Controls on eroded rock volume, a proxy for river incision, in Africa

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ABSTRACT
A database of 3023 river basins in Africa was assembled to investigate the relative effects of uplift and erosion on landscape development. The volume of rock eroded from each basin was calculated by integrating the difference between a topographic summit envelope fit across drainage divides and interfluves, and present-day topography over basin area. Africa is an excellent natural laboratory for this procedure because drainage patterns reflect the Neogene development of topographic basins and swells, themselves surficial manifestations of sub-lithospheric mantle convection. As a result, the loci of major offshore deltas and drainage divides have remained largely static, while epeirogenic (vertical) surface motions are more important than shortening. Eroded rock volume is presented as a proxy for fluvial incision and correlates strongly with long-wavelength gravity anomalies across Africa, but not with mean precipitation, which was calculated by merging satellite estimates with rain gauge data. This finding implies that spatial variations in epeirogenic uplift govern landscape evolution across the continent. Other variables that alter drainage basin geometry and the magnitude of eroded rock volumes, such as varying climate, bedrock erodibility, and drainage capture, are likely subordinate to these variations. First-order estimates of eroded rock volume onshore are potentially the most accurate indicator of offshore sedimentation because they implicitly include information pertaining to basin area and relief, which together control sediment load.

INTRODUCTION
In the absence of significant lateral displacement, landscape development is a convolution of the processes of uplift and denudation, the varied links and mutual feedback loops between which have long been recognized (e.g., England and Molnar, 1990; Willett et al., 1993; Montgomery, 1994). In detachment-limited systems, river incision, a function of rock uplift rate, is generally accepted to set the pace of long-term erosion rates. The volume of eroded rock within a given valley or river basin is a useful first-order approximation of denudation: several studies have computed volumes of material removed between present-day topography and digitally reconstructed paleo-surfaces or planation surfaces (e.g., Pederson et al., 2002; Gani, 2015; Chardon et al., 2016; Grimaud et al., 2018). For non-orogenic domains, especially in Africa, other approaches compute the volume of sediments onshore (Beauvais and Chardon, 2013) delivered offshore over a given time interval (Grimaud et al., 2018).

However, relatively few studies consider the physical processes that govern the volume of rock removed (cf. Chardon et al., 2016). Africa is an excellent natural laboratory for the assembly of a large database of river catchments for such a purpose. A disproportionate area of the continent is drained by a small number of large rivers: six rivers drain 40% of the total land area (Fig. 1A). Drainage patterns are closely controlled by the distribution of topographic basins and swells: the majority of swells (e.g., Angola) have radial drainage, whereas basins and depressions (e.g., the Congo Basin) are characterized by long-wavelength meanders. The quality of this correlation suggests that the present-day drainage planform developed during growth of the striking “basin-and-swell” physiography, likely developed and maintained by convective circulation within the sub-lithospheric mantle during Neogene times (Burke, 1996; Al-Hajri et al., 2010; Paul et al., 2014). This pattern is clearly reflected by that of long-wavelength free-air gravity anomalies, a crude proxy for upper mantle convection; indeed, in Africa, gravity anomaly and topography are unusually strongly correlated at wavelengths >500 km (admittance Z [the wavenumber parameter that modifies topography to produce gravity] = ~35 mGal km⁻¹; McKenzie and Fairhead, 1997). Moreover, in southern and western Africa where three amagmatic swells straddle the continent-ocean boundary, the variation in Quaternary surface uplift rates, calculated from emergent marine terrace deposits, mirrors that of gravity anomaly (Fig. 1B).

The relative spatial disposition of principal river catchments has likely remained relatively fixed over Neogene times. The loci of the largest deltas have remained fixed throughout post-Paleocene times, during which time landscape development has been driven by long-wavelength, discrete pulses of uplift and subsidence (i.e., epeirogeny; Burke, 1996; Al-Hajri et al., 2010). Moreover, reconstructions of dated paleolandscapes have suggested that drainage for most of western Africa probably stabilized by end-Eocene times (Chardon et al., 2016). The corollary is that major drainage divides are relatively static singularities where the speed of propagating knickzones approaches zero and the morphodynamic Péclet number becomes very small (Paul et al., 2014).

