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Connectivity as a crucial determinant of badland morphology and evolution

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ABSTRACT

The way in which threshold behaviour, landscape sensitivity and connectivity [1] operate together at the *meso-* and *macro-scale* in badlands is initially considered from a theoretical energy-utilisation perspective. The argument is developed that *intrinsic* changes to process domain dominance can result in progressive shifts in process connectivity without the need to invoke external climatic or tectonic change. From this premise, a *meso-scale* closed system model for the evolution of connected states in regionally isolated badlands is developed, applicable to systems evolving towards a fixed base level within a less erosive 'host' landscape. The model shows how badlands disconnected from regional drainage can develop from a wide range of *initial states* into a convergent *quasi-equilibrium*, followed by a period of *complex response* as energy is dissipated across thresholds, giving rise to a range of equifinal *maximum entropy* landscapes. This classification is illustrated using a range of global badland examples. Longer-term *macro-scale* interruptions to this semi-deterministic model of badland relief degradation are also considered. From this longer-term/larger-scale perspective, it is argued that *extrinsic* changes to relative relief can be driven by base-level changes (tectonically, isostatically or eustatically induced), in which case the continuity and linkages of 'information' within the system are modified by effects which move up through the system ('bottom-up' control). *Macro-scale* climatic changes also alter connectivity by changing the power distribution of prevailing events, and by causing long-term changes in mean precipitation, temperature and *E/P* ratio which affect vegetation, and therefore runoff resistance all across the landscape. From this perspective longer-term climatic change operates in a 'top-down' manner. The interplay between these two larger-scale controls will inevitably determine the pattern of connected states that the landscape experiences through time. The 'top-down' and 'bottom-up' combinations that can lead to either *rejuvenation* (and a return to the stages described for the closed system model) or *stabilisation* (enhanced phases of both morphological and geochemical stabilisation) are discussed.

1. Introduction

Badland geomorphology and function has fascinated geomorphologists for the last 25 years and there is now a convergence of views as to many aspects of badland development and formation, and considerable literature on the subject (Bryan et al., 1978; Yair et al., 1980; Bryan and Yair, 1982; Harvey, 1982; Wells, 1983; Gerits et al., 1987; Benito et al., 1993; Torri et al., 1994; Howard, 1994a, Calvo-Cases and Harvey, 1996; Howard, 1997; Bull and Kirkby, 1997; Gutierrez et al., 1997; Torri and Bryan, 1997; Imeson and Verstraten, 1988; Howard, 1999; Farifteh and Soeters, 1999; Rodolfi and Torri, 2000; Faulkner et al., 2000; Kuhn et al., 2004).

Over the last decade, the way in which hillslope and channel network coupling changes during rainfall and runoff events with differing recurrence probabilities has attracted the interest of several hydrologists (Ward and Stanford, 1995), soil scientists (Helming et al., 1998), and geomorphologists (Kirkby, 1971, 1992; Baird et al., 1992; Kirkby, 1993; Harvey, 1997; Favis-Mortlock, 1998; Kirkby and Bull, 2000; Harvey, 2002; Betts et al., 2003; Hooke, 2003), and several network connectivity models have been developed (Baird et al., 1992; Kirkby, 1994; Favis-Mortlock, 1998, Leibowitz et al., 2000). Research considering seasonal shifts in process dominance and patterns in several landscape types (Collins and Bras, 2004; Hattanji and Onda, 2004) supports the view that the seasonal coupling and decoupling of process sets is a fundamental part of system dynamics. Models exploring coupled and de-coupled drainage at the smaller scale have been developed for Mediterranean/semi-arid areas by Kirkby and Bull (2000); Kirkby et al. (2002); and for arid areas by Kuhn et al. (2004).

At the *meso-scale*, connectivity changes caused by the development and removal of 'buffers and barriers' during drainage network operation have been described as a crucial aspect of sediment transfer in recent papers by Brierley et al. (2006) and Fryirs et al. (2007). In particular, 'disconnection' is argued to produce shifts in the subsequent (post-event) pattern of process domain dominance as distributed within the landscape. In systems with perennial flow,

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[1] In this paper, Harvey's (2001) term 'coupling' is reserved for references to the seasonal behaviour of process domain interactions at the relatively *small scale*, and the term 'connectivity' applied to the physically integrated status of a system (Thomas, 2001) at the *meso-* and *macro-scale*.

