Int J Earth Sci (Geol Rundsch) (2008) 97:179–192
DOI 10.1007/s00531-006-0164-9

ORIGINAL PAPER

Channelized and hillslope sediment transport and the geomorphology of mountain belts

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Received: 22 April 2005 / Accepted: 2 November 2006 / Published online: 26 January 2007

Abstract This paper uses the results of landscape evolution models and morphometric data from the Andes of northern Peru and the eastern Swiss Alps to illustrate how the ratio between sediment transport on hillslopes and in channels influences landscape and channel network morphologies and dynamics. The headwaters of fluvial- and debris-flow-dominated systems (channelized processes) are characterized by rough, high-relief, highly incised surfaces which contain a dense and hence a closely spaced channel network. Also, these systems tend to respond rapidly to modifications in external forcing (e.g., rock uplift and/or precipitation). This is the case because the high channel density results in a high bulk diffusivity. In contrast, headwaters where landsliding is an important sediment source are characterized by a low channel density and by rather straight and unstable channels. In addition, the topographies are generally smooth. The low channel density then results in a relatively low bulk diffusivity. As a consequence, response times are greater in headwaters of landslide-dominated systems than in highly dissected drainages. The Peruvian and Swiss case studies show how regional differences in climate and the litho-tectonic architecture potentially exert contrasting controls on the relative importance of channelized versus hillslope processes and thus on the overall geomorphometry. Specifically, the Peruvian example illustrates to what extent the storminess of climate has influenced production and transport of sediment on hillslopes and in channels, and how these differences are seen in the morphometry of the landscape. The Swiss example shows how the bedding orientation of the bedrock drives channelized and hillslope processes to contrasting extents, and how these differences are mirrored in the landscape.

Keywords Geomorphology · River network · Modeling · Alps · Andes

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Introduction

It is generally accepted that except from glacial erosion, long-term erosional processes result in the formation of landscapes that consist of channels and adjacent hillslopes (Fig. 1). They form a branched network in the headwaters of drainage basins, and a predominantly linear geometry farther downstream in the trunk stream segment. The channelized nature of erosion and sediment transport comprises fluvial processes and debris flows. Erosion and sediment transport by fluvial processes occurs if critical flow strengths are exceeded (e.g., Tucker and Slingerland 1997). In contrast, sediment is transported as debris flows if slopes and pore pressures surpass specific thresholds. This situation is frequently observed in headwaters of drainage systems (e.g., Benda 2003). Also, channelized processes are considered to roughen the topography by incision due to the strong dependence on runoff and runoff variabilities. The hillslope component of erosion and sediment transport includes soil creep that is often referred to as hillslope diffusion in modeling studies (e.g., Tucker and Slingerland 1994, 1996, 1997),

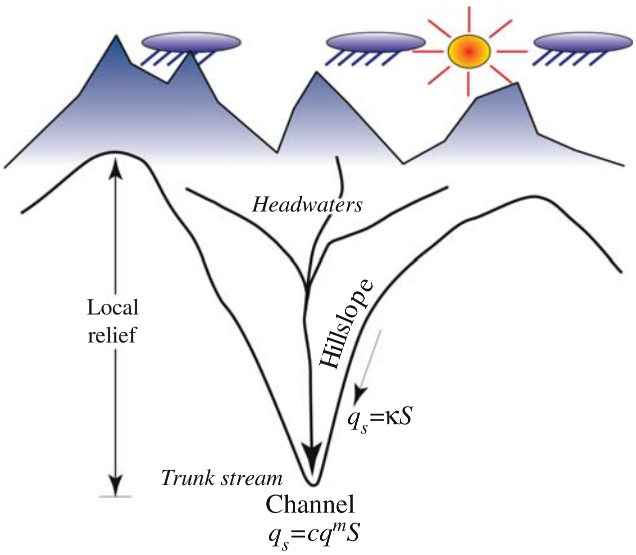

Fig. 1 Conceptual overview of most important landforming processes. Equations relate sediment flux in channels (q_s) to local slope (S), water discharge (q), and the channelized transport coefficient (c). Note that m is a power law exponent quantifying the dependency of sediment transport on fluid discharge. On the hillslopes, sediment flux (q_s) is proportional to the local slope (S) and the hillslope diffusivity (κ). Modified after Schlunegger and Hinderer (2003)

overland flow (unchannelized) erosion and landsliding if critical values for slopes and/or pore pressures are exceeded (Anderson 1994). Landslides are likely to be triggered by earthquakes and/or storm events. In contrast to processes in channels, erosion and sediment transport on hillslopes tend to fill depressions and smooth topographies thereby resulting in a reduction in the topographic roughness and relief. Despite these general agreements, little detailed research has been carried out on the important aspects about the coupling that exists between hillslope and channel processes (see, however, Tucker and Bras 1998).

This paper explores how, and at which scale, hillslope processes and especially landsliding influence the development of landscapes for long timescales (>100 Kys). Specifically, it discusses how the relative importance of channelized versus hillslope sediment transport and erosion influences the formation of landscapes, the channel density, the spacing between channels, and possibly the sediment flux. This topic will be addressed to the mountainous landscape of the headwaters of the Piura drainage basin in northern Peru at 5°S latitude and to the eastern Swiss Alps. Specifically, this paper presents morphometric data to identify the various components of the sediment routing system in these two example areas, and to interpret the relationships between the flux of mass in channels and on the adjacent hillslopes. These information will then be used to infer regional differences in the relative importance of channelized versus hillslope sediment transport, and to interpret the implications regarding the topographic evolution, sediment flux, and timescales. This second interpretative step will be guided by the results of landscape evolution models and by those of Simpson and Schlunegger (2003) model in particular.

We use the Peruvian and Swiss case studies because they show contrasting controls on the relative importance of channelized versus hillslope processes. Specifically, the Peruvian example will be used to illustrate how regional differences in the pattern of precipitation rates have influenced production and transport of sediment on hillslopes and in channels, and how these differences are seen in the morphometry of the landscape. The Swiss example will show how the bedding orientation of the bedrock drives channelized and hillslope processes to contrasting extents, and how these differences are mirrored in the landscape.

Motivation

As outlined above, it has been known that runoff in channels tends to roughen topography by channel incision due to the strong relationship between sediment flux and water discharge (Graf 1971). This generally linear process is counteracted by processes on hillslopes that tend to fill depressions and smooth topographies (Culling 1960). The occurrence of two competing classes of processes, one operating in channels causing positive feedback, and one being effective on hillslopes causing negative feedback, are recognized as minimum requirements to explain landscapes with an incised channel network and adjacent hillslope interfluves (Fig. 1). Note that this statement does not include landscapes formed by glacial processes. Despite this agreement, there are differences in interpretations of how and to what extent these two components drive the evolution of landscapes. Some researchers consider erosion and sediment transport in channels to exert the first-order control because these processes are anticipated to set the lower boundary conditions for geomorphic processes on the adjacent slopes (e.g., Whipple et al. 1999; and review article by Whipple 2004). Accordingly, increasing (or decreasing) rates of erosion in channels result in equivalent modifications in the local relief (Fig. 1) and, hence, in enhanced (or reduced) rates of erosion and sediment flux on the adjacent hillslopes. The conclusions by Whipple (2004), however, requires that sediment flux in channels is supply-limited, i.e., that sediment flux is lower than the channel transport capacity (Schlunegger and Schneider 2005). In the case where sediment flux is transport-limited, however, hillslope processes potentially exert a substantial influence on the evolution of channel morphologies and mountainous landscapes in general (Hovius et al. 1998). For instance, based on detailed studies carried out in the Andes of Northern Chile, Strasser and Schlunegger (2005) found that hillslope mass wasting at channel heads govern the mode of drainage basin modification as well as channel densities. Finally, it is also possible that the predominant control on sediment transport (i.e., channelized versus hillslope processes) depends on whether or not mountainous drainage basins undergo active tectonics. Specifically, sediment flux in tectonically active drainage basins might be governed by channelized processes. In contrast, hillslope processes possibly drive sediment flux in low-gradient landscapes that experience tectonic quiescence.

