Late Quaternary intensified monsoon phases control landscape evolution in the northwest Himalaya

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ABSTRACT

The intensity of the Asian summer-monsoon circulation varies over decadal to millennial time scales and is reflected in changes in surface processes, terrestrial environments, and marine sediment records. However, the mechanisms of long-lived (2–5 k.y.) intensified monsoon phases, the related changes in precipitation distribution, and their effect on landscape evolution and sedimentation rates are not yet well understood. The arid high-elevation sectors of the orogen correspond to a climatically sensitive zone that currently receives rain only during abnormal (i.e., strengthened) monsoon seasons. Analogous to present-day rainfall anomalies, enhanced precipitation during an intensified monsoon phase is expected to have penetrated far into these geomorphic threshold regions where hillslopes are close to the angle of failure. We associate landslide triggering during intensified monsoon phases with enhanced precipitation, discharge, and sediment flux leading to an increase in pore-water pressure, lateral scouring of rivers, and oversteepening of hillslopes, eventually resulting in failure of slopes and exceptionally large mass movements. Here we use lacustrine deposits related to spatially and temporally clustered large landslides (>0.5 km^3) in the Sutlej Valley region of the northwest Himalaya to calculate sedimentation rates and to infer rainfall patterns during late Pleistocene (29–24 ka) and Holocene (10–4 ka) intensified monsoon phases. Compared to present-day sediment-flux measurements, a fivefold increase in sediment-transport rates recorded by sediments in landslide-dammed lakes characterized these episodes of high climatic variability. These changes thus emphasize the pronounced imprint of millennial-scale climate change on surface processes and landscape evolution.

Keywords: Himalaya, landslides, paleoclimate, precipitation, Asian monsoon.

INTRODUCTION

Climate change at variable time scales exerts a profound control on hillslope and fluvial transport processes and hence on landscape development (e.g., Hancock and Anderson, 2002; Hartshorn et al., 2002). In the Himalaya, monsoonal circulation has varied at millennial, centennial, and decadal time scales (e.g., Altabet et al., 2002; Clemens et al., 1991), and corresponding changes in precipitation distribution have left strong imprints on landscape evolution and sedimentation (e.g., Barnard et al., 2001; Bookhagen et al., 2005; Goodbred and Kuehl, 2000; Pratt et al., 2002; Prins and Postma, 2000).

The Indian summer monsoon results from a thermal gradient between a low-pressure cell over Tibet and high pressure over the oceans, producing counterclockwise moisture transport from the Bay of Bengal along the southern Himalayan front toward the northwest (e.g., Hastenrath, 1994; Lang and Barros, 2002). There, at the termination of the northwestward monsoonal moisture transport near the Sutlej Valley region (Fig. 1), rainfall amounts under normal conditions are less compared to regions farther east, and affect areas along the southern Himalayan front between 1 and 3 km elevation, (Bookhagen et al., 2005; Lang and Barros, 2002). In this segment of the Himalaya, orographic barriers (>4.5 km in elevation) block moisture of the present-day weak monsoonal circulation, resulting in an arid high-elevation region to the north. Only during abnormal (i.e., strengthened) monsoon years does rainfall penetrate more than 75 km farther into the orogen to reach these areas, which have hillslopes near the threshold angle for failure (Bookhagen et al., 2005). Due to its position near the terminus of the monsoon conveyer belt, the northwestern Himalaya is thus a climatically sensitive zone where changes in the strength of the monsoonal circulation system and their influence on hillslope processes can be evaluated (Fig. 1).

To unravel environmental changes during longer (>2 k.y.) intensified monsoon phases and to evaluate their influence on geomorphic processes and rates, we studied large (>0.5 km^3) landslides that impounded drainages of the Sutlej River network in the northwest Himalaya and the associated transient lacustrine basins in order to determine erosion and sedimentation rates. We thus use the landslide clusters as indicators of former rainfall distribution and sediment transport in the climatically sensitive zones. It is important to note that precipitation patterns of present-day, abnormal monsoon years mimic the spatial distribution of late Pleistocene and Holocene landslide clusters observed in the Sutlej River and its tributaries. This relationship suggests an intensification of surface processes in the arid parts of the orogen over at least decadal to millennial time scales due to an increase in available moisture during intensified monsoon phases.

