Earth and Planetary Science Letters 428 (2015) 255–266

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

Increased late Pleistocene erosion rates during fluvial aggradation in the Garhwal Himalaya, northern India

Dirk Scherler[a,b,c,*], Bodo Bookhagen[d,e], Hendrik Wulf[f], Frank Preusser[g], Manfred R. Strecker[e]

[a] *Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, USA*
[b] *Earth Surface Geochemistry, Helmholtz Centre Potsdam GFZ German Research Centre for Geosciences, Potsdam, Germany*
[c] *Institute of Geological Sciences, Free University of Berlin, Berlin, Germany*
[d] *Department of Geography, University of California, Santa Barbara, USA*
[e] *Institute of Earth and Environmental Science, University Potsdam, Potsdam, Germany*
[f] *Department of Geography, University of Zurich, Zurich, Switzerland*
[g] *Institute of Earth and Environmental Sciences – Geology, University of Freiburg, Freiburg, Germany*

ARTICLE INFO

Article history:
Received 19 January 2015
Received in revised form 19 June 2015
Accepted 21 June 2015
Available online 29 July 2015
Editor: A. Yin

Keywords:
paleo-erosion rates
climate change
river terraces
landscape evolution
hillslopes
Himalaya

ABSTRACT

The response of surface processes to climatic forcing is fundamental for understanding the impacts of climate change on landscape evolution. In the Himalaya, most large rivers feature prominent fill terraces that record an imbalance between sediment supply and transport capacity, presumably due to past fluctuations in monsoon precipitation and/or effects of glaciation at high elevation. Here, we present volume estimates, chronological constraints, and ^{10}Be-derived paleo-erosion rates from a prominent valley fill in the Yamuna catchment, Garhwal Himalaya, to elucidate the coupled response of rivers and hillslopes to Pleistocene climate change. Although precise age control is complicated due to methodological problems, the new data support formation of the valley fill during the late Pleistocene and its incision during the Holocene. We interpret this timing to indicate that changes in discharge and river-transport capacity were major controls. Compared to the present day, late Pleistocene hillslope erosion rates were higher by a factor of ∼2–4, but appear to have decreased during valley aggradation. The higher late Pleistocene erosion rates are largely unrelated to glacial erosion and could be explained by enhanced sediment production on steep hillslopes due to increased periglacial activity that declined as temperatures increased. Alternatively, erosion rates that decrease during valley aggradation are also consistent with reduced landsliding from threshold hillslopes as a result of rising base levels. In that case, the similarity of paleo-erosion rates near the end of the aggradation period with modern erosion rates might imply that channels and hillslopes are not yet fully coupled everywhere and that present-day hillslope erosion rates may underrepresent long-term incision rates.

1. Introduction

Understanding the transient response of high-mountain landscapes to climate change is important for assessing the geomorphic impact of global warming and for unraveling potential linkages between climate, tectonics, and surface processes. For example, changes in temperature and precipitation can affect rates of weathering, runoff, and sediment transport (e.g., Tucker and Slingerland, 1997). How these changes combine and ultimately impact landscapes depends on their relative signs and magnitudes. River terraces are arguably the most common landforms used to infer climate change impacts on landscapes, because they record periods of valley aggradation and incision that are typically related to changes in runoff and sediment supply (e.g., Bull, 1991). Whereas changes in runoff can, at least qualitatively, be inferred from paleoclimatic records, changes in hillslope sediment supply are more difficult to assess and often remain speculative.

In the past two decades, significant advances in understanding and quantifying hillslope weathering and erosion have been achieved with *in situ*-produced terrestrial cosmogenic nuclides (TCN), which are rare isotopes that are produced by cosmic radiation in the uppermost meters of the Earth's surface (e.g., Lal, 1991). In particular, catchment-average erosion rates, derived from TCN abundances in river sediments, have propelled new insights into relations between erosion, climate, tectonics,

* Corresponding author at: Earth Surface Geochemistry, Helmholtz Centre Potsdam GFZ German Research Centre for Geosciences, Potsdam, Germany. Tel.: +49 331 288 28646.
E-mail address: scherler@gfz-potsdam.de (D. Scherler).

http://dx.doi.org/10.1016/j.epsl.2015.06.034

and topography (e.g., Granger et al., 1996; Riebe et al., 2001; Scherler et al., 2014a). TCNs in fluvial sediments integrate hillslope erosion rates over time spans that are roughly equal to the time it takes for eroding the uppermost 60–100 cm, that is, $\sim 10^2$–10^4 yr in most tectonically active landscapes. Such time scales are usually long enough to avoid anthropogenic land use changes, but short enough to potentially detect climate-induced erosion rate changes (von Blanckenburg, 2005).

A promising application for studying landscape response to climate change is measuring TCN abundances in ancient fluvial deposits to obtain paleo-erosion rates for entire catchments (Schaller et al., 2002; Charreau et al., 2011; Bekaddour et al., 2014). However, this approach has not been often used and its applicability in different landscapes remains to be tested (Schaller and Ehlers, 2006). Here, we study hillslope erosion rates during a late Quaternary episode of river aggradation in the Garhwal Himalaya, northern India, by comparing TCN concentrations in recent and ancient fluvial sediments. We supplement these data with chronological constraints on the aggradation period and an assessment of the amount of transiently stored material to test existing models of geomorphic response to climate change in the Himalaya.