The bottom line of the open issues addressed above is the question whether mobile hillslopes have the potential to suppress the formation of channels and thus reduce the degree of dissection and the channel density, and at what scale this suppression might occur. This issue will be discussed in more detail in this paper.

Methods

The question of how and to what extent hillslope mobility influence the topographic development of landscapes is addressed here by studying the morphology of (1) the Piura drainage basin at 5°S latitude and (2) the headwaters of the Rhine river located in the eastern Swiss Alps. These two examples are selected because they illustrate how contrasting climate and lithological conditions drive hillslope and channelized processes to different extents, and how these contrasts are seen in the landscape. This requires the calculation of morphometric parameters in order to identify the nature of processes in channels and on hillslopes, and needs a conceptual model to interpret the morphologies in terms of differences in the relative importance of channelized and hillslope processes.

Calculation of morphometric properties

Digital elevation models (DEM) that build the basis for morphological analyses are calculated using different sources. The DEM that is used for the Piura area has a horizontal resolution of 20 m. This model is based on several sources of remotely sensed datasets (Aerial photography ASTER, SRTM) and topographic lines, and was constructed using standard techniques in GIS and photogrammetry. The DEM was then subdivided into triangles connecting each cell node of the DEM. Hence, each group of three cells defines one triangle, and the total of all the triangles approximates the surface of the topography. The topographic slope is then the arc cosine of the ratio between the planimetric area and the area of this approximated surface. Areas with constant gradients indicate low topographic variabilities in these areas. The Peruvian DEM was combined with an ASTER-mosaic to yield a 3D view of the topography. The resulting image was then analyzed for topographic features [the courses and relative densities of valleys, the presence of scars indicating efficient erosion in channels, and the character of slopes (continuous dip, or change in dip angles, etc.)]. In addition, observations from the field allowed to confirm the interpretations of the remotely sensed datasets.

The analysis of morphology of the eastern Swiss Alps is based on morphometric parameters calculated on the base of the 25-m resolution DEM from the Swiss Topographic Survey (Swisstopo). Process rate on hillslopes are taken from a survey carried out by Noverraz et al. (1998). In addition, we performed a photogrammetric analysis of stereo images taken in 1956 and 2003 to quantify changes on hillslopes for regions where no survey measurements are available.

Landscape evolution model

The interpretation of the morphometric properties in terms of potential differences in the relative importance of channelized versus hillslope sediment transport in particular, and of implications regarding the topographic evolution, sediment flux, and timescales in general, requires the concepts provided by landscape evolution models. Various numerical landscape evolution models have been developed that have used equations describing processes on hillslopes and in channels (e.g., Ahnert 1987; Howard 1994). The concepts of these models were used to explore the evolution of landscapes in general (Slingerland et al. 1994; Kooi and Beaumont 1996; Tucker and Slingerland 1994; Braun and Sambridge 1997), the effect of climate and tectonics on the geomorphic development (Beaumont et al. 1992; Tucker and Slingerland 1996, 1997; Willett et al. 2001), the landscape self-organization (Rigon et al. 1994), and the coupling itself that possibly exists between hillslope and channel processes (Tucker and Bras 1998; Schlunegger 2002; Simpson and Schlunegger 2003).

From the theoretical investigations listed above, the Simpson and Schlunegger (2003) model was explicitly designed to explore questions concerning (1) the relative importance of channel and hillslope sediment transport on the development of landscapes and network morphologies, and on the timescales of landscape evolution, and (2) possible controls on the channel spacing and the branching behavior of channelized network systems in general. The Simpson and Schlunegger model is based on numerical solutions of equations that describe the conservation of surface water and sediment. These equations are combined with a simple transport law connecting the sediment flux to the local slope and water discharge, i.e.,

$$\frac{\delta h}{\delta t} = -\Delta(n q_s) \quad (1)$$

$$\Delta(nq) = \alpha \quad (2)$$

$$q_s = \kappa S + c q^m S \quad (3)$$

where h is the surface elevation, n is a unit vector directed down the surface gradient, S is the local slope of the surface, α is the effective rainfall, and q and q_s are the water and sediment discharge, respectively. In Eq. 3, κ is the hillslope diffusivity driving sediment flux on the hillslopes, c is the channel transport coefficient (Fig. 1), and m is a power law exponent quantifying the dependency of sediment transport on fluid discharge. The equations were solved using the finite element method on an irregular triangular mesh. Thus, the Simpson and Schlunegger (2003) model considers two sets of processes that are the minimum requirements to explain the formation of landscapes (Fig. 1): Processes that operate in channels where sediment flux depends on water discharge, the local slope and the channelized transport coefficient (second addend of Eq. 3), and processes on hillslopes where the sediment flux is proportional to the local surface gradient and the hillslope diffusivity (first addend of Eq. 3). Boundary conditions of this model comprise (1) a symmetrical ridge crest with zero water and sediment flux, (2) zero sediment and water flux normal to lateral boundaries, and (3) fixed topographic elevation at the slope base. These boundary conditions imply that the system is open with respect to transport of sediment and fluid.

Note that the model is based on the most simple assumptions of how surface processes can be treated, and its application needs to be justified. Specifically, it assumes that processes in channels is a transport-limited behavior that is linear in slope. Other models present formulations that consider detachment-limited incision and non-linear slope dependence (e.g., Anderson 1994; Tucker and Slingerland 1994, 1996, 1997 and many others). We justify the use of the simplest way to treat channelized processes based on two arguments. First, sediment flux is generally transport-limited in the studied systems where we see a strong control of hillslope processes on the drainage basin morphometry. Furthermore, results of previous studies that used a detachment-limited formulation of processes in channels and that aimed at exploring effects of slope/stream process interactions came to similar conclusions (see below, and van der Beek and Braun 1998). Consequently, the scope of this paper, i.e., the generic analysis of effects of various slope/stream process interactions does not really need a specific selection of the channel process formulation (i.e., transport-limited versus detachment-limited). Second, we justify the use of a linear relationship between channelized sediment flux and local slope because we are interested from a conceptual point of view of how the relative importance of channel and hillslope sediment transport drives the development of landscapes and network morphologies. This general consideration does not require a sophisticated model as developed by other researchers (see references above). Similarly, the hillslope processes are modeled here as a linear diffusion. Several authors showed that such a model is not able to reproduce landscapes controlled by landsliding (e.g., Anderson 1994; Densmore et al. 1998; Roering et al. 1999). However, similar to hillslope diffusion, landsliding can be considered as dispersive process operating on hillslopes that is not driven by the concentration of runoff. Therefore, considering the scope of this paper and the temporal scale (>100 Kys), it does not really matter whether hillslope processes are considered as stochastic (e.g., landsliding) or continuous process (diffusion). The effects of increasing process rates for both situations will be the same, i.e., mobile hillslopes tend to inhibit incision in channels.

