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An automated method for producing synoptic regional maps of river gradient variation: Procedure, accuracy tests, and comparison with other knickpoint mapping methods

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ABSTRACT

The study of abrupt changes in longitudinal river profiles, or knickpoints, is currently approached through an empirical power law: the slope–area relationship. Results based on digital elevation model (DEM) analyses and stream extractions are generally intended to determine crustal uplift rates and identify transient landscape conditions. In this article, we present an alternative geomorphometric method for locating knickpoints and knickzones based on local slope gradient and curvature attributes. Intended as a rapid, regional scale, automated knickpoint detection technique, the accuracy of this slope–curvature method is tested on two digital elevation grids, NASA's SRTM (ground resolution of 90 m, resampled here to 75 m) and the ASTER DEM (15 m) in the Sierra Nacimiento (New Mexico, USA), a basement-cored mountain range recently exhumed by waves of headward drainage integration in response to remote tectonic deformation in the adjacent Rio Grande rift. Out of every 10 gradient anomalies detected by the SRTM-derived numeric routine, up to 8 are certifiable knickpoints recognized among a population of georeferenced occurrences surveyed in the field. An independent comparison with the slope–area method provided a further accuracy test, which was particularly useful at sites that could not be validated in the field for practical reasons. Given the low tectonic activity of the study area, the majority of knickpoints was also found to coincide with lithologic boundaries, making it difficult without further geomorphological data to single out dynamic knickpoints directly caused by the upstream propagation of channel instabilities relating to base level change.

1. Introduction

1.1. Knickpoints and the knickpoint problem

The main goal of digital elevation data processing today is to improve the mapping and modeling of landforms (Mitášova, 1995; Bocco et al., 2001; Minár and Evans, 2008), to understand soil and vegetation patterns (Moore et al., 1993; Van Niel et al., 2004), and to monitor changes in land use or predict natural hazards (Adediran et al., 2004; Gessler et al., 2009; Ulmer et al., 2009; Martha et al., 2010). In this study we use geomorphometric parameters to improve the recognition of, and accuracy in locating, knickpoints in drainage systems over wide regions. Knickpoints coincide with rapids or underpin waterfalls on rivers. Apart from spectacular tourist attractions, hindrances to navigation, or potential sites for hydroelectric dams, these widespread steeper reaches in the longitudinal profiles of rivers (Gardner, 1983) help to understand patterns of fluvial incision into bedrock, which is a rate-limiting process in the long-term evolution of landscapes (e.g. Howard et al., 1994; Formento-Trigilio and Pazzaglia, 1998; Stock and Montgomery, 1999; Whipple, 2001; Stock and Dietrich, 2003; Zaprowski et al., 2005; Bishop, 2007).

Depending on scale, e.g. catchment or reach, and hence on purpose and emphasis, knickpoints have received many definitions. Whipple and Tucker (1999) have defined them generically as abrupt changes in river gradient, whereas Crosby and Whipple (2006) used the term to describe a local convexity in the typically concave-up equilibrium channel profile at catchment scale. Likewise, Hayakawa and Oguchi (2006) have defined knickpoints as segments in a stream long profile than are steeper than the broader trend of the longitudinal profile. They also define knickzones as segments of river long profiles that are steeper than immediately adjacent segments. With a change of emphasis, Phillips and Lutz (2008) describe a knickpoint or knickzone rather as a locus of incision. Zaprowski et al. (2001) use the term

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knickzone to describe broadly convex profiles over tens of kilometers. At and below the knickzone, the channel incises bedrock, abandoning a floodplain and forming a bedrock strath. Above the knickzone, the channel is much less incised, resulting in a broader valley floor. Yet another definition is provided by Foster (2010), who has emphasized instead that the upstream extremity of a high-gradient reach is the knickpoint, which therefore is a distinct point of inflection between a high-gradient reach and a lower-gradient reach situated upstream. On a local scale, a knickpoint is also described as an isolated object in a river segment, with a particular morphology including an upper lip and a basal knick. Gardner (1983) has defined such a knickpoint lip as a break in slope where the channel floor becomes markedly steeper, with the knickpoint face being the segment that extends from the lip to the base of the knickpoint (Fig. 1). Where the water surface oversteepens on the lip (drawdown reach), flow acceleration and amplified erosion are observed (Haviv et al., 2010). At the knickpoint face, over a limited width, convergence and erosion prevail. Beyond the base of the knickpoint, flow dissipation prevails and depositional processes are dominant (Malavoi, 1989; Haviv et al., 2010).

The theoretical behavior of knickpoints has also been much studied through modeling of knickpoint propagation across synthetic landscapes (numeric grids) governed by erosion "laws" or analog models (e.g. Gardner, 1983; Schumm et al., 1987; Dorsey and Roering, 2006; Frankel et al., 2007; Loget and van den Driessche, 2009; Schippa and Pavan, 2009). The location of knickpoints in fluvial systems has been argued to result from changes in base level, river discharge, sediment flux, bedrock resistance or tectonic deformation across the river course (Howard et al., 1994). Stream power increases along the steepened gradient, potentially causing enhanced bedrock erosion (Heinio and Davies, 2007), and controls the rate at which material is removed from the catchment. Knickpoints are given as indicating either a state of stream disequilibrium in which changes in base level propagate channel instability upstream (Bishop et al., 2005), or a dynamic equilibrium between fluvial processes and localized tectonic displacement (Whipple, 2001). Accordingly, many studies have examined fluvial network patterns and stream profiles to infer landscape responses to tectonic and other geomorphic processes (e.g. Wells et al., 1988; Harbor, 1997; Pazzaglia et al., 1998; Wegmann and Pazzaglia, 2002; Tomkin et al., 2003; Densmore et al., 2004, 2005; Wobus et al., 2006; Wegmann et al., 2007; Stock et al., 2009).

