin, generally consistent with estimates of exhumation since 20–30 Ma based on apatite fission-track thermochronology (*11, 24*). However, it is difficult to attribute this sediment to denudation in specific drainage basins. Are stream profile data consistent with the offshore record of sedimentation, and capable of giving us a more detailed picture of landscape evolution? Is the landscape adjusting similarly to external forcing (whether tectonic or climatic) across the ENAM region, or is transient deformation affecting different regions in different ways? Is late Cenozoic transient erosion in the Susquehanna basin unique along the ENAM margin? Do geomorphic variables correlate with imaged mantle structures, once lithologic or lithospheric structures have been factored for? Finally, is the long-term geomorphic record consistent with the record of deformation measured by classic and new geodetic tools (GPS, InSAR), or can the comparison between these two datasets (e.g., *25*) provide insight into how deep structures are evolving?

The upcoming deployment of US Array throughout the ENAM region, as well as the new focus of the GeoPRISMS along the Atlantic passive margin, presents a unique opportunity to begin to address these outstanding questions. Improved, high-resolution images of the velocity and density structure of the ENAM mantle will provide the basis for finer resolution of potential surface deformation. At the same time, a more comprehensive regional analysis of river profiles coupled with focused studies of erosion rates could elucidate spatial patterns in erosion over 10^4–10^5-year time-scales with resolution previously unavailable, and help calibrate landscape evolution models. Similarly advances in the cosmogenic and magnetostratigraphic dating of cave sediments (*26-28*), and of terrace surfaces (e.g., *29, 30*) afford the opportunity to provide quantitative constraints on the timing and rates of fluvial incision. Coupling of these data with the predictions of geodynamic models presents a real opportunity to test the role of dynamic topography in ENAM and discriminate other possible mechanisms driving transient landscape erosion in the Appalachians (*31*).

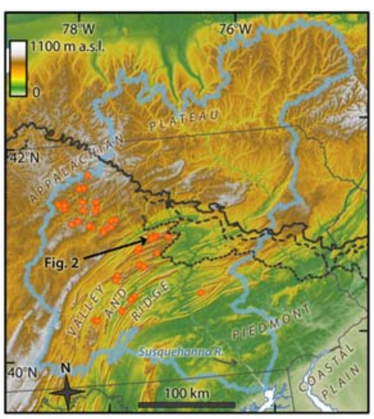

Fig. 1. Topographic map of Susquehanna River drainage basin (blue outline), showing analyzed tributary drainage basins (orange circles), glacial limits (dotted line—Wisconsin; dashed line—Illinoian; solid line—pre-Illinoian), and location of stream in Fig. 2.

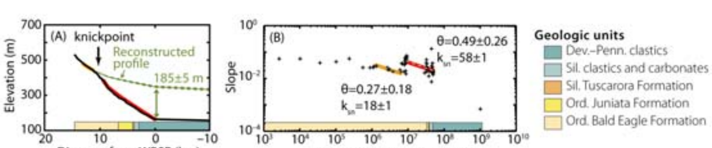

Fig. 2. Example stream profile (A) and slope-area plot (B) showing knickpoint separating two profile segments (orange and red). The stream shown is McElhattan Creek, a tributary of the West Branch Susquehanna River (WBSR) in the Valley and Ridge near Lock Haven, Pennsylvania.

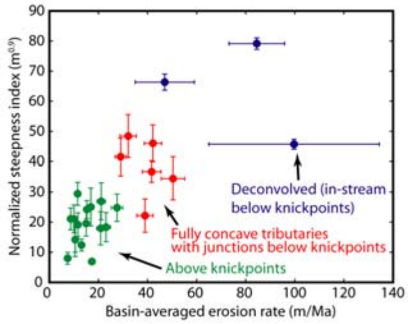

Fig. 3. Scatterplot of normalized steepness index, or channel slope normalized for drainage area, plotted against basin-averaged erosion rate (*32*). Data are from basins above knickpoints (green), basins with fully concave streams that join larger streams below knickpoints (red), and basins in which erosion rates below knickpoints have been deconvolved using erosion rates estimated above knickpoints on the same stream (blue).

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