Results

Numerical modeling

Simpson and Schlunegger (2003) identified a non-dimensional parameter D_e that combines the variables describing effective rainfall (α), the width of the drainage basin (L) as well as the hillslope diffusivity (κ), and the channelized transport coefficient (c):

$$D_e = \frac{c \alpha^m L^m}{\kappa} \quad (4)$$

This parameter D_e is a measure of the relative importance of channelized and hillslope sediment transport and erosion. Hence, large values of D_e imply that sediment transport is predominantly channelized. The model results imply that the formation of landscapes appears to depend to large extents on this ratio (Fig. 2). The predominance of channelized processes (high D_e) results in the establishment of landscapes that are characterized by rough, high-relief, highly incised surfaces, that contain a dense and hence closely spaced channel network and highly branched valleys. In contrast, landscapes resulting from low D_e-values are predicted to display smooth topographies, low relief, greater channel spacing, and less sinuous valleys. Furthermore, the model results imply that headwaters of fluvial- and debris-flow-dominated systems (i.e., high D_e) have short timescales within which the landscape responds to erosion (Simpson and Schlunegger 2003), i.e., they potentially respond quickly to external perturbations (such as climate and tectonic variabilities). In contrast, headwaters where hillslopes significantly contribute to the development of topographies (low D_e) display longer timescales within which they respond to erosion, i.e., these landscapes need significantly more time than the fluvial-dominated systems to adapt to changes in external forcing. Note that a similar approach was selected by van der Beek and Braun (1998). These authors defined a parameter *R* which expresses the relative efficiency of hillslope versus fluvial transport. Using this model, van der Beek and Braun found that the parameter *R* influences landscape form and the length scale over which the landscapes are self-affine. Note, however, that the original idea of considering the evolution of landscapes as a function of the relative importance between hillslope and channelized processes goes back to a publication by Kooi and Beaumont (1994).

Geomorphology of the Piura drainage basin

Description

The Piura drainage basin located in northern Peru comprises the headwaters in the Cordillera with a

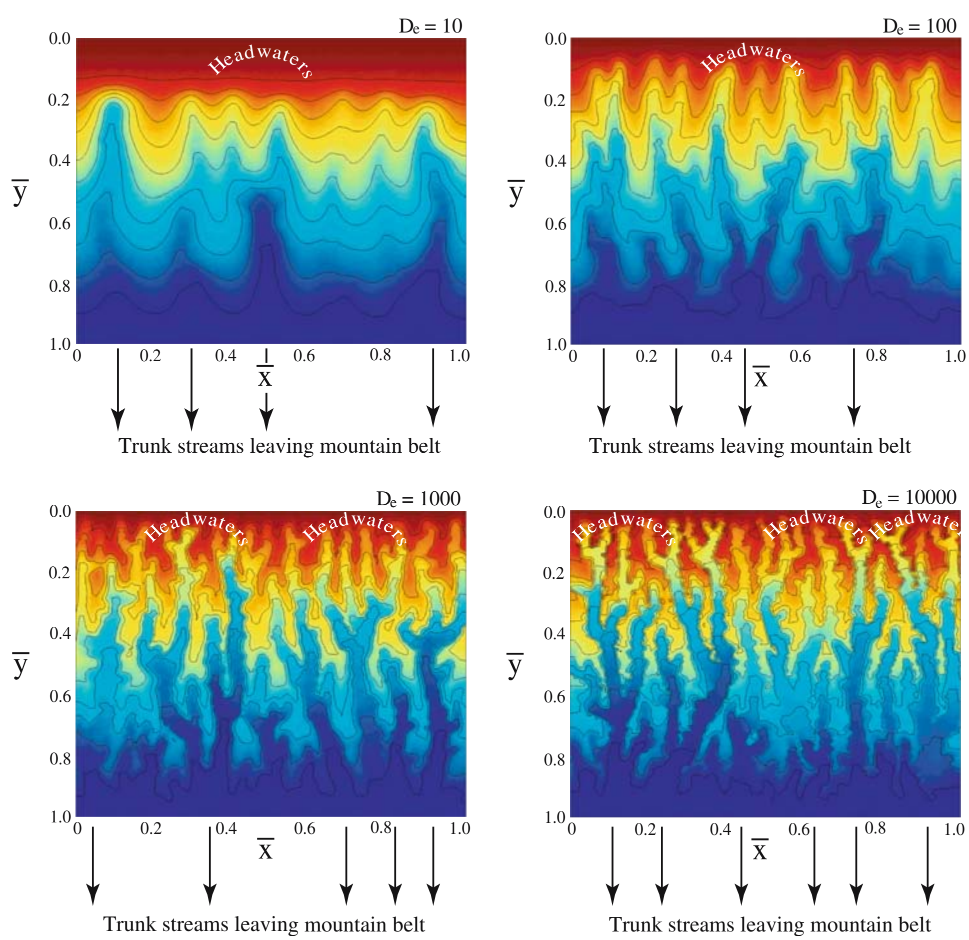

Fig. 2 Contour plots showing the influence of D_e on surface morphology in response to constant base level. The magnitude of erosion is 0.2 for all experiments. This value of erosion represents the total erosion which has taken place since the experiment was initiated. Thus an erosion of 0.0 represents the initial conditions (with an initial slope of 1/10 dipping toward the bottom of the page) whereas a value of 1.0 indicates the time when all the initial topography has been removed. Large values of D_e indicate that channelized processes dominate sediment transport, whereas for small D_e, hillslope sediment transport becomes more important. Note that relative elevations decay from the top to the bottom of the figures (modified from Simpson and Schlunegger 2003)

predominant transverse drainage, the axial drainage, and the mudflat with a terminal lake (La Niña) in the Sechura desert (Fig. 3). The headwaters that is the focus of this (Fig. 4) study is made up of three domains that differ in the nature of surface erosion and sediment transport, and in the drainage architecture. The area with the highest altitude is the Meseta located at 3,600 m above sea level (Fig. 4). It has a generally flat topography and is made up of a >10-m-thick cover of unconsolidated material that forms *m*-thick successions of amalgamated floodplain/paleosoil sequences. In some locations, the regolith is deeply dissected by gullies that are several meters deep. They are characterized by an abrupt upper termination with headscarps and funnel-shaped concavities with ca. 10–50 m wide diameters.