2. Geomorphic response to climate change in the Himalaya

Throughout the Himalaya, remnants of thick valley fills straddle most major transverse drainages and testify to periods of transient imbalances between hillslope sediment supply and river capacity. Although some of these fills are clearly due to landslide dams (e.g., Bookhagen et al., 2005; Pratt-Sitaula et al., 2007) or glacier dams (e.g., Scherler et al., 2014b), many others have been linked to climate change (e.g., Lavé and Avouac, 2001). In the Marsyandi Valley, Nepal (Pratt et al., 2002) and the Sutlej Valley, India (Bookhagen et al., 2006), the most recent period of aggradation has been related to a pulse of enhanced sediment supply that overwhelmed river capacity during a phase of intensified monsoon precipitation in the early Holocene (Fig. 1a). Enhanced precipitation is assumed to have resulted in higher pore pressures on hillslopes that would have triggered landslides more frequently (Carson, 1976; Pratt et al., 2002); hence we refer to this model as '*hillslope-driven aggradation*'. An alternative model, which is mainly based on comparison of fluvial chronologies from the Alaknanda River, NW India, with paleoclimatic records, has related aggradation to reduced river discharge during a phase of weakened monsoon precipitation in the late Pleistocene and ensuing incision to a phase of strong monsoon precipitation (Srivastava et al., 2008; Juyal et al., 2010; Ray and Srivastava, 2010). Because changes in hillslope sediment flux are of minor importance relative to changes in river discharge and transport capacity, we term this model '*discharge-driven aggradation*' (Fig. 1b).

The main testable differences between these two models are (1) the timing and rate of aggradation and (2) the coupling between hillslopes and rivers. Depositional ages are currently only available from the Alaknanda Valley and support the discharge-driven model, but significant differences in between studies (Srivastava et al., 2008; Ray and Srivastava, 2010; Juyal et al., 2010) complicate a clear correlation with climatic variations. If aggradation occurred during the late Pleistocene in the Sutlej and Marsyandi Valleys, too, it does not preclude the possibility that it was driven by enhanced hillslope sediment supply during earlier humid periods. Moreover, modeling work suggest that hillslope-driven aggradation can also occur due to changes in vegetation cover or runoff intensity without changing mean annual precipitation (Tucker and Slingerland, 1997). Therefore, the temporal correlation of landforms with climatic records may not be enough to distinguish between these models.

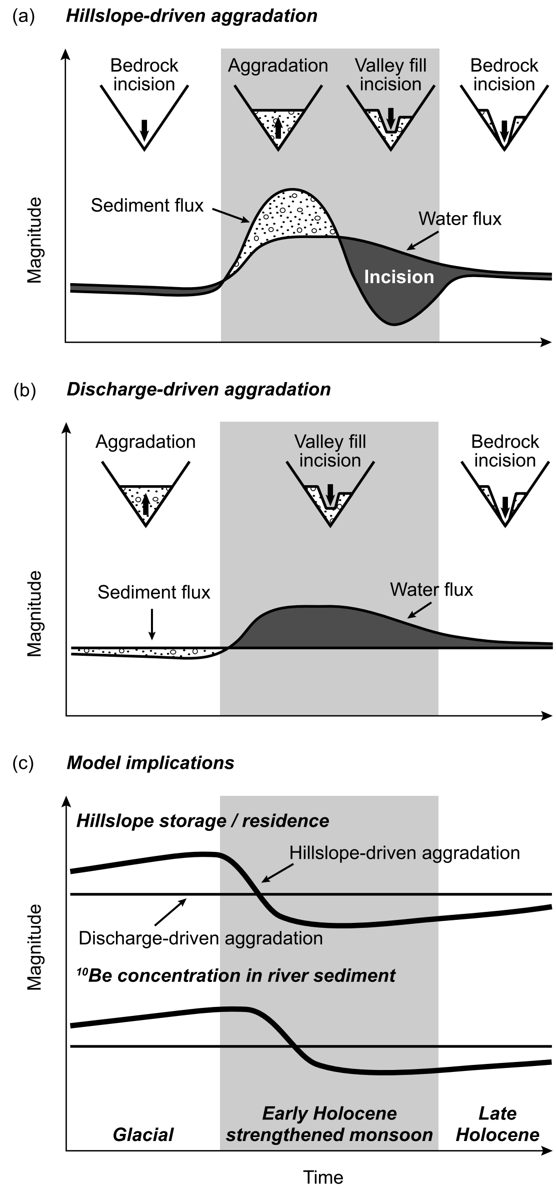

Fig. 1. Sketch showing different models of river response to climate change in the Himalaya. (a) Hillslope-driven aggradation (modified after Pratt et al., 2002). (b) Discharge-driven aggradation. (c) Model implications for hillslope storage and ^{10}Be concentrations in river sediment. Note that ^{10}Be concentrations in river sediments are damped and lag behind hillslope storage due to finite integration times (e.g., Schaller and Ehlers, 2006).

Changes in hillslope erosion rates due to changes in weathering and soil production, for example, could principally occur in both models. However, it is central to the hillslope-driven model that during a period of reduced landsliding, hillslopes temporarily accumulate weathered material that is later removed during a period of enhanced landsliding and other mass movements (Pratt et al., 2002; Bookhagen et al., 2005). Such temporal variations in hillslope sediment storage and residence time reflect changes in hillslope erosion rates and thus the accumulation of TCNs (Fig. 1c). In the hillslope-driven model, TCN concentrations (erosion rates) are expected to decrease (increase) during aggradation as the "hillslope reservoir" is progressively depleted. In addition to chronologic data, comparison of TCN abundances in fluvial sediments from rivers and terraces should therefore help distinguishing between hillslope-driven and discharge-driven aggradation. We will test this approach in the Garhwal Himalaya of Northern India.