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Profile convexities in bedrock and alluvial streams

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ABSTRACT

Longitudinal profiles of bedrock streams in central Kentucky, and of coastal plain streams in southeast Texas, were analyzed to determine the extent to which they exhibit smoothly concave profiles and to relate profile convexities to environmental controls. None of the Kentucky streams have smoothly concave profiles. Because all observed knickpoints are associated with vertical joints, if they are migrating it either occurs rapidly between vertical joints, or migrating knickpoints become stalled at structural features. These streams have been adjusting to downcutting of the Kentucky River for at least 1.3 Ma, suggesting that the time required to produce a concave profile is long compared to the typical timescale of environmental change. A graded concave longitudinal profile is not a reasonable prediction or benchmark condition for these streams. The characteristic profile forms of the Kentucky River gorge area are contingent on a particular combination of lithology, structure, hydrologic regime, and geomorphic history, and therefore do not represent any general type of equilibrium state. Few stream profiles in SE Texas conform to the ideal of the smoothly, strongly concave profile. Major convexities are caused by inherited topography, geologic controls, recent and contemporary geomorphic processes, and anthropic effects. Both the legacy of Quaternary environmental change and ongoing changes make it unlikely that consistent boundary conditions will exist for long. Further, the few exceptions within the study area–i.e., strongly and smoothly concave longitudinal profiles–suggest that ample time has occurred for strongly concave profiles to develop and that such profiles do not necessarily represent any mutual adjustments between slope, transport capacity, and sediment supply. The simplest explanation of any tendency toward concavity is related to basic constraints on channel steepness associated with geomechanical stability and minimum slopes necessary to convey flow. This constrained gradient concept (CGC) can explain the general tendency toward concavity in channels of sufficient size, with minimal lithological constraints and with sufficient time for adjustment. Unlike grade- or equilibrium-based theories, the CGC results in interpretations of convex or low-concavity profiles or reaches in terms of local environmental constraints and geomorphic histories rather than as "disequilibrium" features.

1. Introduction

The longitudinal profile of rivers and streams is a fundamental measure in fluvial geomorphology and hydrology, reflecting–and determining–slope and energy gradients and elevation changes. The longitudinal profile is also widely used in geology as a diagnostic indicator of factors such as stages of landscape evolution, tectonic uplift or subsidence, variations in rock resistance, base level changes, and the effects of climate or other environmental changes on landscapes.

The longitudinal (or simply long) profile is a plot of channel elevation over channel distance from the drainage divide or other upstream reference point to the stream mouth. As the "least transient expression of fluvial processes" (Richards, 1982, p. 222), the profile is not only an important morphometric parameter in process studies, but a key topographic signature of a variety of lithologic, tectonic, climatic, and base level effects. Examples go back at least as far as Playfair (1802), and Goldrick and Bishop (2007) presented a review of the uses of longitudinal stream profiles in interpretations of landscape history. A sample of recent work relating long profiles to various external forcings includes Tornqvist (1998) on stratal patterns of basin margin sedimentary sequences and van Heijst and Postma (2001) on sea-level change; Snyder et al. (2000), Duvall et al. (2004), Whipple (2004), and Larue (2008) on tectonic and lithologic controls; Sinha and Parker (1996), Morris and Williams (1997), and Stock et al. (2005) on the relative importance of geomorphic controls along river courses; Bowman et al. (2007) on effects of base level lowering; and Smith et al. (2000) on the steady state equilibrium or grade of a fluvial system.

This paper examines longitudinal profiles of streams in central Kentucky and SE Texas, where earlier work suggested that many stream profiles did not conform to the expectation of a smoothly concave profile. The purpose of this project was to determine the

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extent to which profiles in the two contrasting study areas are smoothly concave and to assess the causes for any deviations therefrom.

2. Theory

2.1. Steady state, grade, and equilibrium

A more-or-less smooth, concave-up longitudinal profile has long been considered a characteristic form in fluvial systems, a normative or attractor state for channel evolution, and an indicator of steady state or grade in fluvially eroded terrain (e.g., Gilbert, 1877; Davis, 1902; Mackin, 1948; Hack, 1957, 1973; Richards, 1982; Leopold, 1994; Sinha and Parker, 1996; Morris and Williams, 1997; Smith et al., 2000; Snyder et al., 2000; Roe et al., 2002; Whipple, 2004; Bowman et al., 2007; Goldrick and Bishop, 2007; Larue, 2008). Concave profiles are indeed widely observed, and the association with grade or steady state (a state where a stream is just able to transport the sediment supplied to it, with no persistent net aggradation or degradation) is based on the notion that, as discharge increases downstream, the slope gradient necessary to transport the available debris decreases. The earlier qualitative expressions of this idea (e.g., Gilbert, 1877; Davis, 1902; Mackin, 1948) are readily linked to stream power theory, where sediment transport is a function of the product of discharge and energy grade slope (e.g., Smith et al., 2000; Snyder et al., 2000; Roe et al., 2002; Duvall et al., 2004; Goldrick and Bishop, 2007).