However, the role of tectonics versus climate in river incision is still highly controversial (e.g., England and Molnar, 1990; Whittaker, 2012). For Africa, while long-wavelength gravity anomalies have been used as proxies for dynamic topography (e.g., Wilson et al., 2010; Paul et al., 2014), the choice of a data set to represent climatic drivers is less clear, especially owing to the difficulty of reconstructing precipitation records through Cenozoic times. However, Feakins and DeMenocal (2008) exploited organic-rich sapropel deposits and terrigenous dust in marine sediments to imply that precessional driven changes in insolation have provided a fundamental pacing of humid-arid cycles from end-Eocene times to the present. Indeed, since ca. 80 Ma, atmospheric circulation above Africa has probably been largely static (Parrish and Curtis, 1982).

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Although the effect of such continent-scale climate change has been shown to affect patterns of incision and offshore sediment flux histories, the morphometric controls of basin area, relief, and elevation must also be considered (Hovius, 1998; Milliman and Farnsworth, 2011). In a global study of 760 rivers, Milliman and Farnsworth (2011) suggested that erosion, transport, and discharge of particulate and dissolved solids mostly reflect the cumulative effects of drainage basin size and morphology (cf. Grimaud et al., 2018). These findings suggest that if catchment geometry can be constrained, the volume of eroded material could be attributed to spatial variations in epeirogenic motion.
This study deconvolves the relative effects of uplift (the “tectonism” of Hovius, 1998) and climate (using precipitation as a proxy) in incision and valley formation by analyzing (1) an extensive database of river catchments in Africa that is representative of a wide range of different morphologies (e.g., relief, area, elevation), (2) mean gravity anomaly, and (3) precipitation rates. Total eroded rock volume is employed as an integration and enhancement of Montgomery’s (2002) two-dimensional metrics of net differences in the mass of rock excavated from below ridgelines (i.e., valley width, relief, and cross-sectional area).

METHODS

I constructed a digital elevation model (DEM) using the one-arcsecond (~30 m × 30 m) Shuttle Radar Topography Mission (SRTM) data set. Drainage (3023 river basins; Table S1 in the Supplemental Material; Fig. 1A) was extracted using standard flow-routing algorithms from the ArcGIS software package (Tarboton, 1997; Wu et al., 2019). The fidelity of these calculated drainage networks and basins was then checked using a geological map (Fig. 1C) and Landsat satellite imagery. Internal drainage (e.g., endorheic basins such as the Okavango Delta of southern Africa) or basins masked by sand seas in arid areas (e.g., northwestern Sahara Desert) were excised from further analysis. Although the total area of these regions is as great as ~1.1 × 10^6 km^2 (or ~35% of Africa’s surface), similar tectonic forcing processes likely also dominate (e.g., Paul et al., 2014).

I then generated a topographic summit envelope by applying cubic spline interpolation across the remaining basin drainage divides and interfluves that were carefully picked between all extracted rivers. The volume of removed material in each basin and sub-basin was then calculated by integrating the difference between this envelope and present-day topography over total basin area (Fig. S1 in the Supplemental Material). Figure 2 presents one example of this procedure for the 170,000 km^2 Ruvuma River catchment in eastern Africa, revealing dramatic patches of incision both in the headwaters (the eastern flank of the East African Rift System) and closer to its mouth where the river carves a 100-m-deep, 4-km-wide gorge through the high sandstone Makonde Plateau (Tanzania). Similar assessments of onshore eroded volume have also been carried out by other workers: Montgomery (2002, p. 1048) assessed the “integrated long-term signature of erosional processes” from between valley walls in Washington State, USA; Chardon et al. (2016) generated their upper-bound topographic envelopes for western Africa using carefully calibrated paleolandscape remnants.

