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Contrasting sediment flux in Val Lumnezia (Graubünden, Eastern Swiss Alps), and implications for landscape development

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ABSTRACT

This paper presents qualitative estimates of sediment discharge from opposite valley flanks in the S–N-oriented Val Lumnezia, eastern Swiss Alps, and relates inferred differences in sediment flux to the litho-tectonic architecture of bedrock. The valley flank on the western side hosts the deep-seated Lumnezia landslide where an area of ca. 30 km^2 has experienced slip rates of several centimetres per year, potentially resulting in high sediment discharge to the trunk stream (i.e. the Glogn River). High slip rates have resulted in topographic changes that are detectable on aerial photographs and measurable with geodetic tools. In contrast, a network of tributary channels dissects the valley flank on the eastern side. There, an area of approximately 18 km^2 corresponding to <30% of the surface has experienced a change in the landscape mainly by rock avalanche and rock fall, and the magnitudes of changes are below the calibration limit of digital photogrammetry. We thus infer lower magnitudes of sediment discharge on the eastern tributaries than on the western valley side, where landsliding has been the predominant erosional process. These differences are interpreted to be controlled by the dip-slope situation of bedrock on the western side that favours down-slope slip of material.

Morphometric investigations reveal that the western valley side is characterized by a low topographic roughness because this valley flank has not been dissected by a channel network. It appears that high sediment discharge of the Lumnezia landslide has inhibited the establishment of a stable channel network and has largely controlled the overall evolution of the landscape. This contrasts to the general notion that channelized processes exert the first-order control on landscape evolution and formation of relief and needs to be considered in future studies about landscape architecture, drainage network and sediment discharge.

Introduction

It has been generally accepted that except for glaciated areas, mountainous landscapes have been shaped by surface erosion and sediment transport in channels and on hillslopes (e.g., Tucker & Slingerland 1997; Simpson & Schlunegger 2003). The channel network comprises bedrock (step-pool) channels, alluvial channels where the channel floor is covered by sediment, and debris flow channels (Whipple 2004). The nature of channelized sediment transport depends on the hydro-morphological properties of the catchment (runoff regime, channel slope gradient, drainage density, and rates and pattern of precipitation) (Tucker & Slingerland 1994; 1996; 1997). Erosion in channels occurs by abrasion resulting in the formation of smooth channel floors with streamline forms, and plucking which roughens the channels by quarrying out large boulders from the bedrock (Whipple 2004). Hillslope processes include soil creep, overland flow (unchannelized) erosion, landsliding, and rock failure (Anderson 1994), dominated by freezing and thawing in alpine environments. The relationships and particularly the connectivity between these two sets of processes, one operating on hillslopes leading to destruction of relief, and the other in channels resulting in dissection and formation of relief, controls the formation of landscapes with distinct morphometric characteristics (Harvey 2001; 2002). As illustrated by landscape evolution models, it is the proportion between sediment discharge on hillslopes and in channels that controls relief formation, response time and topographic roughness (Tucker & Slingerland 1997; van der Beek and Braun 1998; Simpson & Schlunegger 2003).

Contrasts between channelized and hillslope processes and inferred implications for the development of mountainous landscapes are illustrated here for the situation of the S–N-oriented Val Lumnezia, eastern Swiss Alps (Graubünden) (Fig. 1A). In this valley, the western valley flank (Fig. 1B) has gentle slopes, a low channel density and a low extent of dissection. In contrast,

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the eastern side of Val Lumnezia (Fig. 1C) is characterized by deeply dissected tributary valleys that host a highly branched channel network bordered by steep hillslopes (Korup & Schlunegger 2007). We will show that both sides contrast in the nature of modern surface erosion and sediment discharge, and that these differences can be explained by the tilt direction of the underlying bedrock. Data collection includes geomorphologic mapping in the field and on aerial photographs, geodetic surveying, and morphometric modelling.

Geographical and geological setting

The Glogn River (Fig. 1A) that is the trunk stream of the study area originates in the eastern Swiss Alps and discharges into the Rhein River at Ilanz. The western valley side dips towards the east at dip angles that range between 15° and 30° until the valley flank reaches the Glogn River, where slope angles exceed 30°. This valley side hosts the well-known Lumnezia landslide (Fig. 1B; Noverraz et al. 1998). The eastern side consists of several hundreds of meter deep incised tributary valleys that are from north to south the Val Riein, the Val Pitasch and the Val Uastg (Fig. 1A).

The Glogn and tributary valleys have been shaped by multiple phases of Alpine glaciation during the Pleistocene. This is particularly evident in the landscape of the eastern tributary valleys that have U-shaped cross-sectional geometries. These valleys are cut by >100 m-deep inner-gorges (Fig. 1C) that were either formed by Holocene fluvial and associated hillslope processes, or by subglacial fluvial bedrock incision during glacial time intervals (e.g., Korup & Schlunegger 2007)

The bedrock of the study area comprises suites of the poorly resistant Mesozoic units of the Bündnerschists (underlying the Lumnezia landslide) and the Misox zone (underlying the opposite valley flank). Both litho-tectonic units are made up of an alternation of metasandstones, quartzite beds, metacarbonates and marls. The thrust separating both units follows the course