Despite the persistence of the notion of smooth concave-up long profiles as steady state equilibrium forms, and explanations that appeal to intuition and physical reasoning, the notion is problematic (c.f., Richards, 1982, p. 225; Knighton, 1998, pp. 244–245). Some streams–including some alluvial rivers–are not able to adjust gradients in such a way as to achieve concavity (e.g., Xu, 1991). Another issue is equifinality, in that different causes or processes can produce the same effect of a smoothly concave long profile (Snow and Slingerland, 1987; Ohmori, 1991; Sinha and Parker, 1996; Whipple, 2004), including non-steady state conditions.

A longitudinal profile that significantly deviates from a smooth, concave form, and where such deviations are not systematically related to variations in lithological resistance indicates a profile that is not in grade or steady state equilibrium in the sense of Gilbert (1877), Davis (1902), Hack (1957, 1973), or more recent workers (e.g., Snow and Slingerland, 1987; Sinha and Parker, 1996; Goldrick and Bishop, 2007). However, because non-steady state processes can produce such a profile, the presence of a smooth concave profile, without other supporting evidence, does not necessarily indicate grade or steady state.

A study of the long profile of the Mississippi River by Harmar and Clifford (2007) illustrates the importance of scale, the role of multiple processes and adjustments, and the problematic nature of attempting to apply concave profiles as indicators of grade to specific river systems. The Mississippi River profile is concave at the largest scale, but is characterized by discontinuities, shorter trends, and zonal variations. These in turn are a response to morphology and bed material changes relating to a range of physical (lithologic, tectonic, tributary input) and engineering controls. Despite an apparent correspondence to a graded condition, profile shape is actually a complex, scale-dependent property (Harmar and Clifford, 2007). The Mississippi profile is best considered as a complex product of multiple system dynamics operating over (at least?) three process-form domains at the regional, reach, and sub reach (pool-crossing) scales. Thus, classic reasoning based on "global" relationships between discharge, bed material, and channel slope is not appropriate. "At best, the concave river profile [is] … a property emerging from several scales of process-form interaction, and at worst, it is no more than an artefact arising from the juxtaposition of multiple controls and interactions" (Harmar and Clifford, 2007, p. 239).

2.2. Stream power and erosion laws

Attempts to relate qualitative notions of graded profiles to geomorphic processes have generally been based on stream power theories or "erosion laws" relating sediment transport capacity to discharge and slope (Hack, 1973; Knighton, 1998; Smith et al., 2000; Snyder et al., 2000; Roe et al., 2002; Duvall et al., 2004; Stock et al., 2005).

Stream power at a cross section is given by

$$\Omega = \gamma QS \tag{1}$$

where γ is the specific weight of water, Q is discharge, and S the energy grade slope. The latter is typically approximated by channel slope over large spatial and temporal scales.

Erosion laws are typically of the form

$$E = KQ^m S^n \tag{2}$$

with K a constant and the exponents m, n typically constrained by standard flow resistance and stream power relations. Q is often considered a function of contributing drainage area (A), such that

$$E = K'A^m S^n \tag{3}$$

In a topographic steady state, rock uplift is balanced by erosion, so

$$S = (U/K')^{1/n} A^{-m/n} = kA^{-\theta}, \tag{4}$$

where $\theta = m/n$ is considered a concavity index whereby profile form is directly related to energetics.

A number of variations and elaborations have been produced; see Goldrick and Bishop (2007) for a discussion and novel derivation.

Erosion-law-based models have been widely used to interpret longitudinal profiles, but Stock et al. (2005) suggested that in readily erodible rocks and where coarse sediment undergoes breakdown during transit channel slope is set not by bedrock strength or sediment supply, but primarily by threshold motion of some characteristic grain size. In bedrock or mixed bedrock-alluvial streams, the bedload may serve as a "tool" to enhance erosion via abrasion or as a protective cover. Gasparini et al. (2007) showed that, under various circumstances and dominant erosion processes, models may produce smoothly concave profiles or migrating knickpoints. Further, Whipple (2004) indicated that several models may be consistent with the predictions of the power function erosion law, at or away from steady state.

While the index θ has been widely used as a comparative indicator of concavity, it is not employed in this study for several reasons. First, erosion laws of the form of Eq. (2) are not appropriate for the central Kentucky streams where solutional weathering during low flows is an important component of channel incision (Phillips et al., 2004a). Second, the steady state assumption of Eq. (4) is not applicable in either central Kentucky (Andrews, 2004; Phillips et al., 2004a) or SE Texas (Morton et al., 1996; Blum et al., 2002; Blum and Aslan, 2006). Finally, while a statistical relationship between slope and drainage area of the form of Eq. (4) may provide an index of profile concavity even if the assumptions underlying it are violated, for this work a direct assessment of profile geometry of the type used by Larue (2008), derived from the index of Langbein (1964), is preferred (Section 3.1).

2.3. Convexities

As Goldrick and Bishop (2007) pointed out, a fundamental issue is that profile convexities are most commonly interpreted as "disequilibrium" features that will presumably be degraded as streams approach steady state, but are also sometimes interpreted as "equilibrium" responses to lithological variations (e.g., Hack, 1957,