The second area comprises the segment between the Meseta and the city of Frias where discharge occurs to the southwest. There, the topography of the headwaters displays an amphitheatre-shaped concavity with diameters of ca. 5 km (Fig. 5). The upper termination of the headwaters is defined by a sharp scarp-line, which—at a smaller scale—is made up of coalescing concave geometries. The valleys and ridges that initiate at this boundary strike perpendicular to the scarp-line, resulting in a radial texture. In the headwaters, the magnitudes of topographic slopes are low (<20–30°), but they vary considerably within short distances (Fig. 6). High magnitudes of ca. 60° are calculated for the escarpment and for hillslopes bordering the trunk stream. Also in headwaters of the southwestern region, deeply dissected tributaries are absent, and the magnitudes of the local relief range between 100 and 200 m (which is substantially lower than in northeastern region, see below and Fig. 4). First evidence of deeply dissected channels is seen at ca. 8 km distance from the headwaters (Fig. 4). In this region, almost all hillslopes and channels are covered by unconsolidated sediment.

The third region is characterized by a northeast-directed dispersion. In this area, amphitheatre-shaped concavities (that are indicative of landsliding, see below) are completely absent. There, the drainage basin is made up of a high-density channel network that is highly branched (Fig. 4), and the topographic slopes are substantially higher than on the southwestern side. Interestingly, the hillslopes reveal nearly constant slopes with angular lower contacts to the valley floor (Fig. 6). Similarly, the magnitudes of the local relief are substantially higher than on the southwestern side and generally exceed 200–300 m (Fig. 4).

The bedrock geology of the area is mainly homogeneous and comprises Cretaceous granitic intrusive rocks that are overlain by Tertiary volcanic rocks (Cobbing et al. 1981). Climate shows contrasting differences between the Meseta and the northeast-directed drainage basin and the southwest-oriented headwaters. Specifically, in the former region precipitation falls annually during Bolivian Winter between January and March. In this case, moisture is carried by the easterlies, crossing the Amazon basin and releasing up to 1,300 mm per year in the Cordillera at ca. 3,500 m above sea level. Precipitation rates then decrease to 0 farther west toward the Sechura desert close to the Pacific. In contrast, the southwest-directed

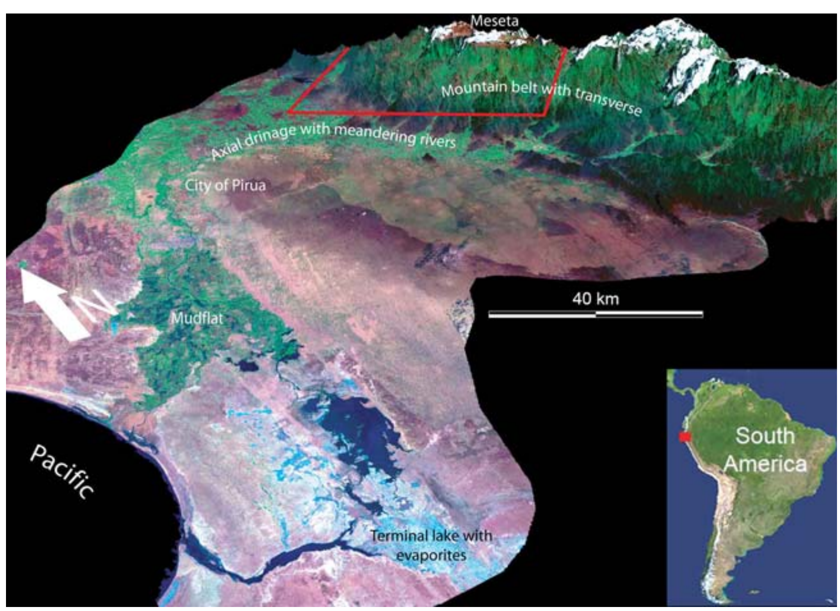

Fig. 3 Three-dimensional overview of the Piura drainage basin, northern Peru. Landsat ETM+7, US Geological Survey (1993–2000). The *red lines* mark the limit of Fig. 4. Elevation model, US Geological Survey (2006). Source for this dataset was the Global Land Cover Facility

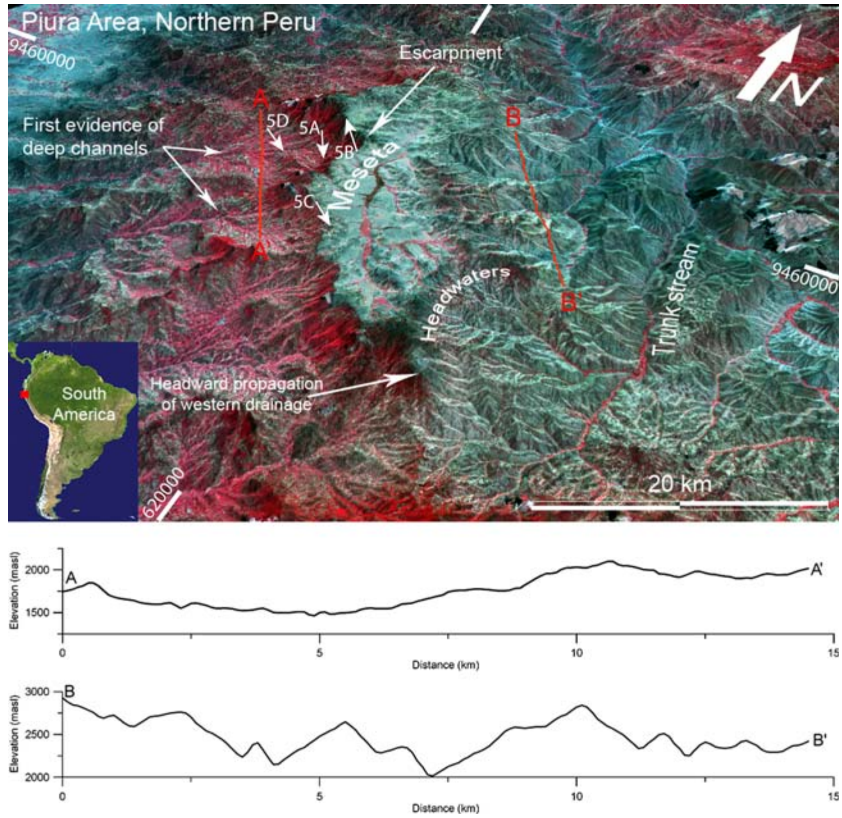

Fig. 4 ASTER mosaic-scene of the Andes of northern Peru (**a**). The Meseta is located at an elevation of ca. 3,600 m above sea level. *Small arrows* show the location and direction of photos in Fig. 5. Note the difference in morphometry between the western and eastern drainages