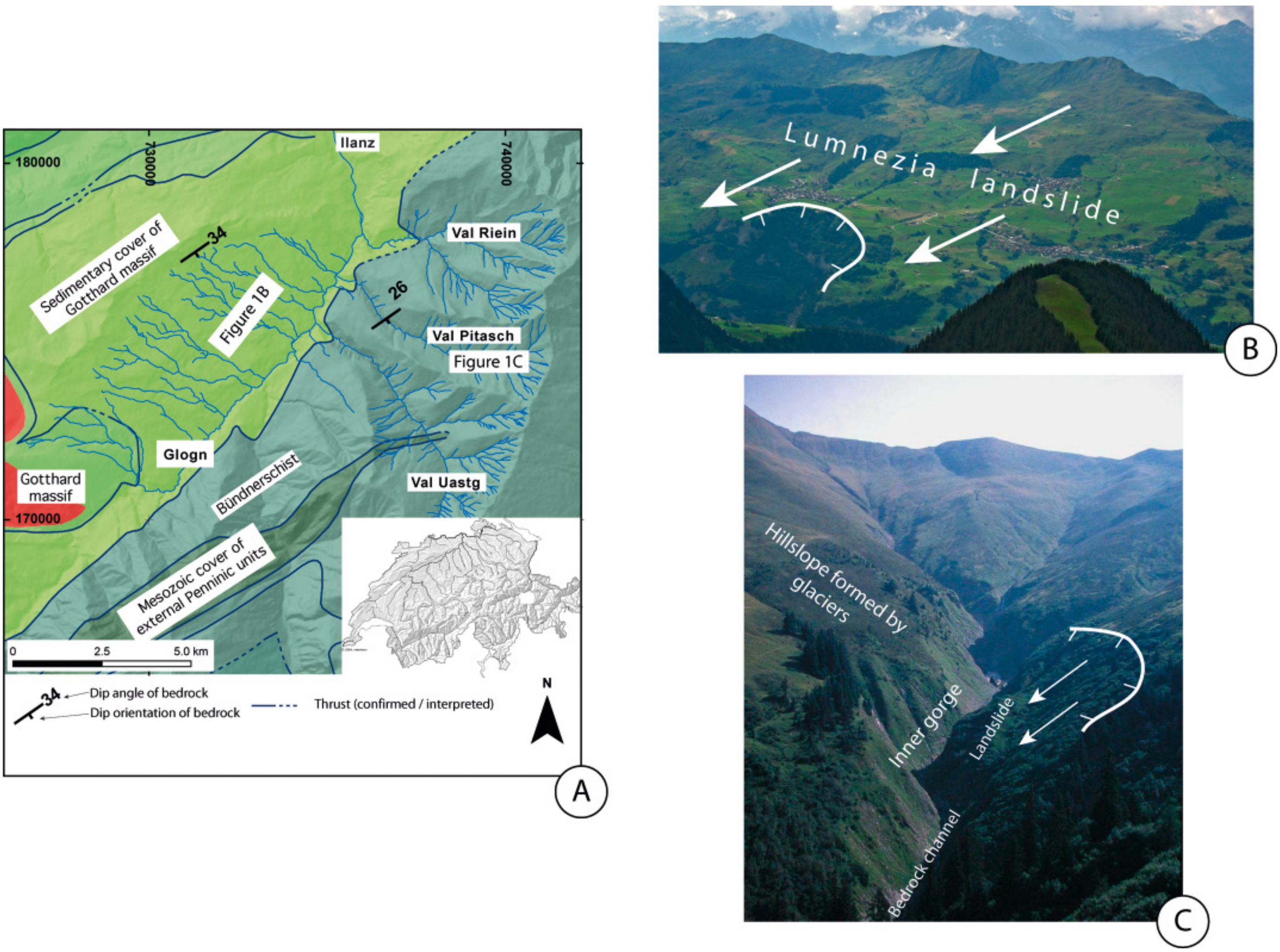


Fig. 1. (A) Geological map of the Lumnezia area, south of Ilanz. Source according to Spicher (1984). The inset shows the location of Val Lumnezia. The thrust between the Bündnerschists and the Mesozoic cover of the Gotthard Massif (Misox zone) runs parallel to the Glogn River. (B) and (C) are photos from the western and eastern valley sides. See text for further explanation. Reproduced with permission from Swisstopo (BA091200).

of the Glogn River and was mapped at the base of the Val Lumnezia (Fig. 1A). Both litho-tectonic units reveal a regional dip with dip-angles ranging from 25° to 35° and a dip-orientation that is oriented towards the southeast. This implies that the surface of the western valley flank parallels the bedding orientation of the underlying bedrock (dip-slope situation, Fig. 1A). The persistent dip orientation of the metasandstone-schist alternation is to large extents responsible for the presence of the Lumnezia landslide (Fig. 1B). Note that despite the differences in the litho-tectonic situation between western and eastern valley sides, the geotechnical properties (e.g., rock strength) are identical (Steinmann 1994), and differences in hillslope stabilities and inferred contrasts in mass flux on hillslopes only result from the intersection of the topography with the bedding orientation (see below, and Schneider et al. 2008).

The climatic conditions are dryer than in the adjacent Alpine regions of Switzerland (900–1350 mm y^{-1} in the study area, 2000 mm y^{-1} in the Swiss Alps on the average). This is the case because large portions of Graubünden lie in the rain shadow of the surrounding mountain chains (Frei & Schär 1998). Runoff measurements of the Glogn River at Ilanz show the typical profile of an Alpine river with discharge peaks in spring during snow melt and in late summer after heavy thunderstorms (Schädler & Weingartner 1992).

Methods

The relationships between bedding orientation, morphometry, and sediment discharge was reconstructed using a variety of methods including field mapping, qualitative estimation of sediment discharge by digital photogrammetry, compilation of data derived from geodetic surveys, and morphometric analyses.