I generated a grid of free-air gravity anomalies from the NASA Gravity Recovery and Climate Experiment (GRACE) data set (Tapley et al., 2005). These were passed through a cosine taper low-pass filter between 800 and 2000 km; these long wavelengths can be regarded as a proxy for sub-plate density anomalies (i.e., upper mantle convection; Fig. 1B; Crosby et al., 2006). To analyze precipitation, satellite estimations, such as the various products of the NASA Global Precipitation Measurement Mission (GPM; Hou et al., 2014), are useful in complementing sparse rain gauge networks. However, these products employ smoothing algorithms that can result in major underestimation of extremes (Manz et al., 2016). Here, I generated a new map of satellite–rain gauge climatologies (i.e., 5-yr-averaged annual precipitation) by merging the two data sets, using inverse distance weighted interpolation (Manz et al., 2016; Fig. 1D; Table S2). The GPM_2ADPR product (raw orbital data, https://disc.gsfc.nasa.gov/datasets/GPM_2ADPR_06/summary) is used after attenuation corrections and re-gridding to obtain rainfall rate estimations. Gauge time series from the 433 World Meteorological Organization–maintained gauges in Africa (Nitu and Wong, 2010) were extracted and reformatted into 15 min bins before the merging procedure.

RESULTS

The instantaneous volume of removed rock, V, mean free-air gravity anomaly, and mean annual precipitation were calculated and are presented as a function of downstream distance for the principal tributaries of seven major African catchments in Figure 3. Each metric was calculated across 50-km-long strips orthogonal to average river azimuth. V was then normalized to basin area (A) (per Montgomery, 2002) for all 3023 basins and sub-basins (Fig. 4). Figure 4A shows that a high proportion (68%) of the African continent is drained by the 12 largest basins; morphometric data for these basins are given in Table S1. Figures 4B–4D present V/A as a function of elevation, long-wavelength free-air gravity anomaly, and annual precipitation, averaged across each basin. The most statistically significant relationship is between V/A and gravity: R^2 = 0.92; two-tailed p value = 0.001.

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1Supplemental Material. Morphometric information, including total area and eroded rock volume, of river basins in Africa. Please visit https://doi.org/10.1130/GEOLO.S.13232384 to access the supplemental material, and contact editing@geosociety.org with any questions.
DISCUSSION AND CONCLUSIONS

Figure 3 shows the strong relationship between long-wavelength gravity anomaly and eroded rock volume (i.e., the “volume” of a valley over discrete length intervals). This relationship is especially striking for the principal tributaries of the Congo River (depressed volumes of rock eroded in the central portion of the Congo River as it traverses the Congo Basin), the Niger River (western Africa), and the Orange River (southern Africa) (mean gravity anomaly and eroded rock volume both an order of magnitude greater than all other larger basins; Quaternary coastal uplift rates of >0.25 mm yr⁻¹). When all >3000 catchments and sub-catchments across Africa are gathered together, the positive correlation is very strong (Fig. 4C).

Equally striking is the contribution of several smaller catchments such as the Ruvuma (eastern Africa) and Cuanza (Angola) Rivers that straddle gravity anomaly highs of >20 mGal and, where these intersect the coastline, have calculated Holocene uplift rates of >0.2 mm yr⁻¹. For instance, the total eroded volume of the Cuanza catchment (6.9 × 10⁵ km³) is comparable to that of vastly larger catchments such as the Nile (8.2 × 10⁵ km³) and Niger Rivers (7.4 × 10⁵ km³).

While mean catchment elevation (Fig. 4B) has a less-significant relationship with eroded volume, typical valley relief (i.e., incision) in the Cuanza catchment is greater than in the Nile and Niger catchments, consisting almost exclusively of a complex system of interlocking gorges and slot canyons (Fig. 1A; longitudinal profiles given by Paul et al. [2014]).