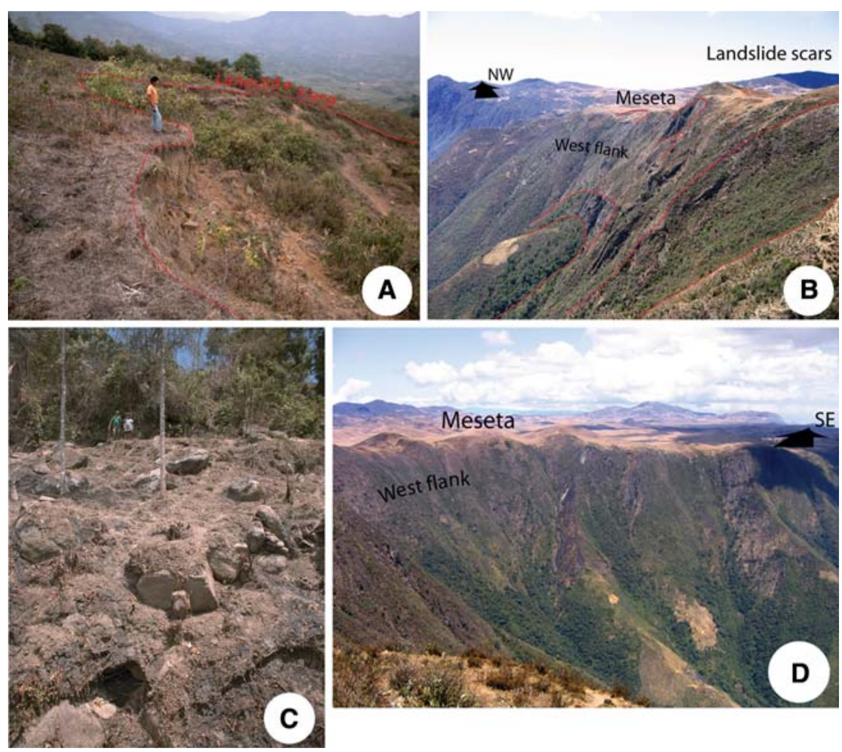

Fig. 5 Photos from the Andes of northern Peru showing **a** scar in the landscape caused by landsliding, **b** several tens to hundreds of meters-long scar resulting from large landslide, **c** landslide deposits that will be re-mobilized by further landsliding, and **d** flat topography on Meseta. This latter surface was probably formed somewhere in the Palaeogene

drainage systems are strongly affected by highly episodic ENSO (Rasmusson and Carpenter 1982) events, releasing up to 4,000 mm of precipitation between January and March. This corresponds to an enhancement of precipitation rates by several orders of magnitude compared to non-ENSO years.

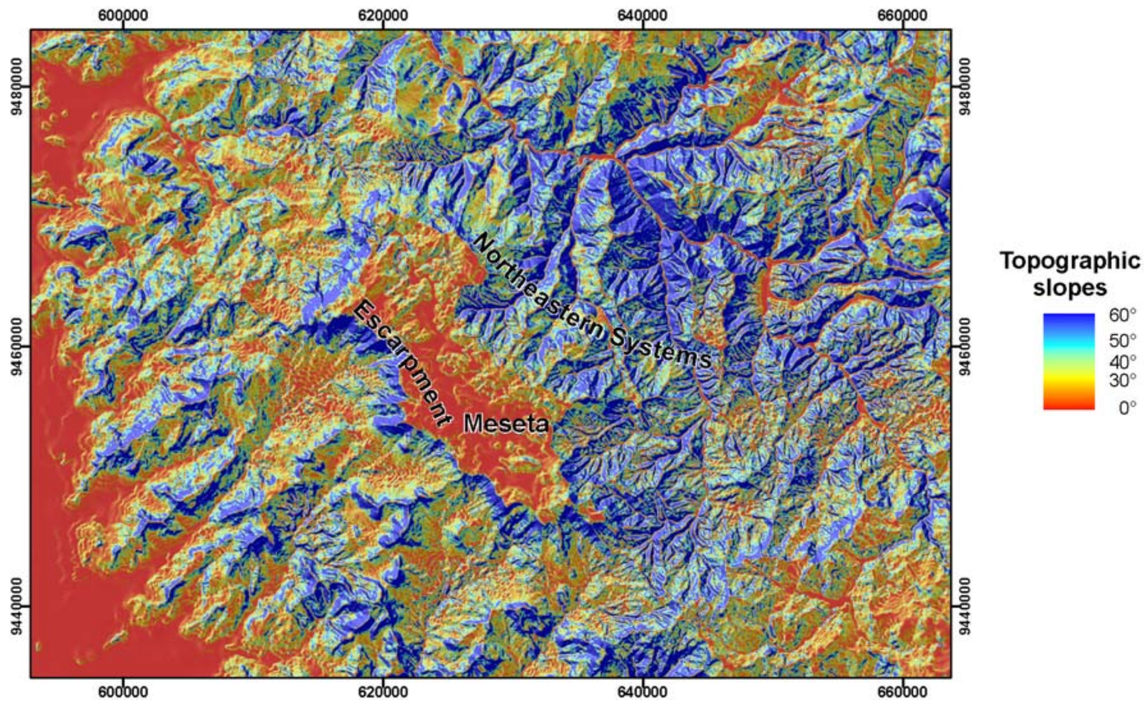

Fig. 6 Pattern of topographic slopes in the Andes of northern Peru. Projection, UTM Z17S WGS84

Interpretation

The Meseta appears to be a high-altitude low-relief platform where the sediment is dispersed within a closed system. This interpretation is supported by the presence of *m*-thick successions of amalgamated floodplain/paleosoil sequences, implying multiple phases of sediment accumulation and soil formation. Sediment transport appears to occur either by soil creep processes as indicated by the smooth shape of the hillslopes, or episocially by debris flows in gullies. The sharp upper terminations of these then suggest that headward propagation of the gullies occurs by groundwater sapping.

For the southwestern region, we interpret the amphitheatre-shaped concavity of the headwaters and the smaller coalescing concave geometries to have resulted from landsliding of different magnitudes (Fig. 4). We then consider the frequent occurrence of landsliding to explain the low extent of dissection and the low magnitudes of the local relief. This interpretation is supported by the results of the Simpson and Schlunegger model that suggest that landsliding (and a high hillslope mobility in general) tends to suppress the incision of channels and to deviate the course of existing channels. This also explains why the topographic slopes are high in the escarpment where landslides initiate, and generally low and highly variable over short distances in the depositional realm of the landslides. Furthermore, it implies that the drainage network of the headwaters has been unstable in the geologic past. Also, since landsliding controlled the courses of channels and influenced the extent of dissection, we interpret a down-slope flux of mass that exceeded the transport capacity of the channelized processes. This suggests a transport-limited sediment flux in the headwaters. Finally, because first evidence of deep dissection is seen at ca. 8 km distance from the headwaters (Fig. 4), we interpret that landsliding, and hillslope processes in general, have driven the evolution in the headwaters at a scale of at least several kilometers.

The situation is completely different in the headwaters of the northeastern region. There, the angular lower contacts of the hillslopes are interpreted to imply a balanced flux of mass between processes in channels and on the adjacent hillslopes. Specifically, sediment that is supplied from hillslopes to the bounding channels has been efficiently removed by processes in channels. In addition, the nearly constant and steep dip angles of the hillslopes imply that the hillslopes are most probably at the verge of mechanical failure. The findings that (1) channelized processes have efficiently removed sediment supplied by hillslope processes, and (2) sediment flux in channels is most likely supply-limited (e.g., model results of Tucker and Slingerland 1997) implies that channelized processes appear to have driven the topographic development in the geological past. The well-defined course of channels and the deeply dissected nature of valleys suggests the presence of a well-defined and therefore stable channel network (Fig. 4). Hence, in the northeastern area, hillslope processes drive the topographic evolution at the hillslope scale at most, which, in this case, is less than 1 km.