1.2. This study: focus and goals

Studies that have focused on mapping the regional distribution of knickpoints across an extensive landscape continuum (see Harbor et al., 2005; Hayakawa and Oguchi, 2006, 2009; Wobus et al., 2006; Pérez-Peña et al., 2009) are much less common than any of the aforementioned lines of enquiry, which tend to focus on the dynamics or propagation rates of a small population of knickpoints in response

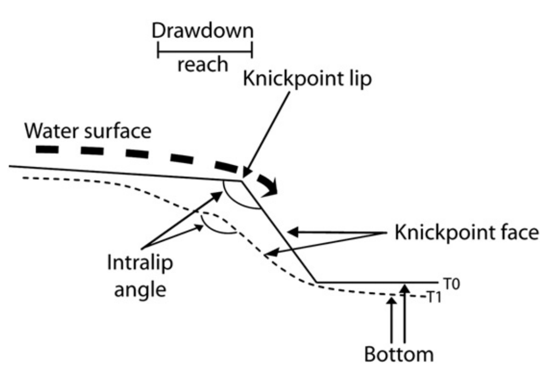

Fig. 1. Detailed morphology of a knickpoint. T0: initial form; T1: knickpoint form after some time has elapsed.
After Gardner (1983).

to base-level changes (Formento-Trigilio and Pazzaglia, 1998; Bishop et al., 2005; Crosby and Whipple, 2006; Frankel and Pazzaglia, 2006; Gunnell and Harbor, 2010). This situation arises perhaps because regional mapping requires systematic scanning of a topographic surface and implementation of automated routines of knickpoint extraction using varyingly accurate digital elevation data sources. Pioneers such as Baulig (1928), working in the Massif Central in France, had to rely exclusively on field exploration and manually-drawn river profiles to infer regional information about topographic response to relative eustatic changes. Even today, generating an accurate regional map of knickpoints is no trivial undertaking, with visual inspection of individual (1-D or 2-D) river longitudinal profiles still being the dominant approach. Yet the benefits of producing synoptic maps of river gradient variability is that these can serve as useful working documents for hydrological predictions and tectonics studies, for in-stream biological habitat surveys, for estimates of valley-slope or channel bank stability, for carrying out geomorphological sampling strategies, and many other field applications.

As a step toward filling this gap in river gradient mapping tools, this study seeks to elaborate and test automated numeric methods capable of mapping abrupt changes in river gradient on regular numeric grids. The approach involves implementing, testing and validating a new numeric script that articulates three topographic attributes: slope, and the vertical and horizontal curvatures of topography, also known as profile and plan curvature, respectively. These parameters are commonly used in soil studies and landform classifications but have not so far been used as tools for detecting variation in river channel steepness. Here we demonstrate how they can assist in locating channel knickpoints, and hereafter term this approach the slope–curvature method, or Method A. We test the accuracy of the method against georeferenced knickpoints observed and validated in the field in the Sierra Nacimiento, New Mexico.

In order to further test the performance of Method A, we also conduct a comparison with another method known in the literature as the slope–area method — termed here Method B for convenience. Method B typically aims to determine uplift rates through the study of longitudinal river profiles. It has been more widely tested in the literature and relies on the detection of knickpoints. It relies on an empirical formula based on a power law originally proposed by Hack (1957) and Flint (1974), which treats the shape of the river profile as a mathematical curve:

$$S = k_s A^{-\theta} \tag{1}$$

where S is the local channel slope, A is the upstream drainage area, k_s is the steepness index and θ the dimensionless concavity index of the curve. k_s and θ are constants of the slope–area relationship of Eq. (1), but they are considered as variables here, because we examine spatial differences of their values. Studies that use this slope–area formula operate under the assumption that a channel profile is related to topography, rock uplift, climatic change and/or local rock strength. Empirical log/log regression models relating slope to upstream drainage area are used to determine both k_s and θ for drainage areas above a critical size threshold. Whipple (2004), Harbor et al. (2005) and Wobus et al. (2006) have justified the value of Method B for determining the location of knickzones because this slope–area approach defines them as deviations (i.e. anomalies) from an ideal (i.e. theoretical) longitudinal channel profile lacking irregularities (Table 1).

The nuts and bolts of river network analysis following Method B are detailed in Harbor et al. (2005), Wobus et al. (2006) (after Snyder et al., 2000) and in Whipple et al. (2007). Variants relying on geomorphometric parameters such as Hack's stream length gradient index (*SL*, which describes how the local slope of a stream depends on distance from the drainage divide) have been implemented by Hayakawa and Oguchi (2006, 2009) for the determination of