In many locations, the nature of the bedrock exerts an important control on the degree to which rock is removed: deeply incised valleys are more commonly found over basement and volcanic rocks rather than alluvium (e.g., deep incision at the Batoka Gorges as the Zambezi River passes over Karoo [Jurassic] basalt lava flows ~2000 km from its source). However, additional data are needed to analyze the role of bedrock lithology on a catchment-by-catchment basis. For instance, the erodibility of a river channel can be inferred from the compressive strength of the substrate; laboratory experiments have shown that tensile strength, σ_t, is a proxy for rock erodibility (Sklar and Dietrich, 2001).

Structural anisotropy may also exert an important influence on drainage patterns; however, the time and length scales over which lithology influences incision are poorly understood. For long wavelengths (>2 km) such as those considered here, channel gradient and valley width exhibit little correlation with Δσ_t (Roberts and White, 2010).

Figure 4D demonstrates a lack of a clear relationship between catchment-averaged annual precipitation, calculated from the new satellite-gauge merged product, and volume of removed material. Indeed, of the 12 largest catchments, the driest exhibit a wide range of removed material, from the Orange (4 × 10⁵ km³; 74 mm annual precipitation) to the Niger (7 × 10⁵ km³; 201 mm). Discharge, sediment load, and sediment yield (Table S1) cannot be correlated directly with incision or rates of valley formation because of long-term sediment storage in fluvial systems (Montgomery, 1994).
However, this analysis does not consider the variation of uplift, exhumation, and incision rates over time, for which dated erosional marker beds or volcanic rocks are a prerequisite (e.g., Gani, 2015). Variations in valley shape or the volume of eroded rock cannot directly address governing rates of river incision, and it is difficult to disentangle feedback loops, e.g., the potential for isostatic rebound in response to pulses of river incision. Montgomery (2002) suggested that in the western United States, the highest mountain peaks may reflect Pleistocene glacial valley widening; similarly, the most deeply incised African catchments feature very high peaks above the calculated summit envelope (red areas on Fig. 2B).

A consideration of sediment supply to major deltas is an indirect, yet important, means of determining the governing controls on onshore rock removal and delivery of sediment offshore. Many features of African deltaic sedimentation are better explained by variations in surface uplift rather than changes in climate (Walford, 2003). For instance, the total volume of sediment in the offshore Orange Delta, whose relatively small catchment has experienced high rates of surface uplift since at least 30 Ma (e.g., Burke, 1996; Partridge, 1998), is more than triple that of the offshore Congo Basin: respectively 19 × 10⁶ km³ versus 6 × 10⁶ km³ (Walford, 2003). Rouby et al. (2009) used thermochronologic data and solid sediment isopach mapping to testify to the fideity of this offshore-onshore sediment relationship since Cretaceous times.

In summary, eroded rock volume integrates Montgomery’s (2002) measures of valley relief and cross-sectional area to provide a proxy for river incision, which correlates strongly with long-wavelength gravity anomalies (but not precipitation) across Africa, suggesting that spatial variations in epeirogenic uplift govern landscape evolution across the continent. Milliman and Farnsworth (2011) originally postulated onshore eroded rock volume as potentially the most accurate indicator of offshore sedimentation because it implicitly includes information pertaining to basin area and relief and/or elevation, which together govern sediment load. Indeed, the eroded onshore volume neatly encompasses “tectonism”, a generic term suggested to explain sediment budgets worldwide (Hovius, 1998; Milliman and Farnsworth, 2011).

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Figure 4. Relationship between normalized eroded rock volume (eroded volume, V, divided by basin area, A) and basin area (A), mean basin elevation (R² = 0.76) (B), mean gravity anomaly (R² = 0.92) (C), and mean annual basin precipitation (R² = –0.39) (D). The 12 largest basins (see Fig. 1A) are shown with open circles: Co—Congo; Cu—Cuanza; L—Limpopo; Ng—Niger; Ni—Niile; Og—Ogouee; Or—Orange; R—Ruvuma; S—Senegal; Sh—Shebelle; V—Volta; Z—Zambezi.
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