Geomorphology of the eastern Swiss Alps

Description

The eastern Swiss Alps between Ilanz and Lenzerheide are drained by the Rhein river that discharges toward the east thereby collecting the waters from four valleys that generally reveal a N-directed dispersion (Fig. 7). Each of these valleys shows contrasting differences in the morphometries between the east- and west-facing valley flanks. The east-facing sides have gentle slopes (16–30°), display a low topographic roughness, a low channel density, and a low extent of dissection (Fig. 8). Channels, if present, are mainly straight; they run parallel to the dip direction and reveal a poor degree of branching (Fig. 9). These hillslopes have been affected by large landslides that were already surveyed in detail in the late nineteenth century (Noverraz et al. 1998). Average horizontal displacements reach 1 m per year over a survey period of about 100 years (105 years for the Lumnezia landslide). In some locations, the trunk streams are redirected by the advection of hillslope-derived material. Note that in the valley located at the western border of the study area, landslide deposits are present on the opposite valley flank.

In contrast, on the west-facing valley flanks, no large-scale (>5 km^2) mass movements could be detected on the hillslopes after extensive field survey and a comparative photogrammetric analysis of aerial photographs taken in 1956 and 2003. There, the pro-

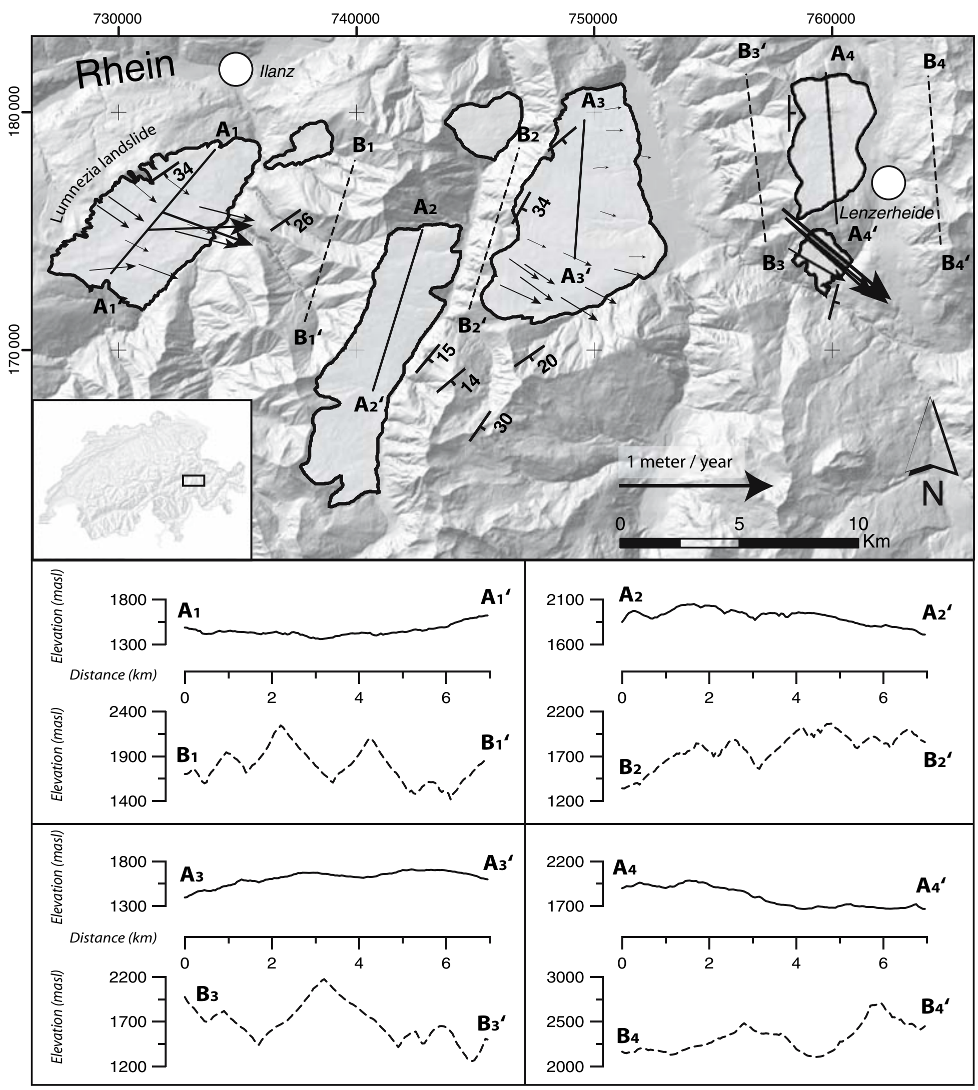

Fig. 7 Shaded relief of a digital elevation model showing a clipping of the topography of the eastern Swiss Alps and the locations of large landslides. Projection, CH1903 LV03

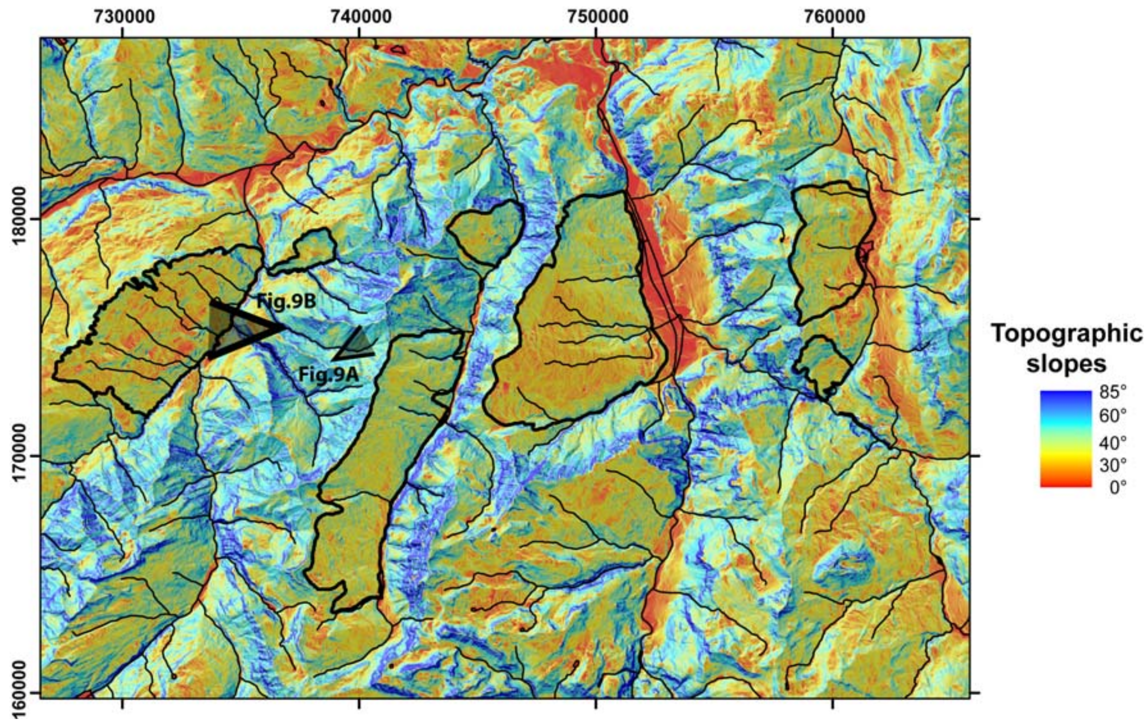

Fig. 8 Pattern of topographic slopes in the eastern Swiss Alps. Projection, CH1903 LV03