Field mapping, and morphometric analyses

Data collection in the field was guided based on the concept that landscapes can be segregated into hillslopes and channels (Tucker & Slingerland 1997). Accordingly, during summer 2003, the area surrounding Val Riein, Val Pitasch and Val Uastg as well as in the lower part of the Lumnezia landslide was mapped in detail for the nature of erosion and sediment transport in channels (abrasion, plucking; Whipple 2004) and on hillslopes (hillslope creep, landsliding, rock failure; Anderson 1994). Special attention was focused towards exploring the landscape for potential sediment sources (Fig. 2) based on the mapping standards developed for natural hazard studies in Switzerland (Lateltin 1997). In addition, we explored the interface between hillslope and channelized processes using the concept of geomorphic connectivity (Harvey 2001; 2002, Brierley et al. 2006). According to this concept, hillslopes that are kinematically linked with channels are considered as being part of the hillslope-channel connected network. The geomorphic features that represent a connected system are then presented on the geomorphologic map (Fig. 3) as they have contributed to the formation of relief and transformation of sediment during the last decades. Our geomorphic map of the Lumnezia landslide was completed with data presented in the synthesis by Novarraz et al. (1998). Indeed, the Lumnezia landslide is one of the best-surveyed landslides in the Swiss Alps with measurements that started in 1887. This landslide was also mapped and analyzed by Ziegler (1982) and presented by Noverraz et al. (1998) as well as by Jäckli AG in the natural hazards cadastre of the area (Keusen et al. 2004).

The extraction of morphometric properties (Fig. 4) such as slope, relief and roughness was performed using classical GIS algorithms. We used the DHM25 of Swisstopo with a horizontal pixel resolution of 25 meters as basis. Roughness is calculated using the methods described by Jenness (2004). Specifically, the DHM25 was subdivided into triangles connecting each cell node. Hence, each group of three cells defines one triangle, and the total of all the triangles approximates the surface of the topography. The roughness is then the ratio between this approximated 3D surface and the 2D planimetric area. In addition, we calculated the mean topographic roughness and the standard deviation per catchment. Stream profiles are also extracted from the 25 m resolution DEM. Elevation points were sampled every 200 meters.

Orthophoto and geodetic surveys, and comparative estimates of sediment discharge

We used historical aerial photographs (Fig. 5) to digitally restore the topography at the time of photo acquisition. The oldest stereo-coverage of the Lumnezia region dates from 1956 and was performed by the Swiss Federal Office of Topography (Swisstopo). The image that we used for comparison was acquired in 2003. This was also the time when field mapping was carried out. Ground control points were measured in the field with a differential GPS. The camera calibration protocol from Swisstopo served to calculate orthophotos and to correct the aerial photographs for camera distortions. The digital data of the 1956 and 2003 photos with scales of approximately 1 :25'000 provided the basis for a stereo-model in order to directly compare the topography at different times. Note that we used the identical ground control points for both sets of photos in order to minimize possible systematic errors (e.g., relative tilts between the 1956 and 2003 stereo models; Schwab et al. 2008). For the Val Riein, the Val Pitasch and the Val Uastg, 3D stereoscopic devices were used to allocate the regions that experienced a topographic change between 1956 and 2003. Because in steep terrains the limit for the detection of vertical topographic changes by aerial photogrammetry is in the order of 1 m (that certainly is beyond the magnitude of erosion during this time span), it is not possible to yield quantitative information about sediment discharge (see Schwab et al. 2008, for discussion of resolution of digital photogrammetry). However, our approach will deliver a first order estimate of the proportion of the catchments that have delivered material during the past 49 years.

The survey of the Lumnezia landslide is probably one of the longest in time in the Swiss Alps. The first measurements

Fig. 2. Illustrations of the characteristic landforms leading to process interpretation. See Fig. 3 for location of photos. A: Shallow-seated landslide: only the superficial (>5 m) layer is mobilized. This occurs mostly on steep slopes at the border of inner gorges. Once the scar is open, sediment is regularly mobilized in response to precipitation. B: Headwater channel: The upper, ephemeral part has runoff mostly during snow melt. Accumulated material (e.g., by snow avalanche) is washed out in spring. In summer and autumn the exposed bedrock is subjected to plucking. C: Rock failure affecting the entire valley flank: It mobilizes sediment when episodic large-scale hillslope collapses occur. D: Rock failure on the sidewall of the inner gorge: These collapses initiate at the break-in-slope between the gorge and the U-shaped valley. They are episodic and thus difficult to quantify for sediment discharge. The mixed material (tree, regolith and blocks) accumulates in the trunk channel and can temporarily deviate the river course (see photo E). E: Accumulation of a mixture of wood, boulders and mud in the channel. This sediment will be transported as debris flows or as bedload by fluvial processes during flood stages. F: Situation in inner-gorge illustrating the variabilities in erosional processes during different runoff levels. G: Deep seated landslide: The deep movements of the Riein landslide are imperceptible; it is probably stabilized at the moment. Associated processes like rock failures or superficial landslides are still modifying the topography. H: Material transported during snow avalanches that transport sediment from normally decoupled adjacent hillslopes into the channel network. I: Lobate fabric of colluvium indicative of hillslope creep. J: Debris flow channel.

date from 1887. In this study, we used a synthesis of the data published by Noverraz et al. (1998) that also includes the synthesis by Ziegler (1982). Slip rates of the landslide were measured by the regional survey office (Amt für Landwirtschaft und Geoinformation) and survey campaigns of the Swiss Federal Institute of Technology Zürich (ETHZ). In these studies, displacements of fix points, church towers or houses were determined using total stations, and the displacement rates were then averaged over 30 years. Note, however, because the depth of the décollement of the Lumnezia landslide is not known with sufficient precision, and since data about depth profiles of slip rates are not available with adequate resolutions, a quantitative estimate of sediment discharge to the Glogn River is not possible. Nevertheless, the data about the relative proportions of hillslopes that have operated as sediment source (as presented in this paper) will provide a solid basis for comparing and contrasting the pattern of sediment discharge in relation to the litho-tectonic architecture of the bedrock, which is the scope of this paper.