METHODS

We are confident that we have identified all large landslide deposits (>0.5 km^3) through extensive satellite imagery analysis (Corona, Landsat ETM+, and Advanced Spaceborne Thermal Emission and Reflection Radiometer [ASTER]) and detailed field observations in the Sutlej Valley region. Absolute age control for onset and duration of landslide-related lacustrine deposition is provided by accelerated mass spectrometry ^{14}C dates on charcoal and plant remains from the bottom and top layers of the lake sediments (Table DR1[1]). Where absolute age control could not be obtained, deposits were correlated with adjacent dated units on the basis of stratigraphic relationships, such as superposition of fluvial terraces by landslide debris and associated lake sediments. Only late Pleistocene and Holocene large mass-movement deposits and their related basin fills were found. The amount of eroded sediment, longitudinal river profiles, and river geometry differ significantly in the late Pleistocene and Holocene data sets. For example, Holocene landslide deposits have retained pronounced knickpoints and are still being downcut, while Pleistocene deposits have been nearly obliterated and river profiles lack knickpoints. We calculated sedimentation rates for two Holocene landslide-related paleolakes of comparable size but different geographic setting by combining age information and volumetric measurements from a digital elevation model (DEM). DEMs were derived from digitized contour lines of 1:25,000

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[1]GSA Data Repository item 2005017, Table DR1, list of landslide-dammed lakes in the Sutlej Valley region, is available online at www.geosociety.org/pubs/ft2005.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA.

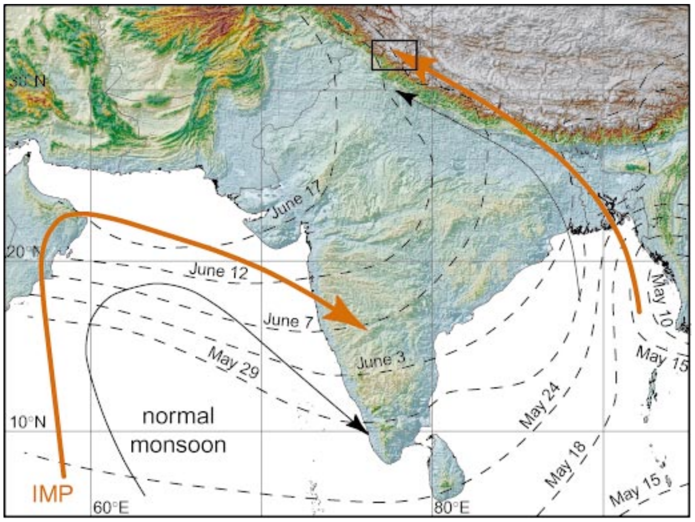

Figure 1. Main wind directions during Indian summer monsoon (southwest monsoon). Thin black arrows indicate present-day, weak monsoonal wind directions. Bold orange arrows show prevailing wind directions of strong monsoon inferred to represent intensified monsoon phases (IMP) during late Pleistocene and Holocene. Dashed lines depict temporal evolution of Indian summer monsoon and its northwestward propagation. Dates of rainfall onset are compiled from passive-microwave satellite observation and rain-gauge measurements (Bookhagen et al., 2005; Hastenrath, 1994; Parthasarathy et al., 1992). Black box outlines Sutlej Valley region (Fig. 2).