cesses operating on hillslopes include sediment production by weathering, soil creep, and rock avalanches (Fig. 9). The debris is then transported within a deeply incised and highly branched channel network by fluvial processes and debris flows. These channels expose the bedrock along most of their course, and some of them are deeply cut into a glacial morphology thereby forming inner-gorges that are bordered by up 30°-steep hillslopes with a planar geometry (Fig. 9). The comparison of the aerial photographs taken in 1956 and 2003 reveals a stable network of rills and channel that has not changed in location and depth of incision during this time span.

Precipitation rates are constant between the eastern and western valley flanks and reach magnitudes of up to 1,000 mm per year (Frei and Schär 1998). The underlaying geological architecture is made up of a suite of metacarbonates and a several 10^3-m thick sequence of highly erodible shales and arenites (Bündnerschits) that underlay most of the studied drainage basins (Spicher 1980). These latter units reveal a regional dip with dip-angles ranging from 15° to 35° and a dip-orientation that is oriented toward the southeast (Fig. 7). A succession of thrust faults duplicates the series from West to East and therefore contributes to the homogenous structural architecture of the underlying bedrock. This implies that the geometry of east-facing valley flanks reflects the regional dip-orientation of the underlying bedrock. In addition, the valleys were shaped extensively by a network of ice streams during the last (Würm) glaciation, above which protruded only the highest peaks. In some locations, hillslopes remain mantled by glacial tills several tens of meters thick.

Interpretation

We interpret that the differences in the topographic architecture between the east- and west-facing valley flanks reflect the contrasts in the relative importance of hillslope versus channelized processes. On the east-dipping valley flanks, enhanced slip rates of landslides appear to inhibit the establishment of a stable and therefore deeply dissected drainage network. In addition, the re-direction of trunk streams that has occurred in response to a high sediment discharge by landsliding implies that sediment flux has been to large extents transport-limited. Support for this interpretation is provided by the presence of landslide deposits on the opposite valley flank. This indicates that a presumably episodic event of enhanced slip rates of the landslides resulted in a down-slope flux of mass that exceeded that transport capacity of the trunk stream for a limited time interval. Ongoing incision into the landslide deposits allowed the trunk stream to re-establish a balanced situation between landsliding and

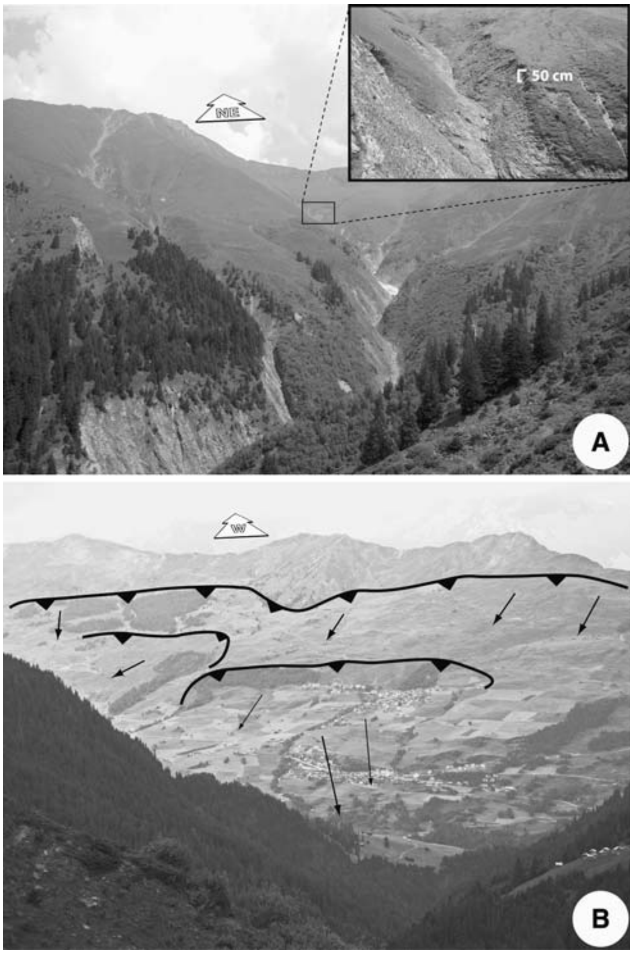

Fig. 9 Photos from the eastern Swiss Alps showing **a** highly dissected landscape, and **b** topography with large landslides (see Fig. 8 for location of photos)

export of mass. Such episodic events could have been triggered by earthquakes as was observed near Lenzerheide. Hence, on the east-facing valley flanks, processes on hillslopes and landsliding in particular have exerted a substantial control on the overall geomorphic development.

The situation is completely different on the west-facing valleys. There, the presence of inner gorges with planar hillslopes imply the presence of threshold hillslopes with process rates that reflect the passive adjustment of hillslopes to channelized processes. This implies that sediment flux has been supply-limited on most of the west-oriented valley flanks. In support of this interpretation are the presence of bedrock channels that reflect an efficient export of sediment. It appears, therefore, that the deeply dissected nature of the channel network, the high topographic roughness and the high degree of branching indicates a high relative importance of sediment transport and erosion in channels (see also model results). Here, processes in channels are considered to drive the overall geomorphic development.

Discussion

Importance of channelized and hillslope processes and the formation of landscapes

The comparison between the Piura northeastern and southwestern headwaters and the eastern Swiss valleys is interpreted here to reveal contrasting differences in the importance of hillslope mass wasting as sediment source. Specifically, we interpret that landscapes with low magnitudes of local relief and high spatial scales that were described for the southwest-directed catchments in Peru and the east-facing valleys in eastern Switzerland reflect a high importance of hillslope processes in relation to channelized sediment transport and erosion. This interpretation is consistent with the observation of abundant landslides in these regions and the results of numerical models. Specifically, the Simpson and Schlunegger model predicts that a high importance of hillslope processes relative to processes in channels results in the formation of landscapes with smooth topographies, low relief, greater channel spacing, and less branched valleys.

In contrast, the high extent of dissection as well as the stable and highly branched channel network that is found in headwaters on the northeastern side of the Meseta and on the west-oriented valleys in eastern Switzerland are considered to reflect a high importance of channelized processes in relation to sediment transport and erosion on hillslopes. This interpretation is consistent with the absence of large landslides and the results of numerical models. In particular, the Simpson and Schlunegger model produces landscapes with rough, high-relief, highly incised surfaces, that contain a dense and hence closely spaced channel network and highly branched valleys for model runs with high D_e-values. This corresponds to a high relative importance of channelized and hillslope sediment transport and erosion.