Results

Field mapping, and morphometric analysis

The Lumnezia landslide is the largest slope instability in the area (Fig. 3) and covers an area of 30 km^2. According to Noverraz et al. (1998) the detachment lies at a depth of approximately 150 m. These authors also showed that this depth represents an average and increases from a few meters at the landslide head to approximately 250 meters its toe. The cumulative slip rates of the Lumnezia landslide allow the identification of two zones. The higher segment shows slip rates ranging from 2 to 10 cm y^{-1} (Fig. 6). The lower and steeper segment of the landslide, directly connected with the Glogn River, exhibits the highest slip rates, reaching in some parts 40 cm y^{-1}. Except for the interface between the landslide and the Glogn River, the slip rates have experienced little variations through time (Noverraz et al. 1998). Note that because the complete western slope has slipped at nearly constant rates towards the Glogn River, the whole Lumnezia landslide can be considered as connected with the trunk stream (Fig. 3).

The northern side of the Val Riein is characterized by the presence of an inactive landslide that is superimposed by shallow landslides and rock avalanches (Site I on Fig. 3, and Fig. 2G). The assignment to an inactive stage is based on a geodetic survey that revealed zero movements of geodetic control points at least during the past 10 years (Vermessungsamt Graubünden). Rock avalanches and shallow landslides have been responsible for most of sediment supply as evidenced by the presence of several-m-thick accumulations on the northern side of the channel (Fig. 2C). The thickness of the regolith cover generally ranges between 0.5 to 2 m, and steep slopes are subjected to rock avalanches and landslides especially in the headwaters (Site II on Fig. 3). Except for uppermost segments, where the steep slopes of the rills inhibit the storage of sediment, the channel floors are generally covered by several m-thick accumulations of boulders and pebbles embedded by a sandy matrix (Fig. 2E).

The Val Pitasch farther south is a typical U-shaped valley with a prominent inner gorge (e.g., Fig. 1C). Sediment derived from large sections of the hillslopes will not reach the trunk channel and are thus disconnected from the channel network. The headwaters are affected by hillslope creep (Fig. 2I), but none of these zones are connected with the channel network. Farther down from the drainage divide, in the region where channels initiate, the channel type alternates from mixed bedrock-alluvial channels with lag deposits, to bedrock channels with bedrock steps several-m-high where plucking and abrasion have been the dominant erosional processes (Fig. 2F). The main sediment sources appear to be located on the bordering hillslopes along the gorge that show evidence of mass failure (fresh scars with arcuate shapes, Fig. 2D). On the channel floor, sediment is temporarily stored behind tree stems and m^3-large blocks. In these particular locations sediment is only remobilized during phases of peak runoff.

Val Uastg represents the deepest gorge of the three incised valleys (Fig. 1A). It has a distinct inner gorge that is approximately 300 m deep, and a U-shaped morphology in higher segments. In the headwaters of the southern part, sediment transport has occurred by debris flows (Fig. 2J) as indicated by matrix supported deposits on the channel floor, whereas the northern part is more characterized by bedrock channels (Fig. 2B) where plucking has been the dominant channelized process. Along the main channel, the sidewalls have experienced multiple rock fall events as seen by several m-thick clast-supported diamictons on the channel floor. Nevertheless, distinct segments with bedrock outcrops are present at three locations. Note the presence of a deep-seated landslide that probably rerouted the trunk stream of the valley (site III on Fig. 3).

The roughness map (Fig. 4) shows a clear contrast between the SE- and NW-facing valley sides of the Glogn River. Specifically, the area affected by the Lumnezia landslide has an average roughness of 1,08 and a low roughness variability (StDev. 0.08). These magnitudes are lower than the averaged values of the opposite valleys (Mean >1.2, StDev. >0.15). The extraction of longitudinal stream profiles reveals a graded geometry for the Glogn River with a continuously decreasing channel gradient downstream, and multiple step-pool and straight segments for the trunk channels of Val Riein, Val Pitasch and Val Uastg (Fig. 4).

Orthophoto and geodetic surveys, and comparative estimates of sediment discharge

The comparison of the 2003 and 1956 orthophotos reveals that the foothill of the Lumnezia landslide has experienced multiple shallow-seated landslides that delivered unconsolidated material directly into the Glogn River. In particular, at the southern tip of the Lumezia landslide, the m-wide advance of the land-

