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Environmental signal propagation in sedimentary systems across timescales

Brian W. Romans [a,*], Sébastien Castelltort [b], Jacob A. Covault [c], Andrea Fildani [d], J.P. Walsh [e,f]

[a] Department of Geosciences, Virginia Polytechnic Institute and State University, Blacksburg, VA 24061, United States
[b] Section des Sciences de la Terre et de l'Environnement, Université de Genève, 1205 Genève, Switzerland
[c] Bureau of Economic Geology, University of Texas at Austin, Austin, TX 78713 United States
[d] Statoil RDI Research Center, Austin, TX 78730, United States
[e] East Carolina University, Greenville, NC 27858, United States
[f] UNC Coastal Studies Institute, Wanchese, NC 27981, United States

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ABSTRACT

Earth-surface processes operate across erosionally dominated landscapes and deliver sediment to depositional systems that can be preserved over a range of timescales. The geomorphic and stratigraphic products of this source-to-sink sediment transfer record signals of external environmental forcings, as well as internal, or autogenic, dynamics of the sedimentary system. Here, we evaluate environmental signal propagation across sediment-routing systems with emphasis on sediment supply, Qs, as the carrier of up-system forcings. We review experimental, numerical, and natural examples of source-to-sink sediment routing and signal propagation during three timescales: (1) historic, which includes measurement and monitoring of events and processes of landscape change and deposition during decades to centuries; (2) centuries to several millions of years, referred to as intermediate timescale; and (3) deep time. We discuss issues related to autogenic dynamics of sediment transport, transient storage, and release that can introduce noise, lags, and/or completely mask signals of external environmental forcings. We provide a set of conceptual and practical tools for evaluating sediment supply within a source-to-sink context, which can inform interpretations of signals from the sedimentary record. These tools include stratigraphic and sediment-routing system characterization, sediment budgets, geochronology, detrital mineral analysis (e.g., thermochronology), comparative analog approaches, and modeling techniques to measure, calculate, or estimate the magnitude and frequency of external forcings compared to the characteristic response time of the sediment-routing systems.

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* Corresponding author.

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1. Introduction

1.1. What is an 'Environmental Signal'?

From the perspective of sedimentary system analysis, signals are changes in sediment production, transport, or deposition that originate from perturbations of environmental variables such as precipitation, sea level, rock uplift, subsidence, and human modifications. The origin of the perturbations can be 'natural' when they relate to tectonic and climatic processes that have happened over the course of Earth's history, or 'anthropogenic' if they are linked with human actions. Environmental signals occur over many temporal scales, ranging from several hours to millions of years in response to tectonic and climate changes. Signals involve a large range of spatial scales such as localized precipitation affecting small catchments to eustatic sea-level change that affects the globe.

An environmental signal can trigger a response of the Earth's surface in the form of erosion, sediment transport, and deposition, and the surface response may be local initially and further afield eventually as it propagates away. A sea-level fall, for example, can create local incision and shoreline regression, but also up-system knickpoint migration and down-system deposition in the deep sea. Similarly, an increase in precipitation can create a wave of incision, alluvial aggradation, and eventually a pulse of sediment discharge to the ocean. The overarching challenge of geomorphology and stratigraphy is to invert the history of environmental signals from landscape and rock records.

The transfer, or propagation, of signals is generally examined in the down-system direction, as this is the dominant direction of mass transfer (e.g., Castelltort and Van Den Driessche, 2003; Allen, 2008a; Jerolmack and Paola, 2010). However, up-system signal propagation driven by base level change has long been considered in the interpretation of the sedimentary record (e.g., Fisk, 1944), is important for distributive systems (e.g., backwater effect in deltas, Lamb et al., 2012), and is the subject of theoretical work (Voller et al., 2012).

Environmental signals are potentially preserved in the geomorphic expression of landscapes around us, as well as in the stratigraphic record of depositional basins. This review examines how signals propagate within the context of sediment-routing systems with emphasis on the nature of sediment supply, or Qs, as the indicator of up-system forcings (Fig. 1A) (Allen et al., 2013). We think that reconstructing the rates and magnitudes of signal-generating processes from stratigraphy requires consideration of the nature of system response, and the potential modification of the original signal. It is also important to recognize that signals can be masked or significantly altered by what can be referred to as 'noise.' In the present context, 'noise' has the broad meaning of any modification of the primary signal of interest, irrespective of its origin, frequency, or magnitude. It is one fundamental goal of stratigraphy to disentangle signal from noise, but what can be considered noise at one timescale may represent a signal at another. One notable type of noise is the result of internal, self-organized, dynamics of a sediment-routing system (e.g., Jerolmack and Paola, 2010), that can potentially 'shred' environmental signals as a result of their large magnitude and period relative to the primary signal of interest (e.g., Jerolmack and Paola, 2010; Wang et al., 2011).

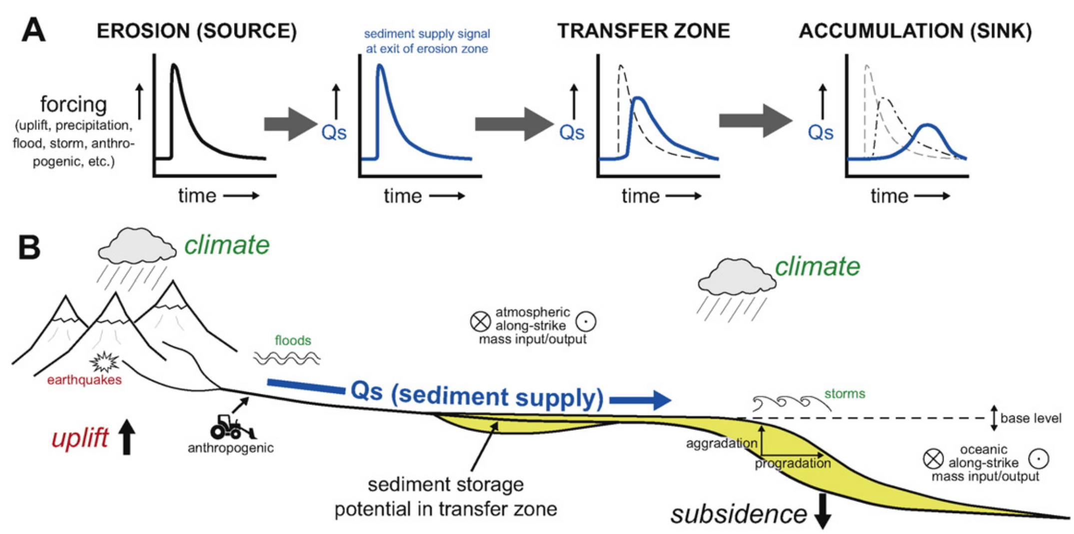

Fig. 1. (A) Schematic portrayal of a sediment supply (Qs) signal from the erosion zone and how that signal propagates through the system. The leftmost Qs signal represents as measured at the exit of the erosion zone and for simplicity is the same as the original forcing of interest. The transfer zone Qs signal is measured within the transfer zone at some distance from exit of erosion zone and the rightmost signal represents that which reaches the accumulation zone and is an input for the stratigraphic record. Dashed lines refer to Qs signal(s) in up-system segment(s) to illustrate that a signal can be modified during propagation. (B) 2-D profile of a generic sediment-routing system emphasizing erosion, transfer, and accumulation zones (potential for intermediate to deep time stratigraphic preservation in yellow) and important controls of tectonics (including earthquakes), climate (including storms), base level, and anthropogenic factors.
Part B modified from Castelltort and Van Den Driessche (2003).