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Climate-driven unsteady denudation and sediment flux in a high-relief unglaciated catchment–fan using ^{26}Al and ^{10}Be: Panamint Valley, California

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ABSTRACT

Environmental changes within erosional catchments of sediment routing systems are predicted to modulate sediment transfer dynamics. However, empirical and numerical models that predict such phenomena are difficult to test in natural systems over multi-millennial timescales. Tectonic boundary conditions and climate history in the Panamint Range, California, are relatively well-constrained by existing low-temperature thermochronology and regional multi-proxy paleoclimate studies, respectively. Catchment–fan systems present there minimize sediment storage and recycling, offering an excellent natural laboratory to test models of climate-sedimentary dynamics. We used stratigraphic characterization and cosmogenic radionuclides (CRNs; ^{26}Al and ^{10}Be) in the Pleasant Canyon complex (PCC), a linked catchment–fan system, to examine the effects of Pleistocene high-magnitude, high-frequency climate change on CRN-derived denudation rates and sediment flux in a high-relief, unglaciated catchment–fan system. Calculated ^{26}Al/^{10}Be burial ages from 13 samples collected in an ~180 m thick outcropping stratigraphic succession range from ca. 1.55 ± 0.22 Ma in basal strata, to ca. 0.36 ± 0.18–0.52 ± 0.20 Ma within the uppermost part of the succession. The mean long-term CRN-derived paleodenudation rate, 36 ± 8 mm/kyr (1σ), is higher than the modern rate of 24 ± 0.6 mm/kyr from Pleasant Canyon, and paleodenudation rates during the middle Pleistocene display some high-frequency variability in the high end (up to 54 ± 10 mm/kyr). The highest CRN-derived denudation rates are associated with stratigraphic evidence for increased precipitation during glacial–pluvial events after the middle Pleistocene transition (post ca. 0.75 Ma), suggesting 100 kyr Milankovitch periodicity could drive the observed variability. We investigated the potential for non-equilibrium sedimentary processes, i.e. increased landslides or sediment storage/recycling, to influence apparent paleodenudation rates; end-member mixing models suggest that a mixture of >50% low-CRN-concentration sediment from landslides is required to produce the largest observed increase in paleodenudation rate. The overall pattern of CRN-derived burial ages, paleodenudation rates, and stratigraphic facies suggests Milankovitch timescale climate transitions drive variability in catchment denudation rates and sediment flux, or alternatively that climate transitions affect sedimentary process regimes that result in measurable variability of CRN concentrations in unglaciated catchment–fan systems.

1. Introduction

Sediment routing systems consist of an erosional zone, a fluvial transfer zone, and a depositional basin (Allen, 2008). The creation and preservation of stratigraphy within a sediment routing system is the sum of complex processes including up-system environmental changes in the erosion zone, sediment storage and recycling in the erosion and/or fluvial transfer zones, and changes in accommodation and intrinsic system dynamics in depositional basins (Paola et al., 1992). Some geoscientists have conceptualized sediment production, transport, storage, and remobilization dynamics along sediment routing systems in terms of environmental signal propagation (Castelltort and Van Den Driessche, 2003; Romans et al., 2016). In this framework, sediment flux is the carrier of environmental change signals. Inverting sediment flux from stratigraphy is thus complicated by issues including signal to noise ratio, signal delay, signal attenuation, or signal 'shredding', and combinations of these phenomena may preclude preservation or inversion of up-system environmental change from de-

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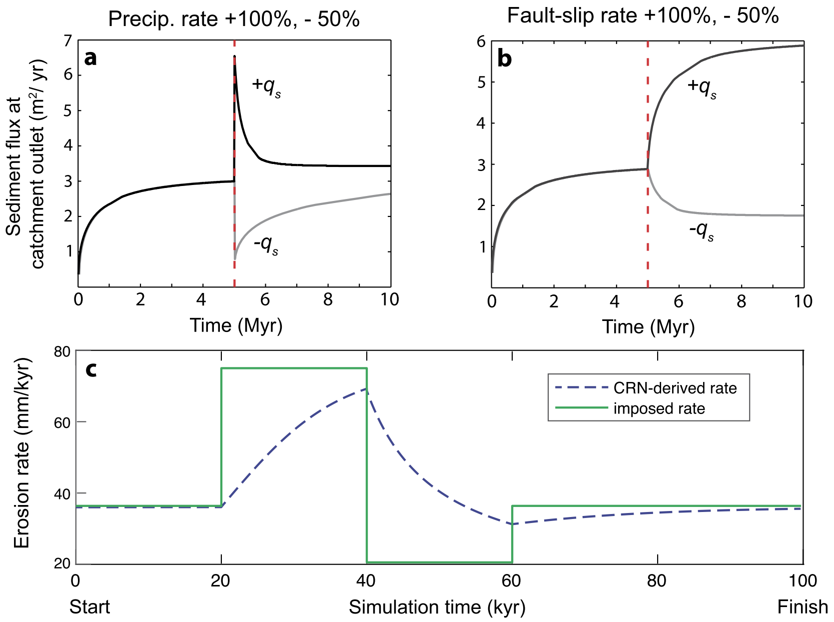