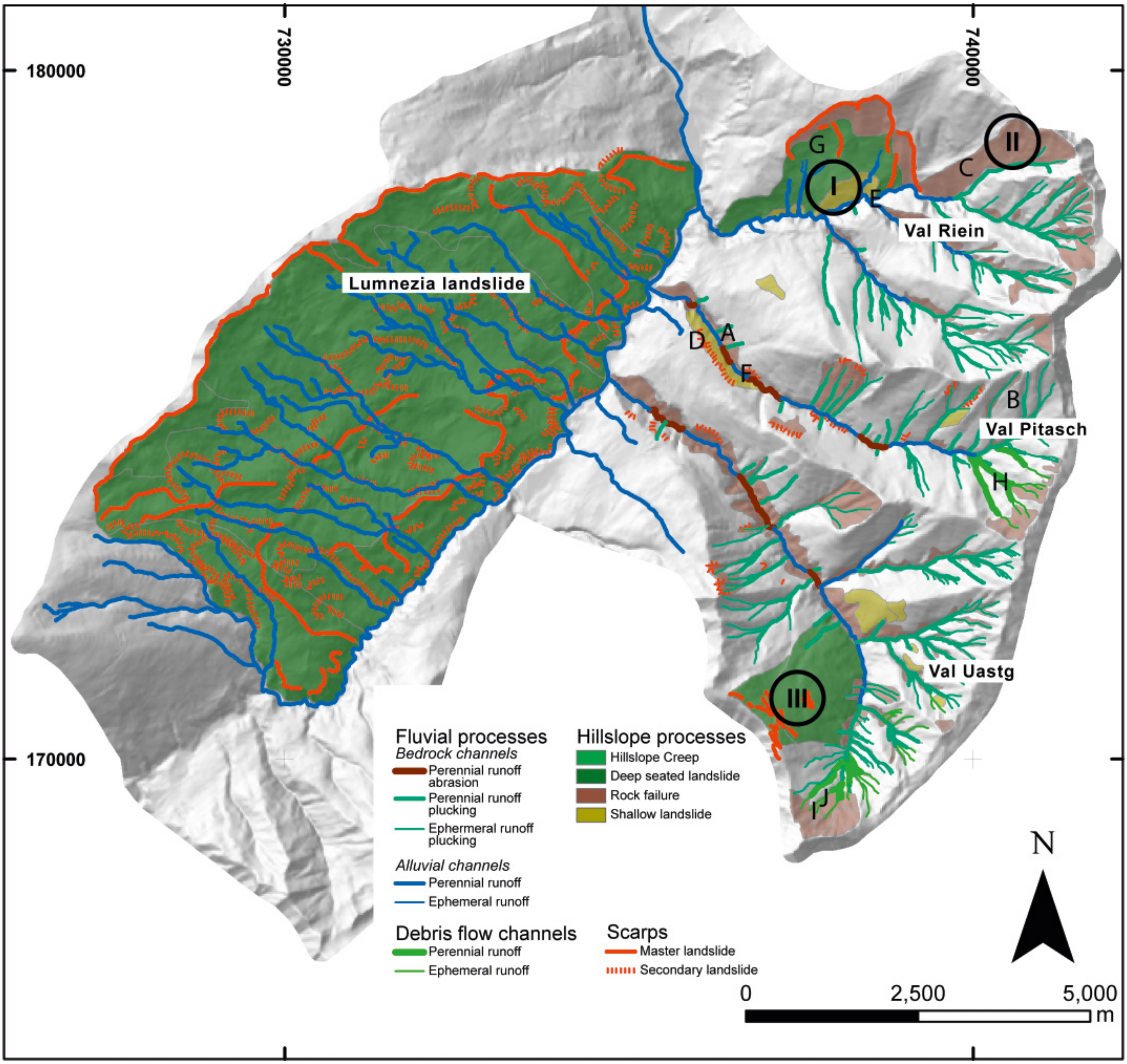
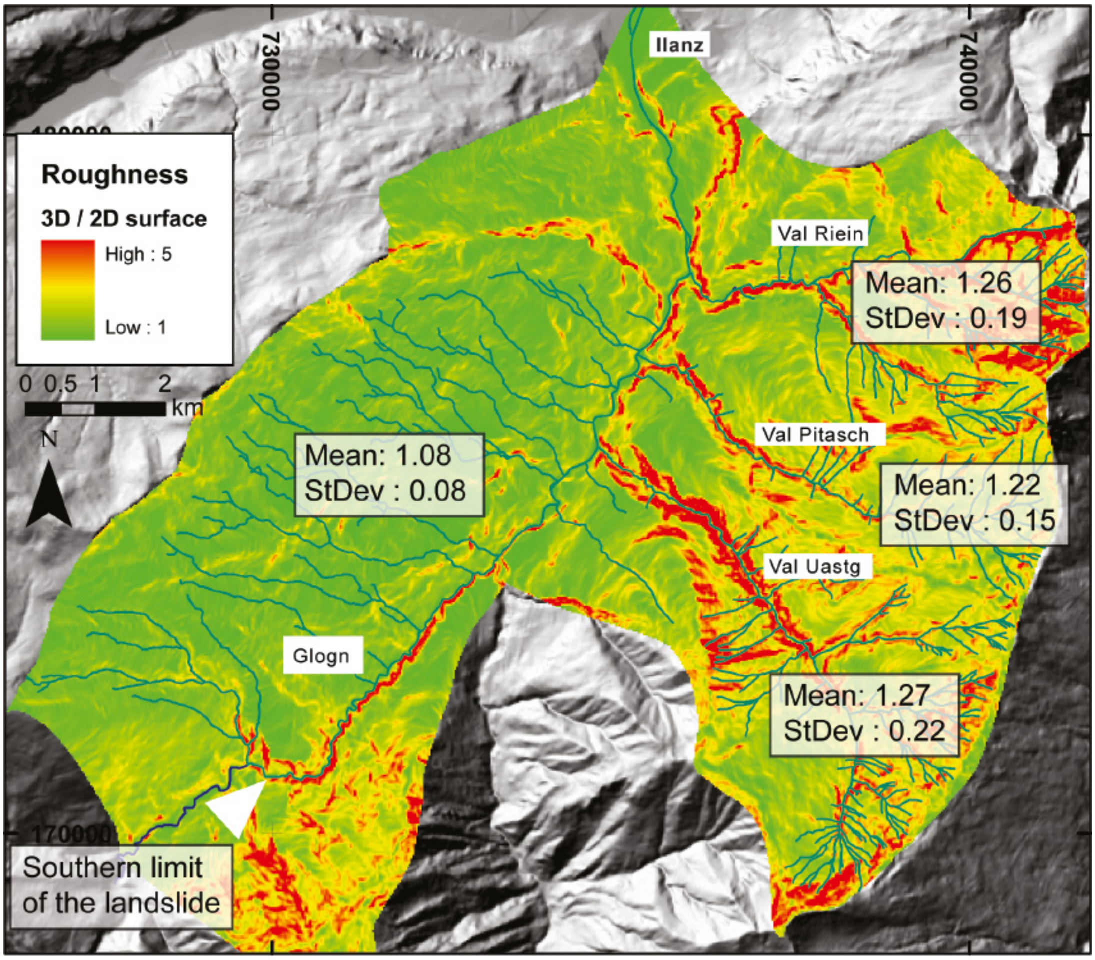


