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Taking the measure of a landscape: Comparing a simulated and natural landscape in the Virginia Coastal Plain

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ABSTRACT

A landform evolution model is used to investigate the historical evolution of a fluvial landscape along the Potomac River in Virginia, USA. The landscape has developed on three terraces whose ages span 3.5 Ma. The simulation model specifies the temporal evolution of base level control by the river as having a high-frequency component of the response of the Potomac River to sea level fluctuations superimposed on a long-term epeirogenic uplift. The wave-cut benches are assumed to form instantaneously during sea level highstands. The region is underlain by relatively soft coastal plain sediments with high intrinsic erodibility. The survival of portions of these terrace surfaces, up to 3.5 Ma, is attributable to a protective cover of vegetation. The vegetation influence is parameterized as a critical shear stress to fluvial erosion whose magnitude decreases with increasing contributing area.

The simulation model replicates the general pattern of dissection of the natural landscape, with decreasing degrees of dissection of the younger terrace surfaces. Channel incision and relief increase in headwater areas are most pronounced during the relatively brief periods of river lowstands. Imposition of the wave-cut terraces onto the simulated landscape triggers a strong incisional response.

By qualitative and quantitative measures the model replicates, in a general way, the landform evolution and present morphology of the target region.

1. Introduction

Over the last 20 years geomorphologists have created landform evolution models (LEMs) which include quantitative treatment of weathering, fluvial and mass wasting processes (e.g. Willgoose et al. (1991); Howard (1994); Tucker and Bras (1998); Coulthard (2001); Tucker et al. (2001a); Hancock et al. (2002)). Most LEMs have been used primarily to explore general characteristics of the spatio-temporal evolution of landscapes without reference to specific locations. A few studies have parameterized LEMs to simulate the historical evolution of specific landscapes (Howard, 1997; Hancock et al., 2002; Barnhart et al., 2009). A number of issues have limited the application of LEMs to model specific landscapes, including 1) lack of sufficient information to characterize geomorphic processes, initial conditions, and environmental controls through time; and 2) limits of computational resources, particularly solution time constraints. The computational limitations primarily revolve about the necessity to route water and sediment. These limitations will recede as faster computers and more powerful algorithms are developed. One method to reduce computational demands is to limit LEMs to treat only the fluvial network with slope processes treated solely as sources or highly parameterized. Fluvial-network models have been widely utilized to explore the effects of base level change and tectonic deformation on rates and patterns of erosion (e.g., van der Beek and Braun, 1998; Whipple and Tucker, 1999, 2002; Tucker and Whipple, 2002; Snyder et al., 2003; Tucker, 2004; Braun, 2006; Berlin and Anderson, 2007; Crosby et al., 2007).

Relatively little attention has focused on modeling evolution of low-relief, vegetated landscapes. Among the reasons for this deficit are the difficulty of quantifying rates of process and historical evolution as a result of vegetation cover. Vegetation obscures deposits containing the historical record of landform evolution, and the rates of geomorphic processes are generally slow and difficult to quantify where the vegetation cover is high. For example, although the presence of vegetation inhibits runoff and rainsplash erosion and a vast literature exists on the influences of vegetation on erosion in agricultural settings, only a few studies have tried to incorporate the influence of vegetation in controlling the pace of erosion in LEMs (e.g., Howard, 1999; Collins et al., 2004; Istanbulluoglu and Bras, 2005).

The effect of base-level variations on landform evolution is another topic that has received scant attention. Models have been used to explore simple scenarios of base level controls, including changes in rates of relative land-sea uplift, rapid base-level fall, and oscillatory variations, primarily focusing on response of the fluvial network (Howard, 1982; Howard et al., 1994; Garcia-Castellanos et al., 1997; Anderson et al.,

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1999; Whipple and Tucker, 1999; Whipple, 2001; Garcia-Castellanos, 2002; Snyder et al., 2002; Tucker and Whipple, 2002; Tucker, 2004; Gasparini et al., 2006). Fagherazzi et al. (2004, 2008) explored the influence of sea level variations on fluvial incision and deposition on continental shelves. Incorporation and testing of variable base level control in specific landscapes, however, has received little study.

A landscape along the Potomac River in Virginia (Figs. 1 and 2) offers the opportunity to investigate at one location three important controls on landscape evolution 1) long-term erosion of three contiguous, dissected surfaces with differing ages of formation; 2) the role of vegetation in controlling the pace of landform evolution; and 3) a complex history of base level control. The following sections detail the geologic history of the site, implementation of the LEM procedures to model vegetation–erosion interactions, base-level control and erosional history, and development of quantitative measures of landform morphology used to statistically compare the simulated and natural landscape.

2. Study area geologic setting

The study focuses on the Rollins Fork and Colonial Beach South USGS 7.5-minute topographic quadrangles which border the Potomac River to the northeast and the Rappahannock River to the southwest (Fig. 2). The Colonial Beach South quadrangle geologic map (Newell et al., 2006) identifies three major geomorphic surfaces. During the Pliocene, relative sea level was about 53 m higher than today and a fluvial bench was deposited as a cap over a mixed fluvial–estuarine sedimentary sequence of the proto-Rappahannock River and formed a low-relief surface over the study area. The capping unit is the Bacons Castle Formation, which is composed of medium to coarse gravelly sand and sandy gravel with thick to very thick bedding. The local thickness is approximately 10–15 m. Deep, saprolite-like weathering has subsequently occurred on this surface. Beneath this is an unnamed fluvial unit of sand and gravel mapped as a single unit with the Bacons Castle. This upland surface is strongly dissected except in the southwestern corner of the quadrangle which features broad, nearly flat divides, suggesting that the divides are slightly eroded remnants of the original depositional surface of the fluvial mantle.