Fig. 1. Modeled changes in sediment flux (q_s per unit width) and erosion rate across two timescales (Myr and kyr), resulting from perturbations in climatic or tectonic boundary conditions in a catchment–fan system bounded by a range-front normal fault, and simulated imposed erosion rate plotted with resultant CRN-derived erosion rate. Time progresses from left to right in all plots. **a**: q_s response to stepwise increase (+100%, black line) or decrease (−50%, gray line) in precipitation rate. **b**: q_s response to stepwise increase (+100%, black line) or decrease (−50%, gray line) in fault slip rate. Dashed vertical red line indicates timing of change in forcing in parts a and b. Modified from Densmore et al. (2007). **c**: Simulated response of cosmogenic radionuclide (CRN) derived erosion rates to a change in actual (imposed) erosion rate. The duration of the simulation is similar to that of middle to late Pleistocene Milankovitch periods of 100 kyrs. Green solid line represents user defined erosion rate, and blue dashed line represents the model output, or CRN-derived erosion rate through time. ^{10}Be production rate for simulation as described in main text and code described in Garcin et al. (2017). (For interpretation of the colors in the figure(s), the reader is referred to the web version of this article.)

positional products (Jerolmack and Paola, 2010; Romans et al., 2016). Given this context, *a priori* assumptions of minimal signal delay, attenuation, or shredding are required to explore effects of up-system drivers on magnitude and variability of signals of erosion-deposition dynamics. A steep catchment–fan system with a continuously subsiding depositional segment represents an ideal natural laboratory for the investigation of sedimentary signal propagation because: (1) it may react rapidly to changes in boundary conditions, (2) it likely experiences minimal signal delay or attenuation because it lacks, or has a very short transfer zone, and (3) rapidly subsiding alluvial basins contain relatively complete records of past surface dynamics (Straub and Esposito, 2013). Catchment–fan systems have previously been used to explore effects of environmental change on catchment erosion, sediment flux, and sediment caliber exiting catchments (Fig. 1) (Allen and Densmore, 2000; Densmore et al., 2007; Armitage et al., 2011). In such a framework, changes in erosion and sediment flux from catchment to fan are direct signals of environmental change in a catchment. A fundamental question then is what are the magnitudes of signals emitted from the erosive source of a natural catchment–fan system? And a related question is by how much do such magnitudes vary through time? Placing constraints on denudation rate variability — a proxy for sediment supply at a catchment outlet — through time, in a single sediment routing system, allows for the examination of signals of environmental change.

Predicting catchment response to environmental change, specifically climatic transitions, on a global to individual catchment basis is challenging, because with several exceptions there is a lack of empirical data sets that constrain high-resolution and long-term (10^{3-4} yr and 10^6 yr, respectively) records of changes in catchment-scale erosion or sediment flux (Granger and Schaller, 2014; Puchol et al., 2017; Oskin et al., 2017). Researchers have addressed this topic by measuring CRNs in alluvial and lacustrine stratigraphy to derive a time series of paleodenudation rates (Balco and Stone, 2005; Granger and Schaller, 2014), by utilizing volumetric estimates of basin fill (Covault et al., 2011), or by analyzing provenance of dated sedimentary deposits spanning climatic transitions (Mason et al., 2017). Results indicate many glaciated sediment routing systems have responded to changing climatic boundary conditions within resolution of the various chronometers (Stock et al., 2005; Glotzbach et al., 2013; Marshall et al., 2015; Gulick et al., 2015; Mason et al., 2017), whereas other records from glaciated and unglaciated systems show a complex response, or a lack of any measurable change in denudation rate or fluxes to basins across major climate transitions (Granger et al., 2001; Oskin et al., 2017). For instance, in the Tibetan Plateau, ^{10}Be-derived denudation rates across the Plio-Pleistocene transition show a complex, asynchronous, or weak transient response to onset of glaciation (Puchol et al., 2017). In the unglaciated Peninsular Ranges of southern California, ^{10}Be-derived paleodenudation rates across the Plio-Pleistocene transition (ca. 4–1 Ma) remained constant (Oskin et al., 2017). However, in the unglaciated Northern Kenya Rift erosion/deposition rates saw a significant transient increase during the African Humid Period, between ca. 5–15 ka, (Garcin et al., 2017), and tectonically quiescent, unglaciated sediment routing systems along the Texas Gulf Coast responded to interglacial warm periods with increased CRN-derived denudation rates (Hidy et al., 2014). Yet in the Pacific Northwest, periglacial conditions during the last glacial maximum increased CRN-derived denudation rates relative to the Holocene (Marshall et al., 2015). These results highlight the complexity in natural system response to changing climate, complicate interpretations of sedimentary records of environmental change, and prediction of system response to future global climate change.

Numerical simulations of linked catchment–fan systems represent a tool to bridge the gap between modern and geologic-timescale empirical studies, and may be used to explore effects of up-system forcings on depositional products. Simulations typically impose changes in catchment or orogen-scale boundary conditions