Fig. 3. Geomorphological map representing the situation in 2003. Specific sites are described in the text. The channel floors of alluvial channels are covered by a sedimentary layer and thus contrast to bedrock channels that have been shaped by abrasion and plucking. A–J are sites of photos illustrated on Figure 2; I, II and III are sites of landsliding in the eastern tributary catchments. Reproduced with permission from Swisstopo (BA091200).

slide mass has shifted the river course towards the opposite side (Fig. 5A).

In the watershed of the Val Riein, the most impressive change in the landscape occurred by massive rock avalanches and landslides (Fig. 5B) on the south-east facing side of the valley affecting a 20'000 m^2-wide area and resulting in erosion of a <1-m-thick layer according to the 3D photogrammetric survey. The assignment of <1 m of erosion is given by the detection limit of digital photogrammety (Schwab et al. 2008), i.e. vertical changes at that particular site could not be measured and are thus below that limit. The debris, up to 2 m^3 large, collapsed directly into main channel. Boulders derived from this source are still present in the channel, but most of the material has been removed by debris flows or by subsequent fluvial transport during high discharge events. In Val Pitasch, the sites that experienced a change in the landscape



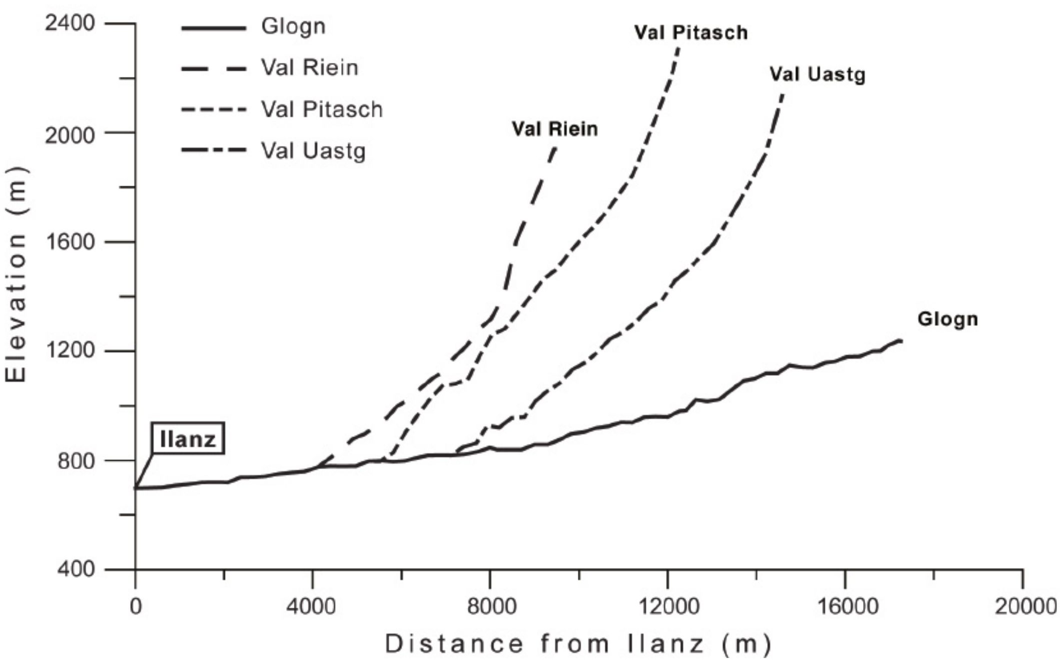


Fig. 4. Morphometric properties of the Glogn valley and longitudinal stream profiles of the Glogn and tributary rivers. The Lumnezia landslide shows a significantly lower roughness magnitude (mean) and standard deviation (StDev) than the three deeply incised valleys on the eastern side of the Glogn. Steps in stream profiles reflect raster points in the DEM. See text for further explanation. Reproduced with permission from Swisstopo (BA091200).