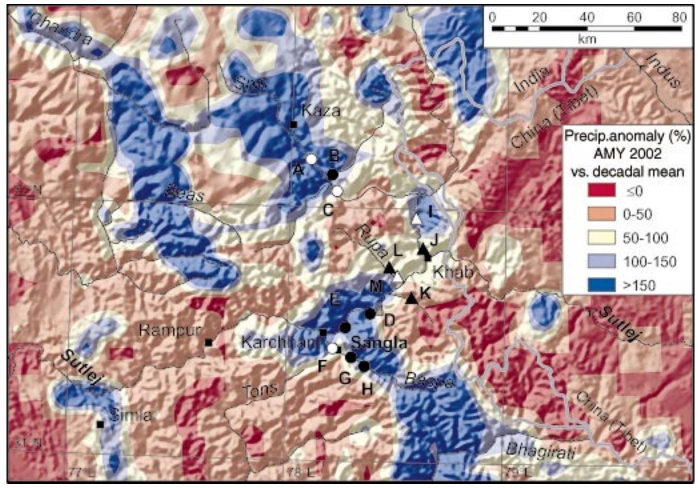

Figure 2. Precipitation anomalies draped over shaded relief of Sutlej Valley region. Topography based on GTOPO30 (U.S. Geological Survey) and precipitation anomalies from 10 yr record of passive microwave data (Bookhagen et al., 2005). Precipitation anomaly map (in percent) depicts magnitude changes between decadal mean (1992–2001) and abnormal monsoon year (AMY; i.e., strengthened monsoon intensity) in 2002. Positive anomalies (blue) show more rain during 2002 AMY, i.e., 100% anomaly represents doubling of precipitation. During AMY, moist air masses penetrate northeastward into orogen through Beas, Chandra, and Bhagirati Valleys and generate high amounts of precipitation in commonly dry areas of Spiti, Baspa, and Sutlej Valleys. Locations of late Pleistocene (triangles) and Holocene (circles) landslides and lacustrine sediments are shown; white symbols indicate radiocarbon-dated deposits, and black symbols denote landslides and their related lacustrine sediments dated by stratigraphic correlation. Letters indicate landslides and associated lacustrine deposits for which more detailed information is available (Table DR1; see footnote 1 in text).

topographic maps and orthorectified ASTER satellite images. The quality of the digitized and ASTER-derived DEM was tested against elevation measurements by differential global positioning system and altimeter readings and yielded consistent results. Prelandslide topography and stream gradients were reconstructed by removing landslide deposits from the DEMs and connecting upstream and downstream channel sections by a simple river profile. The uncertainties introduced by this method are small, because the reconstructed topography in the steep and narrow bottom parts of the landslide-dammed valleys leads to insignificant differences in the paleolake volume calculations. We assume that sedimentation rates of landslide-dammed lakes represent upstream denudation rates, whereas all fluvially transported material is being deposited in the lake basin. Multiple landslides in single drainage basins strongly affect catchment areas upstream of landslide dams. For example, three Holocene landslide deposits in the Baspa Valley truncate each other (Fig. 2). Hence, mean basin-erosion rates derived from lake-sedimentation rates were adjusted for smaller river catchment areas. Present-day summer monsoon precipitation distribution was derived from 10 yr of passive microwave data (Special Sensor Microwave/Imager) (Bookhagen et al., 2005).

INTENSIFIED MONSOON PHASES

The intensified monsoon phases in the northwest Himalaya may be the result of orbital and/or terrestrial forcing by intensifying the monsoonal circulation through a steeper ocean-land thermal gradient (e.g., Clemens et al., 1991; Hastenrath, 1994). This provides greater moisture transport into the continent and also increases precipitation leeward of orographic barriers, when rainfall increases abruptly once it has overcome the moisture-saturation threshold (Bookhagen et al., 2005). Consequently, in the dry, high-elevation sectors of the Sutlej Valley region enhanced rainfall may lead to significant changes in erosional surface processes.

Late Pleistocene (ca. 29–24 ka) and Holocene (ca. 9–4 ka) intensified monsoon phases were previously identified by several authors (Fig. 3). For example, in the northwest Himalaya, Tibet, and south China, numerous lacustrine deposits indicate humid intervals between ca. 29 and 25 ka (e.g., Fang, 1991; Kotlia et al., 2000) as well as during the Holocene (e.g., Gasse et al., 1991). In addition, marine records covering these two periods document enhanced terrigenous input and monsoon-related increased upwelling off the west coast of India (e.g., Prins and Postma, 2000; Thamban et al., 2002); increased sedimentation rates during the Holocene intensified monsoon phase are also known from the Bay of Bengal (Goodbred and Kuehl, 2000). Humid conditions related to a strong southwest monsoon have been inferred (e.g., Phillips et al., 2000) from the expansion of glaciers in the Nanga Parbat regions during the early to middle Holocene. Increased moisture transport during the late Pleistocene and Holocene has also been reported for the southern tip of the Arabian Peninsula (e.g., Bray and Stokes, 2003; Fleitmann et al., 2003). Although the intensified monsoon phases are well documented, processes and rates of erosion and sediment production, as well as the role of transient sediment storage in fluvial systems, remain largely unknown for these intervals of increased humidity.

LANDSLIDES AND LAKE SEDIMENTS

In the Sutlej Valley region, 13 large landslide deposits (>0.5 km^3) and lacustrine sediments constitute the vestige of enhanced hillslope erosion and valley impoundment during intensified monsoon phases in late Pleistocene (at or after 28.8 ka) and Holocene (8.8–4 ka) time (Table DR1; see footnote 1). Field observations, radiometric dating, and stratigraphic and geomorphic correlations allow reconstruction of paleolake surfaces, landslide volumes, and the temporal evolution of sedimentation and erosion.

