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Historical contingency in fluviokarst landscape evolution

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ABSTRACT

Lateral and vertical erosion at meander bends in the Kentucky River gorge area has created a series of strath terraces on the interior of incised meander bends. These represent a chronosequence of fluviokarst landscape evolution from the youngest valley side transition zone near the valley bottom to the oldest upland surface. This five-part chronosequence (not including the active river channel and floodplain) was analyzed in terms of the landforms that occur at each stage or surface. These include dolines, uvalas, karst valleys, pocket valleys, unincised channels, incised channels, and cliffs (smaller features such as swallets and shafts also occur). Landform coincidence analysis shows higher coincidence indices (CI) than would be expected based on an idealized chronosequence. CI values indicate genetic relationships (common causality) among some landforms and unexpected persistence of some features on older surfaces. The idealized and two observed chronosequences were also represented as graphs and analyzed using algebraic graph theory. The two field sites yielded graphs more complex and with less historical contingency than the idealized sequence. Indeed, some of the spectral graph measures for the field sites more closely approximate a purely hypothetical no-historical-contingency benchmark graph. The deviations of observations from the idealized expectations, and the high levels of graph complexity both point to potential transitions among landform types as being the dominant phenomenon, rather than canalization along a particular evolutionary pathway. As the base level of both the fluvial and karst landforms is lowered as the meanders expand, both fluvial and karst denudation are rejuvenated, and landform transitions remain active.

1. Introduction

Landscape evolution can be viewed as a sequence of transitions in landscapes and the landforms that comprise them. While specification of stages may be in some cases an artificial discretization of a continuous process, it is not necessarily misleading to perceive or analyze landscape development in these terms for three reasons. First, given the long time scales of geomorphic evolution relative to human observation, some such simplification is an epistemological necessity. Second, empirical evidence of long-term landscape change is in the form of "snapshots" representing more-or-less distinct stages or episodes (e.g., dated surfaces, space-for-time substitutions, stratigraphic evidence). Finally, many geomorphic changes are threshold-dominated phenomena, such that transitions may indeed be relatively abrupt. In karst, for instance, these include events such as conduit breakthrough, cave or doline collapse, or stream/conduit capture.

This paper investigates the role of historical contingency and canalization in evolution of fluviokarst landscapes in central Kentucky, USA. Here, different stages of development are evident on slip-off slopes of developing meanders of the Kentucky River. The suite of fluvial and karst forms at each stage, and the transitions between stages, are analyzed in a network context to identify and quantify the historical contingency involved.

1.1. Historical contingency and path dependency

Historical contingency and path dependence are ubiquitous in geomorphology (as well as pedology, ecology, and hydrology). Contingency may involve inheritance of features from earlier periods of formation or sets of environmental controls (legacy effects; for example underfit streams occupying glacially-carved valleys; Dury 1964), conditionality, and dynamical instability. Conditionality occurs when different geomorphic impacts–and potentially different developmental trajectories–are dependent on the occurrence of a particular event, disturbance, or threshold exceedance. Quaternary development of the Kentucky River, for instance, described in Section 2.1 below, is conditional on a Pleistocene ice-damming event in the ancestral Teays River system about 1.5 Ma. Dynamical instability involves landscape "memory" of variations in initial conditions or effects of disturbances due to disproportionate growth and persistence of those effects. Chemical weathering phenomena, including karst dissolution, are often characterized by instability, whereby minor initial differences in resistance due to lithological variations or small structural features become magnified by positive feedbacks (e.g., Twidale 1991; Kauffman 2009). Where historical contingency is present, evolution is path-dependent in that developmental trajectories

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depend in part on previous states and events, as opposed to convergent evolution toward some state that is historically independent.

Canalization is a form of historical contingency closely related to positive feedbacks and irreversibility. It refers to situations whereby once a particular evolutionary path has been established, other previously possible pathways are eliminated, and evolutionary trajectory is channeled, or canalized. Waddington (1942) coined the term in the context of evolutionary genetics, but it has since been applied more broadly to geophysical and ecological systems (Caloi 1964; Berlow 1997; Levchenko and Starobogatov 1997; Stallins 2006). Several geomorphologists have used the term path dependence to describe canalized landform and landscape evolution (e.g., Naylor and Stephenson 2010; Verleysdonk and Krautblatter 2011; Wainwright et al. 2011; Perron and Fagherrazi 2012). Using an example where the channelization metaphor is literally applicable, whether a channel forms here or a few meters away may be influenced (via dynamical instability) by such tiny variations that it is essentially pseudorandom. Once formed, however, the new channel is a more efficient flow path, and those flows help maintain it and may enlarge it by scour. The formation of the channel was not preordained or deterministically predictable with respect to its precise location, but once established it closes off some previously possible channel locations and strongly influences downgradient channel locations. Irreversibility can also play a role. Once a portion of a hillslope fails, for example, the slumped material cannot return to its original location. The mass movement and the associated rearrangement of slope morphology influences future slope processes, making some pathways and outcomes more, and others less, likely. Karst landform evolution, in particular, is characterized by important self-reinforcing positive feedbacks between dissolution processes, enlargement of conduits, cavities, and depressions, and hydrologic fluxes (Kauffman 2009).