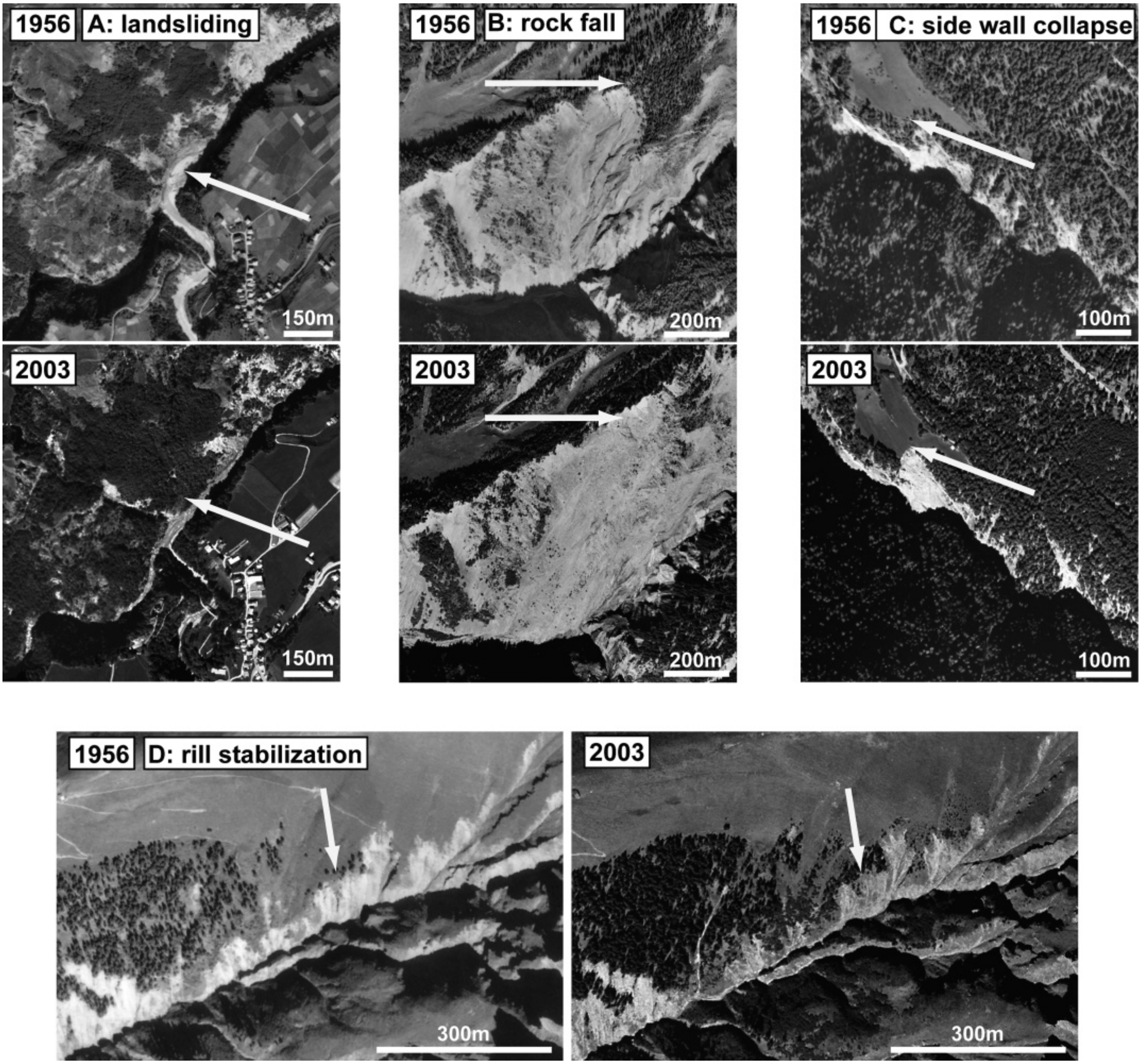


Fig. 5. Comparative orthophoto illustrating examples from the change detection analyses. The arrows mark the location where well-visible changes have occurred. See Fig. 6 for location of examples (squares labelled with A, B, C and D). Reproduced with permission from Swisstopo (BA091200).

between the acquisition times of the aerial photos are located along the hillslope bordering the trunk stream, and near the break-in-slope separating the U-shaped valley and the deep inner gorge (Fig. 5C). The comparison between the trunk and tributary channels on the 1956 and 2003 aerial photographs does not reveal any evidence of erosion or sediment accumulation in the trunk channel. In Val Uastg, the situation is similar to that in Val Pitasch as the main topographic changes are detected at the border of the inner gorge. The channels and upper parts of the sidewalls in the headwaters appear to have gained geomorphic stability as shown by the increase of the extent of the grass cover (Fig. 5D). In general, the comparison between the 1956 and the 2003 topographies reveals multiple evidence that the aerial extent of the grass cover on the bedrock has increased, and that the forest has colonized the deforested mountain pasture.

The compilation of the results described above allows a qualitative comparison between sediment discharge on the eastern and western sides of the Glogn valley (Fig. 6). Note that we only considered hillslopes coupled with the channel net-