The Holocene Kuppa (Baspa Valley) and Sichling (Spiti Valley) lake deposits behind former landslide barriers (Fig. 2 and Table DR1 [see footnote 1]) are well suited for an assessment of process rates in

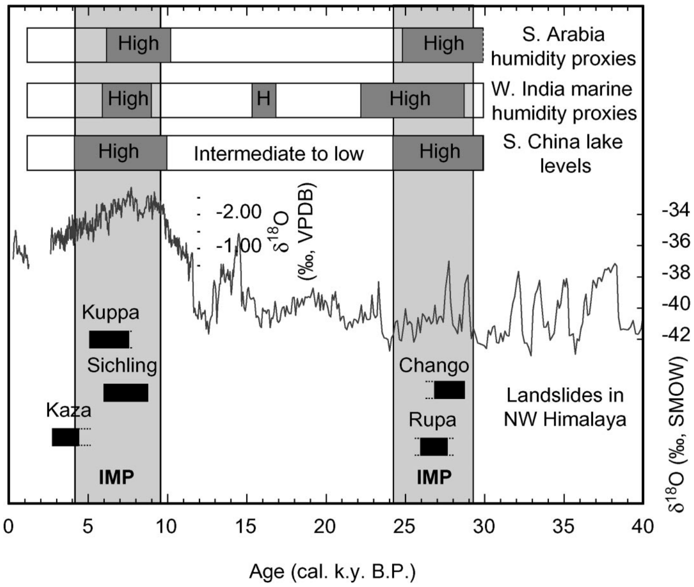

Figure 3. Late Pleistocene and middle Holocene intensified monsoon phases (IMPs). Information on $\delta^{18}O$ measurements (VPDB—Vienna Peedee belemnite; SMOW—standard mean ocean water) is merged from GISP2 (Greenland Ice Sheet Project, 1997) and high-resolution Holocene speleothem data from southern Arabian Peninsula (Fleitmann et al., 2003). Speleothem data indicate strengthened southwest monsoon during late to middle Holocene. Multiple past humid phases in desert of southern Arabia (S. Arabia humidity proxies) show two distinctive wet intervals (Bray and Stokes, 2004). Humidity proxies from north and east Arabian Sea (W. India marine humidity proxies) show intensified summer monsoons (Prins and Postma, 2000; Thamban et al., 2002). Independently derived chronologies of humid phases in adjacent areas (S. China lake levels) from lake highstands and pollen records emphasize regional importance of these humid intervals (e.g., Fang, 1991; Gasse et al., 1991). Black boxes mark existence of landslide-dammed lakes in greater Sutlej Valley region; black lines outside boxes signify age uncertainties (Table DR1; see footnote 1 in text).

this region. Sedimentation rates for the Kuppa landslide are based on 2370 ± 86 yr of lake existence, catchment area upstream of the landslide (115 km^2), reconstructed area of the paleolake (5.6 km^2), and the volume of associated deposits (~1.15×10^9 m^3). Borehole data (Jaiprakash Ltd., 2002, personal commun.) indicate that an additional 50 m of organic material underlies the currently exposed lake sediments. We associate this layer with deposition immediately after landsliding, when riparian vegetation and plants from the hillslopes were deposited in the newly formed basins. This undated but short time period constitutes <5% of the total lake sediment volume. The lacustrine strata comprise clay-rich layers and irregular intercalations of fine-sand layers, 1–6 mm and 1–3 mm thick, respectively. In the proximal parts of the basin, interfingering coarse alluvial-fan sediments document a dynamic, more erosive environment than today, in which large alluvial fans grew with rising lake level. The highest fan elevation always coincides with the highest lake level, so it can be inferred that the landslide barriers were higher or at least as high as these deposits. Similarly, calculations for the Sichling landslide are based on 2550 ± 80 yr of lake existence, 1372 km^2 catchment area, and a paleolake sediment volume and area of ~1.6×10^9 m^3 and 4.7 km^2, respectively.

During the Holocene intensified monsoon phase, basin denudation rates for the duration of the lakes were 4.3 ± 0.4 mm/yr for the Kuppa landslide and ~0.5 ± 0.05 mm/yr for Sichling. Where available, we compared present-day suspended-sediment measurements and Holocene sediment infill in the Baspa and Spiti Valleys. Modern mean basin denudation rates at Kuppa are 0.7 mm/yr during normal monsoon seasons and increase to 1.6 mm/yr during abnormal (i.e., strengthened) monsoon years (Bookhagen et al., 2005). Hence, intensified monsoon phase basin erosion rates are at least five times greater than the average modern rate and more than twice as large as rates during abnormal monsoon years. In the more arid Spiti Valley (Sichling landslide), intensified monsoon phase mean basin denudation rates are six times greater than present rates, ~0.08 mm/yr.