Historical contingency in Earth and environmental sciences has traditionally been dealt with in three general ways. One involves making it the focus of research, with emphasis on working out histories of landform and landscape evolution and environmental reconstruction. In this approach history is paramount and non-contingent controls are seen as constraining and/or explaining historical sequences. A second is essentially opposite, focusing on non-contingent controls (laws, defined broadly) and viewing historical and geographical contingencies as complications or noise, or details of only local importance. A third general strategy is intermediate, starting with explanation based on non-contingent generalizations, but explicitly addressing place and history factors to elucidate aspects not explained by generally applicable laws. Quantification of historical contingency, consistent with these three approaches, has been based on variance explained by temporal patterns, or residual variation not explained by general principles.

In recent years more explicit approaches to historical contingency have emerged. Beven (2015), focusing on hydrology-ecology-geomorphology interactions, developed a modeling strategy based on event persistence. A conceptually similar field-based approach, particularly important in studies of landform-soil-vegetation coevolution, is focused on the key role of disturbances, and on identifying and measuring effects of disturbances over ecosystem and landscape evolution time scales. Some examples from the forest biogeomorphology literature include Samonil et al. (2009, 2013, 2014). A multi-timescale approach to modeling and analysis can also address historical effects; examples include Sommer et al. (2008) on soil landscape evolution and Vercruysse et al. (2017) on fluvial suspended sediment transport. There has also been a recent explicit emphasis on the role of initial conditions in soil, landform, and ecosystem evolution (Raab et al. 2012; Biber et al. 2013; Maurer and Gerke 2016).

My own contributions have focused on graph theory techniques applied to Earth surface systems represented as networks of interacting components. The graph property of inferential synchronization indicates the extent to which a (geomorphic) system experiences changes contemporaneously or in predictable succession (high synchronization). Synchronization in the literal sense is not directly applicable to graphs representing historical or evolutionary sequences. However, inferential synchronization is analogous, indicating the extent to which observations or inferences at one point in the network can be applied to components elsewhere in the graph (Phillips 2013). Low synchronization indicates a high degree of historical contingency (and vice versa). Phillips (2012) introduced the graph-based synchronization concept to geomorphology, and Phillips (2013) applied it explicitly (along with other graph-based measures) as a tool for quantifying historical contingency in geomorphic systems.

The related issue of robustness in soil, vegetation, and landform chronosequences was addressed by Phillips (2015a), who adapted stability analysis techniques to measure path stability. Path stability indicates the extent to which developmental trajectories in historical sequences are likely to be repeated if the system is disturbed or the sequence set back to earlier stages. Path instability is associated with high levels of historical contingency. Phillips (2016) depicted evolutionary patterns and sequences as state-and-transition models represented as directed graphs. Several measures of complexity and synchronization were applied to both archetypes of evolutionary sequences, and empirical examples, including soil landscape evolution and river channel morphological changes. This paper applies the methods of Phillips (2013) to a chronosequence represented by the types of landforms present at each stage.

1.2. Fluviokarst landscape evolution

Fluviokarst landscapes are characterized by an interconnected combination of surface and underground hydrological processes and flux paths, and both karst and fluvial landforms. Some landforms may be transitional or hybrid forms. All components of the fluviokarst system are linked to the same base level and regional drainage controls, and thereby coevolve. Both karst-to-fluvial and fluvial-to-karst transitions occur at the scale of individual landforms in the central Kentucky study area (Thrailkill et al. 1991; Phillips et al. 2004; Ray and Blair 2005; Phillips 2017) and in fluviokarst systems in general (e.g., Jaillet et al. 2004; Ortega Becerril et al. 2010; Tiria and Vijulie, 2013; Lipar and Ferk 2015; Woodside and Peterson, 2015).

Early researchers proposed a progression from an initially fluvial landscape to fluviokarst and finally to holokarst (e.g., Cvijic 1918; Roglic 1964). However, it was soon recognized that this progression is not inevitable, and is potentially reversible (e.g., Sawicki 1909; Ford 2007; White 2009), though Bocic et al. (2015) found that landscape evolution of the Una-Korana plateau in the Dinaric karst did approximate the fluvial-to-karst sequence. But in the Monte Berici karst, Italy, for instance, Sauro's (2002) analysis showed that fluvial development is the main morphogenetic process, driven by climate change and tectonic uplift. Later, karst formed on relatively inactive or relict fluvial features. By contrast, in Spain Ortega Becerril et al. (2010) found a switch from domination by dissolutional erosion and karst forms to a prevalence of mechanical erosion and fluvial forms. In yet another variation, some fluviokarst landscapes exhibit divergent evolution into channel-rich, karst-poor and karst-rich, channel-poor zones (e.g., central Kentucky, USA; Phillips et al. 2004; Phillips and Walls 2004). Other areas exhibit sharp contrasts between nearby karst- and fluvially-dominated landscapes, or between karst areas with or without fluvial impacts (e.g., Benac et al. 2013; Bahtijarevic and Faivre 2016).

The interplay of fluvial and karst processes is often conceived, accurately enough, as a “competition” for the excess precipitation that drives both sets of processes. However, at the landscape scale this competition enhances both sets of processes in the central Kentucky study sites studied by Phillips (2017). Evolution of this fluviokarst is best understood as mutual reinforcement, whereby karstification is enhanced by stream incision, and fluvial dissection is often intensified by presence of karst features. This questions the extent to which canalization and historically contingent lock-in are present.