An extensive surface at altitudes of 21–24 m lies northeast of the Bacons Castle-capped surface closer to the Potomac River. This is capped by the Charles City Formation of gravelly sand grading upwards to moderately well sorted, medium to fine sand, silt and clay. This unit, up to 10 m thick, is interpreted as a relict bay of the Potomac River estuary partly sculpted as a wave-cut bench at a relatively high seastand. A low sand and gravel ridge at the outer edge of this bench is interpreted to have been a spit that prograded across the mouth of the bay. The age of this unit is lower to early-middle Pleistocene, probably formed sometime between 0.6 and 1.0 Ma ago. This surface is moderately dissected with broad, nearly flat interfluves and development of a well-defined regolith.

The lowest extensive surface borders the Potomac River at elevations of about 6–8 m and is capped by the Sedgefield Member of the Tabb Formation, a coarse sand grading upward to sandy and clayey silt. The unit is generally only 1–5 m thick, and like the Charles City terrace, is interpreted to be a late Pleistocene wave-cut bay of the Potomac River, probably forming at the stage 5E sea level highstand 0.12 Ma BP.

Beneath the terrace capping units are units of the Middle to Lower Chesapeake Group, in sequence downward the Pliocene Yorktown Formation and the Miocene Eastover and Calvert Formations. The

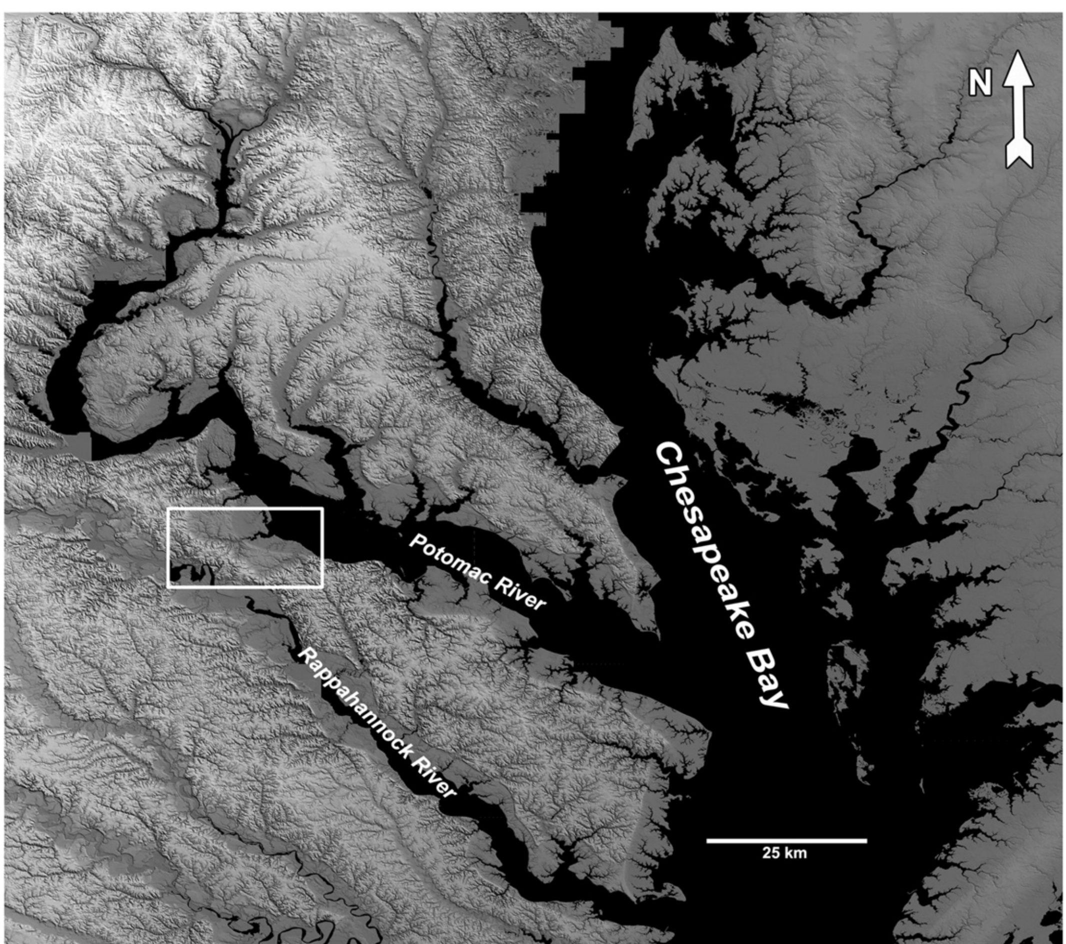

Fig. 1. The middle Chesapeake Bay, USA region, showing the study location (white box).