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Geometric disequilibrium of river basins produces long-lived transient landscapes

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ABSTRACT

Although equilibrium has long been considered the attractor state for landscapes, the time required to reach equilibrium or even the possibility of reaching equilibrium is still debated. Using ^{10}Be-based catchment-averaged denudation rates, topographic analysis, and analysis of the basin topology and geometry, including its area-channel length scaling relationship, we show that an ancient postorogenic dome on the North American Craton, the Ozark dome, is not in a state of equilibrium. The persistent state of disequilibrium on the Ozark dome is characterized by nonuniform erosion rates that vary by a factor of three, asymmetric drainage divides, and evidence for drainage rearrangement via stream capture. We find that planform geometric disequilibrium of river basins and drainage area exchange between adjoining basins can hold river networks in a disequilibrium state for potentially hundreds of million years and that, when sustained over time, erosion rate differences associated with drainage area exchange can lead to transient events such as stream capture and production of relief in the form of elevated, low-relief surfaces. Our results suggest that landscapes with slowly moving drainage divides might not reach equilibrium, and that river basin dynamics may contribute to setting the large-scale morphology of old cratonic landscapes.

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1. Introduction

Owing largely to the manner in which erosion rates increase with increasing topographic gradient and relief (Ahnert, 1970; DiBiase et al., 2010), landscapes naturally evolve towards steady equilibrium forms in which rock uplift is balanced by erosion. The concept of steady state or equilibrium landscapes as time invariant forms has been central to the development, parameterization, and testing of geomorphic transport laws (Dietrich et al., 2003; Kirkby, 1971) and to interpretations of transient landscapes based on deviations from equilibrium forms (Kirby and Whipple, 2012; Tucker and Whipple, 2002; Whipple and Tucker, 1999). The possibility of reaching equilibrium depends on the response time of a landscape to changes in boundary conditions (Howard, 1982; Whipple, 2001). The time required to reach steady state after a tectonic or climatic perturbation is commonly equated to the timescale for individual basins to adjust river steepness such that rates of erosion and rock uplift are equal, which for many landscapes is thought to be on the order of millions of years (Pazzaglia, 2003; Whipple, 2001; Whipple and Tucker, 1999).

Field observations (Prince et al., 2011), analog experiments (Hasbargen and Paola, 2000; Reinhardt and Ellis, 2015), numerical modeling (Goren et al., 2014), and theory (Willett et al., 2014) demonstrates that planform basin shape and network topology can continue to adjust via divide migration and stream capture long after any perturbation to boundary conditions, which suggests that adjustments to basin geometry (Willett et al., 2014) may prolong landscape response times. If landscape response times are substantially prolonged by changing basin geometry, then transient landscapes may be more common and long-lived than previously thought, relief may be produced in the form of elevated, low-relief surfaces as nonuniform erosion rates persist, and the assumption that steady state conditions are achievable in all landscapes might be invalid. To test the hypothesis that river basin dynamics can protract time to steady state, we map and interpret disequilibrium in river basins draining the Paleozoic-aged Ozark dome. We show that aspects of the morphology of the Ozark dome reflect persistent river basin dynamics and that, although many fluvial lon-

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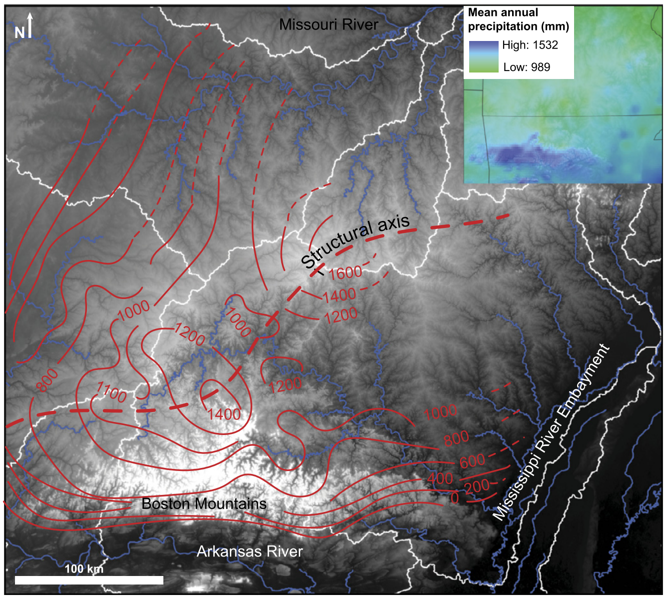

Fig. 1. Map of the Ozark dome. Hillshade of 90 m digital elevation model produced from the Shuttle Radar Topography Mission; white lines show major drainage divides, blue lines show major rivers, and red contours show structure contours mapping the base of the Mississippian limestone adapted from Siebenthal (1915). Inset shows mean annual precipitation (MAP) on the Ozark dome. Colors represent MAP based on 30-year normal data for 1981–2010 downloaded from PRISM Climate Group (http://prism.oregonstate.edu/normals/). (For a color version of this figure, the reader is referred to the web version of this article.)

gitudinal profiles on the Ozark dome have shapes approximating equilibrium forms, the fluvial network as a whole will likely never achieve steady state conditions owing to the disparity in timescales between geometric adjustment in landscapes with slowly moving drainage divides and comparatively rapid fluvial response times.