DISCUSSION

Under present conditions, there is a clear relationship between abnormal (i.e., strengthened) monsoon years, northward moisture penetration into the arid parts of the orogen, and enhanced surface-process rates (Bookhagen et al., 2005). Although these observations only constrain the relationship between precipitation distribution and surface processes in the Sutlej Valley region, coeval phenomena are documented for other areas in the northwest Himalaya as well (e.g., Barnard et al., 2001; Paul et al., 2000). These data suggest that episodic moisture transport into the arid sectors of the orogen is also a fundamental process on longer time scales acting along the southern flank of the orogen (e.g., Goodbred and Kuehl, 2000; Pratt et al., 2002). The present-day process of spatially shifting precipitation patterns may thus serve as a model for explaining higher rainfall, increased runoff, and enhanced sediment production in the arid sectors during intensified monsoon phases in the late Pleistocene and Holocene.

The steep hillslopes in the arid, high-elevation parts of the northwest Himalaya are sparsely vegetated, and during abnormal monsoon years, enhanced precipitation controls shallow hillslope erosion (Bookhagen et al., 2005). However, during longer-lasting intensified monsoon phases, the increased pore-water pressure, enhanced sediment flux, and higher frequency of flood events are expected to have created favorable conditions for deep-seated landsliding. It is important to note that studies relating the influence of extreme climatic events to erosion rates in river basins similar in size to the Spiti and Baspa tributaries document channel widening rather than incision during extreme floods (e.g., Hartshorn et al., 2002). In fact, modeling studies and field observations show that increased runoff and sediment transport result in lateral scouring, undercutting, and subsequent oversteepening of hillslopes (e.g., Hancock and Anderson, 2002). We thus posit that, if such humid conditions were sustained over several millennia, as during an intensified monsoon phase, enhanced precipitation would have led to higher pore pressures, increased lateral scouring, and hillslope instability. Ultimately, these processes may have caused exceptionally large bedrock landslides that are not triggered under present conditions. After the establishment of voluminous landslide barriers, material stripped off hillslopes was stored in these transient basins, before the material was eroded again during ensuing times of lower climatic variability with reduced rainfall and sediment flux.

Analogous observations relating humid phases and landslide triggering in the southwestern United States have been described (e.g., Dethier and Reneau, 1996). Alternatively, it could be argued that massive landsliding may have been triggered by seismicity (e.g., Keefer, 1994). However, despite active seismicity in the Himalaya, these events apparently only play a minor role in supplying increased sediment amounts to rivers in regions with strong monsoon seasons (e.g., Barnard et al., 2001; Owen et al., 1996; Paul et al., 2000).

In summary, our data show that higher precipitation is coupled with increased mass wasting and significantly higher sediment flux during intensified monsoon phases in the currently arid, high-elevation regions of the northwest Himalaya. The large landslides and associated lake deposits therefore constitute the vestige of enhanced hillslope erosion and valley impoundment during phases of increased humidity (Fig. 3). It is interesting to note that the mass movements not only cluster in time, but also in space. Large landslide deposits occur in the semiarid to arid climatic transition zone that receives increased precipitation only during abnormal (i.e., strengthened) monsoon years (Fig. 2).

CONCLUSIONS

We temporally linked intensified monsoon phases with the occurrence of large landslides and documented a strong influence of long-lasting, intensified monsoon circulations on landscape evolution. During intensified monsoon phases in late Pleistocene and Holocene time, moisture migrated into the high arid parts of the northwest Himalaya and dramatically enhanced the sediment flux compared to present-day weaker monsoon conditions. The corresponding increase in averaged basin-erosion rates during these episodes was linked to increased precipitation and the amount of material stripped off the hillslopes. Increased moisture migration is expected to have raised pore pressures along the poorly vegetated hillslopes, eventually leading to massive landsliding in the high-elevation sectors of the orogen. Thus, enhanced sediment evacuation toward the Himalayan foreland and the formation of transient basins are strongly controlled by higher climatic variability during intensified monsoon phases and lead to fundamentally different geomorphic transport and erosion processes. The causative relationship between wetter climate and landsliding explains the absence of large mass movements in the arid, high-elevation regions under both present conditions and during the weak summer-monsoon phases of the Last Glacial Maximum. Thus, the locations of these exceptionally large landslides might serve as a proxy for paleomoisture migration in the interior part of the Himalayas.

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