Note, however, that model was not designed to consider stochastic hillslope processes such as landslides or hillslope failure in general. Note also that linear diffusion model is not able to reproduce landscapes controlled by landsliding. Nevertheless, we justify the comparison between the Peruvian/Swiss landscapes and the results of the Simpson and Schlunegger model because this model predicts that the variations in topographic roughness, channel densities, and extent of dissection are an implicit function of the ration between fluxes of mass on hillslopes and in channels. Certainly, the concavity and overall shapes of landscapes are different whether down-slope flux of mass is accomplished by landsliding or diffusion. But for both situations the effect will be the same, and these are smooth topographies, low relief, greater channel spacing, and less branched valleys for catchments dominated by landsliding and diffusion.

Controls of climate and bedrock geology on the formation of landscapes

Here, we assign contrasting controls on the relative importance of channelized versus hillslope processes for the Peruvian and Swiss case studies. Specifically, the Peruvian example illustrates how regional differences in the pattern of precipitation rates have influenced production and transport of sediment on hillslopes and in channels and hence the morphometry of the landscape. The Swiss example shows how the dip-orientation of the bedrock drives channelized and hillslope processes to contrasting extents and illustrates how these contrasts have controlled the evolution of the landscape.

In the Piura area, hillslope processes were considered above to have been more efficient in driving the evolution of the southwestern than the northeastern tributaries. Since the bedrock geology is homogenous in this region, we do not assign a lithologic control on the differences in morphometric properties between these systems. Instead, we relate these differences to the specific climatic conditions in the area. Specifically, the rather stable seasonal pattern of precipitation in relation to the easterlies from the Atlantic tends to scale processes on hillslopes and in channels at equal magnitudes. As a result a stable network of channels and hillslopes has established. In contrast, in the southwestern tributaries, high magnitude precipitation events in relation to highly episodic ENSOs result in efficient export of sediment in the trunk channels. It appears that this efficiency in removal of sediment by channelized processes causes oversteepening of hillslopes in the headwaters, thereby promoting weathering and landsliding.

In the Swiss drainages, however, climate boundary conditions are homogenous. There, the differences in morphologies between east- and west-facing valley flanks are most likely controlled by the litho-tectonic architecture of the underlying bedrock. In particular, the homogenous succession of lithological series dip sub-parallel to the east-directed slopes, which, in turn, promotes hillslope instabilities and landsliding. This then provides an explanation for the transport-limited sediment flux on these hillslopes. On the opposite valley flanks, this structural setting stabilizes the hillslopes and results in the supply-limited nature of sediment flux.

Implications for drainage basin saturation times and response times

An important conclusion of the Simpson and Schlunegger model is that the magnitude of D_e exerts an important control on the dynamics of the landscape. Specifically, an increase in D_e results in a decrease in the timescale within which a landscape saturates, i.e., within which the channel network is completed. For instance, Simpson and Schlunegger (2003) calculated an increase of D_e by a factor of 10 decreases the response time for saturation by a factor of ~6. The reason for this negative relationships between saturation time and D_e-values lies in the higher channel density and hence in the higher bulk diffusivity for landscapes with a high relative importance of channelized versus hillslope sediment transport and erosion. In summary, an increase in channel densities results in shorter saturation times and also shorter response times of a catchment. Note that we are aware that the response time of landscapes dominate by landsliding might potentially be controlled by the landsliding response time, which then would depend on the stochasticity of the process, or in other words, how long supercritical slopes can be maintained. However, the Simpson and Schlunegger model predict that landscape response times are principally a function of the channel density, which, in turn, is controlled by the relative importance of hillslope versus channelized sediment transport. Therefore, for the scope of our study, we do not need to consider the stochasticity of landsliding for comparing the response times on the northeastern and southwestern systems in Peru, and on the west- and east-directed valley flanks in eastern Switzerland. Note also that the response times for fluvial, diffusive, and landsliding sediment transport (e.g., Anderson 1994) depend on a characteristic length-scale (diffusion quadratically, fluvial transport and landsliding linearly) and also depend on a transport parameter. Therefore one could not automatically say that landscapes with small drainage densities will have larger response times than those with larger drainage densities, because (1) this critically depends on the relative magnitudes for the transport parameters, and (2) the larger spatial scales on the hillslopes will be offset by shorter spatial scales in the river channels. However, the numerical experiments of Simpson and Schlunegger (2003) clearly showed that a high channel density is the ultimate result of a high relative importance of sediment transport in channels versus sediment mobilization on hillslopes, and that such a system has a short timescale of surface evolution.

As outlined above, headwaters where hillslope processes exert a substantial control on the long-term topographic development are characterized by relatively long spatial scales, and sediment flux tends to be transport-limited. In contrast, headwaters where the contribution of hillslope processes to the topographic development is moderate to low display relatively short spatial scales, and sediment flux is to large extent supply-limited. These latter landscapes, characterized by a high channel density, also have a relatively high bulk diffusivity of the system due to the abundance of channels (see above). Because of this high bulk diffusivity, we anticipate that these systems potentially adjust more rapidly to external perturbations than headwaters with, e.g., abundant landslides. Hence, we predict that any modification in the base level (due to, e.g., rock uplift) or precipitation rates will be transmitted within the highly dissected headwaters in relatively short time intervals. In contrast, the generally poorly developed drainage network of landslide-dominated headwaters has a low bulk diffusivity. As a result, these landscapes are predicted to require longer time spans to respond to modifications in external perturbations.

Conclusions

This paper outlines how the ratio of sediment transport on hillslopes to sediment transport in channels influences landscape and channel network morphologies and dynamics. This problem has been illustrated using published results of numerical models, and using two examples where differences in hillslope processes explains much of the landscape's morphometries and of difference in sediment production. The most important result of this paper is that the evolution of landscapes and the resulting morphometric properties (i.e., channel densities, topographic slopes, local relief, and temporal and spatial scales) significantly depend on the ratio between the relative strength of processes in channels to processes on hillslopes. Specifically, fluvial- and debris-flow-dominated systems are characterized by rough, high-relief, highly incised surfaces which contain a dense and hence a closely spaced channel network. These systems are characterized by short scales at which hillslope processes drive the topographic development of landscapes. Similarly, they tend to respond rapidly to modifications in external forcing. This is especially the case in headwaters where the channel density is high. In contrast, drainage systems where hillslope mass wasting is important to contribute to the overall sediment budget are characterized by a smooth topography with straight and relatively unstable channels.

The two case studies are located in northern Peru (Piura drainage basin) and in the eastern Swiss Alps (Rhein headwaters). Both examples show contrasting controls on sediment flux. The location and the displacement of the landslides in the Swiss valleys are directly linked to the litho-tectonic architecture of the area. For the Peruvian case, differences in the overall geomorphometry is strongly influenced by the climatic conditions which permit homogenous sediment production rates but presumably differences in sediment export rates.

Acknowledgment We thank the reviewers Peter van der Beek and one anonymous for their positive contributions. This paper benefited significantly from the fruitful discussions with G.Simpson (ETH Zürich). The project was supported by the Swiss National Science Foundation (SNSF) project 200021–100220.

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