2. Testing for equilibrium and drainage divide motion in a tectonically-stable cratonic landscape

The Ozark dome is well-suited to studying the effects of river basin dynamics on landscape evolution owing to long-term tectonic stability in a continental interior (Arne et al., 1990; Hudson, 2000), large areas of uniform, gently-dipping sedimentary strata, relatively uniform mean annual precipitation (Fig. 1 and Fig. A.1), and a river network composed primarily of bedrock-floored rivers and mixed alluvial-bedrock beds (Adamski et al., 1995; Keen-Zebert et al., 2017). The region was uplifted in the fore-bulge of the Ouachita Orogen in the late Paleozoic (Hudson, 2000). Offsets on faults in the Ste. Genevieve fault zone indicate that the Ozark dome tilted as a block to the southwest as the Illinois basin subsided (Nelson and Lumm, 1984). Subsidence of the Illinois basin occurred in pulses during the Ouachita Orogeny, with the last subsidence event dated to the Middle Mississippian (Heidlauf et al., 1986). The most recent geologic events recorded in the rock record were the formation of the Mississippi Embayment and the development of the Mississippi drainage system on the eastern side of the Ozark dome in the late Cretaceous (Cox and Van Arsdale, 2002). Although there has been historical seismicity around the dome in the New Madrid seismic zone (Arsdale and Cupples, 2013) and in the Ste. Genevieve fault zone (Yang et al., 2014; Fig. A.2), it is thought that with tectonic loading rates near zero, seismicity in stable continental interiors represents a short-lived release of energy from a prestressed lithosphere (Calais et al., 2016), and hence is unlikely to produce long-lived rock uplift.

Apatite fission track cooling ages from Precambrian granites on the northwest portion of the dome indicate exhumation rates of ∼10 m/Ma over the last ∼200 Ma (Arne et al., 1990). The modern river network draining the Ozark dome runs primarily perpendicular to the structure contours at the base of Mississippian limestone (Fig. 1), suggesting that the primary structure of the river network formed in response to the Paleozoic deformation field. The Ozark dome and surrounding region remained above sea level during the Mesozoic (Stoeser et al., 2005). The region is also south of the southernmost extent of the Laurentide ice sheet and south of significant glacial isostatic adjustment (Hammond, 2015). Although eustatic sea-level fluctuations and changes in sediment flux occurred during the Quaternary, the frequency of glacial–interglacial cycles is likely too high to affect fluvial profile evolution (Goren, 2016). Given the tectonic and climatic stability of the region, theory predicts that the Ozark dome should have reached a modified erosional steady state in which relief and erosion rate are steady and uniform (Montgomery, 2001).

3. Methods

3.1. Catchment-averaged erosion rates from cosmogenic nuclides

To test whether erosion rates are uniform across the Ozark dome as would be expected in an equilibrium landscape, we measured basin-averaged denudation rates using ^{10}Be in 0.25–0.5 mm quartz grains from recent fluvial deposits in 16 basins that comprised 8 pairs in which each pair share a common divide (Fig. 2a). Samples were collected in streams at drainage areas of $\sim$10 km^2 with paired basins that travel through similar lithologies to minimize effects from heterogeneous lithology. We converted the concentration of ^{10}Be to basin-averaged denudation rates using the CAIRN model (Mudd et al., 2016), which calculates production rates and shielding at each gridcell to account for intra-basin variations in elevation, latitude, slope, aspect, and quartz content. Assuming a uniform denudation rate, the CAIRN model then uses Newton iteration to calculate the denudation rate that results in the closest match to the observed basin-averaged cosmogenic nuclide concentration (Mudd et al., 2016). Production rates are based on the time-independent air pressure scaling schemes of Lal and Stone (Lal, 1991; Stone, 2000) and conversion of elevation and latitude to air pressure (Balco et al., 2008). Denudation rates were converted to erosion rates by assuming a uniform density of 2650 kg/m^3. We used a 90 m resolution DEM for these calculations and eliminated gridcells with non-quartz-bearing lithologies. We considered limestone to be the only non-quartz-bearing lithology; although the limestone in this region is chert-bearing, we did not analyze any chert. We considered the Ordovician dolostone of the Ozark dome (Fig. A.1) to be quartz-bearing because sandstone underlies the dolostone in these formations (Stoeser et al., 2005). Samples were prepared and analyzed at PRIME National Laboratory with standard procedures and 07KNSTD was used as the ^{10}Be standard. See Table A.1 for detailed results and basin-averaged data for each sample. Error bars in Fig. 2c reflect total uncertainty whereas error bars in Fig. 2b reflect only internal uncertainty because each pair of basins were close enough in proximity to assume minimal variation in production rate.

3.2. χ maps and χ profiles

Bedrock erosion scales with either unit stream power (Howard, 1994; Siedl and Dietrich, 1992) or shear stress (Howard and Kerby, 1983), with both relationships resulting in the following model for detachment-limited river incision into bedrock in which the elevation of a point along a stream, z, varies with time, t, and distance along the stream, x, according to:

$$\frac{\partial z(x,t)}{\partial t} = U(x,t) - K(x,t)A^m \left| \frac{\partial z(x,t)}{\partial x} \right|^n \quad (1)$$

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