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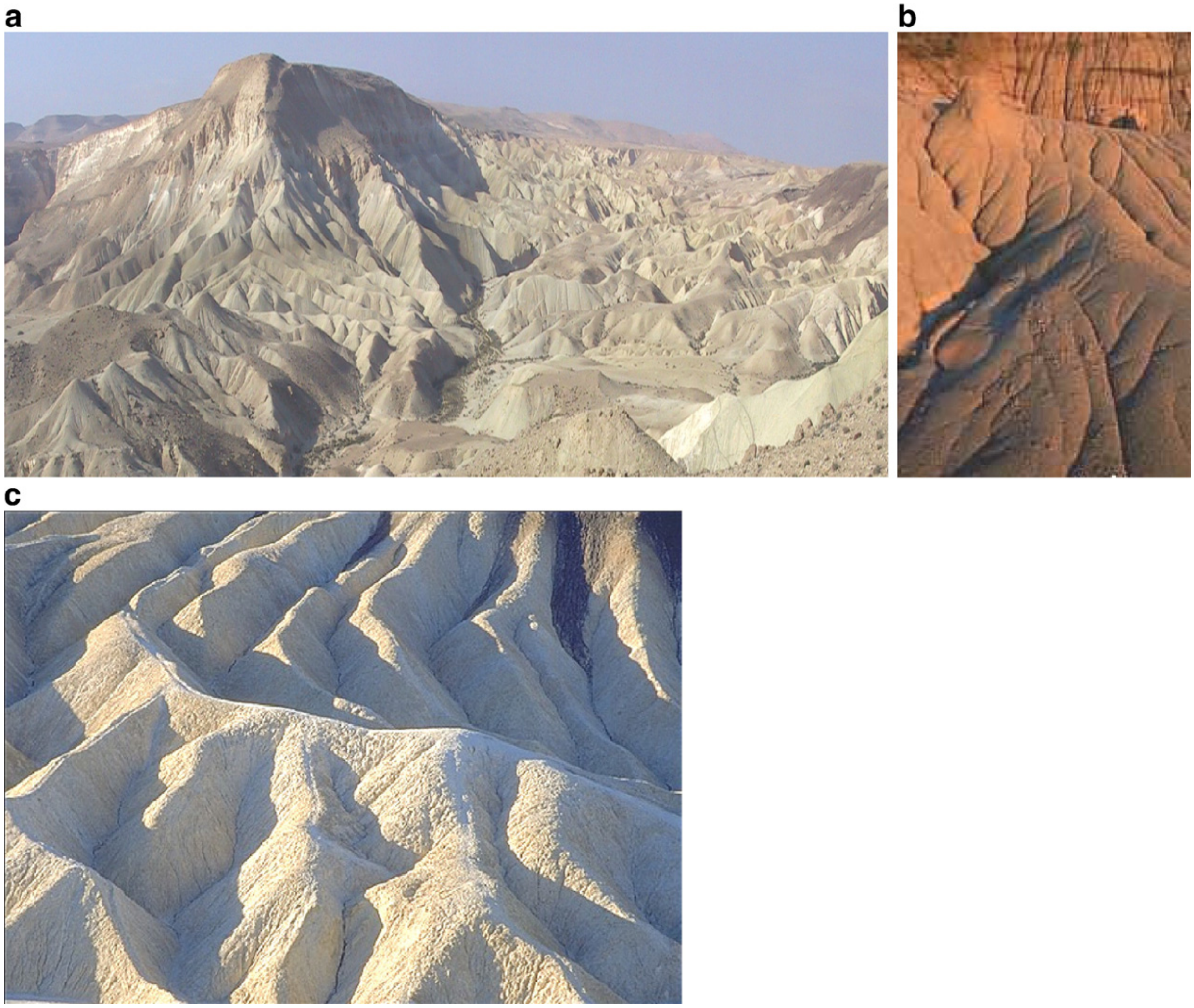

Fig. 1. Connected morphology: (a) badland landscape displaying well-organised networks and competitive divides in part of the Zin Valley badlands, Israel (copyright 2002; kind permission N. Kuhn). (b) organised rill systems (author's image). (c) surface morphology, Borrego Badlands, Anza-Borrego Desert, California (copyright 1998–2000; kind permission Dmitri Zagorodnov).

this effect is largely transient. However, in semi-arid badlands, the ephemeral nature of runoff means that change is particularly associated with extreme events. Erosion occurring on the rising limb of flashfloods is followed at most locations by considerable within-network deposition during flow recession, exacerbated by considerable transmission loss (Faulkner, 1992; Poesen et al., 2003; Kuhn et al., 2004). This 'cut-and-fill' behaviour leads to internal changes to connectivity which have a crucial and permanent impact on the flow accumulation pattern of subsequent events. The pre-existing morphology as well as the event size will determine the location of the barriers. Disconnection may subsequently persist in a system over a longer period. Since location and persistence would appear to be dependent on the size of the subsequent events, the resulting unsure future could be described as *equifinal* (Schumm, 1980).

In this paper, the theoretical formulation of connectivity as a system state is explored for badlands, arguing that a considerable amount of the divergence of *meso-scale* and *macro-scale* morphology encountered in badland settings can be explained in terms of changes to energy utilisation and connectivity shifts within the networks of which these badlands form a part. Drawing largely on existing systems literature and concepts of connectivity as currently developed in geomorphology, a closed system *meso-scale* model for badland evolution is initially proposed which links consideration of energy utilisation to changes in power relationships as relative relief degrades. The discussion of shifts in process domain dominance (wash, piping, mass movements) that can accompany these changes will be understood. A later part of the paper moves up to the *macro-scale*, arguing that the changing interactions between the two main growth contexts for the evolution of the closed system (tectonic and climatic setting) interact to constrain and/or enhance the subsequent pattern of connected states that the landscape experiences through the longer term. This latter formulation is essentially an open system model.

2. Coupling and connectivity

2.1. Continuity, organisation, information and entropy

In the latter part of the 20th century, most geomorphologists would have argued that at equilibrium, a high level of organized self-similarity exists in drainage networks with gradients that nest form and function in a hierarchical log-normal manner, illustrated for instance by Horton's (1945) and Strahler's (1957) 'laws of drainage composition'. An essential underpinning of the interpretation of organised channel networks is that their regularity, which apes that of organised systems of all kinds (Woldenberg, 1968), reflects the requirement of the system to do work. Regularity generates high levels of 'information' or negentropy[2] (Fig. 1a, b, c). More recently, many new simulation models of drainage basin evolution have been

[2] Entropy and negentropy were discussed as basic geomorphic concepts by Leopold and Langbein (1962). Entropy is a measure of the extent to which system energy is unable to perform work, i.e. a measure of its disorganisation.