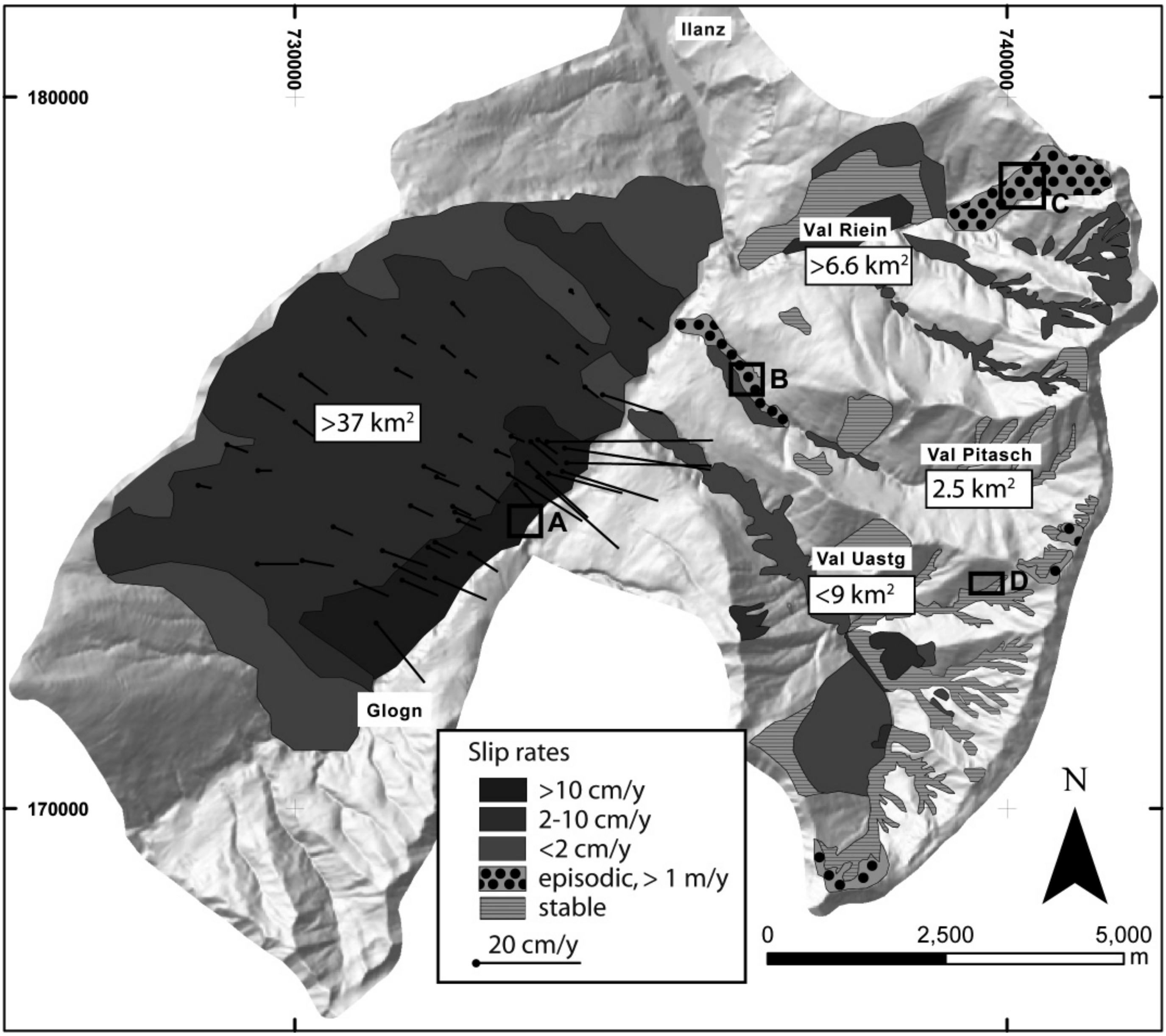


Fig. 6. Areas that are have delivered material to the channel network between 1959 and 2003. A–D represent sites with obvious topographic changes detected on aerial photographs (Fig. 5). Note that landscape changes need to exceed 1 m in order to be detected on aerial photographs (see also Schwab et al. 2008). Reproduced with permission from Swisstopo (BA091200).

work for the sediment budget calculations. Accordingly, along the western side of the Glogn valley that hosts the Lumnezia landslide, an area of approximately 30 km² has delivered sediment to the Glogn River by landsliding. High slip rates of several centimetres per year have resulted in topographic changes that are detectable on aerial photographs and measurable with geodetic tools. In contrast, in the tributary catchments on the eastern side of the Glogn valley, an area of approximately 18 km² that corresponds to <30% of the whole surface has experienced a change in the landscape, and the magnitudes of changes are below the calibration limit of digital photogrammetry and geodetic tools. We interpret that the magnitude of sediment discharge from the eastern tributaries has been lower than that from the western valley side.

Discussion

Possible controls on sediment flux

Along the Glogn River, the presence of landslide material on the eastern side of the channel and the rerouting of the river toward the right side of the landslide at its southern limit (Fig. 5A) indicates that landsliding resulted in a downslope flux of mass that exceeded the transport capacity of the trunk stream for some time. However, the graded character of the longitudinal stream profile of the Glogn River with a decreasing channel gradient in the downstream direction suggests that ongoing erosion of the landslide deposits allowed the trunk stream to keep a balance between landsliding on the bordering hillslope and sediment transport (see also conceptual models by Tucker & Slingerland 1997). Consequently, for longer time scales, the deep movement of the landslide appears to have been controlled by the local base level and the sediment transport capacity of the Glogn River. In Val Riein, Val Pitasch and Val Uastg, however, the presence of step pool and straight channels, and the frequent exposure bedrock on the channel floors suggest transient states in valley development and supply-limited sediment discharge (Korup & Schlunegger 2007).

The reason for the contrasts in sediment discharge is the dip orientation of the bedrock and the intersection with the topography. The internal organization of the hillslope-channel system is therefore different on the western and eastern valley sides. Specifically, on the western flank, the dip-slope situation of bedrock promotes hillslope processes in general and landsliding in particular. The tributaries parallel to the slip direction of the landslide, and particularly the Glogn River perpendicular to it, control the variations of slip rates, which represents ideal boundary conditions for effective sediment transport.

On the west-facing valley side, the tributary trunk-streams are still in a transient state as discussed above. Here, the bedding planes of bedrock intersect at right angles with the topography, which results in a situation where rock fall and rock avalanches have been the predominant process for supply of unconsolidated material to the channel network. The contribution of these processes to the overall sediment budget is presumably small as revealed by the comparison between the 1959 and 2004 aerial photographs, and as indicated by the supply-limited status of sediment discharge.

Implication for understanding the evolution of the Val Lumnezia

A thick ice sheet covered the valleys during glacial time intervals (Florineth & Schlüchter 1998). Nevertheless, indication of glacial erosion is absent on the western valley flank, but evident in the eastern tributary catchment. It appears that after glacial times, high erosion rates of the Lumnezia landslide has eliminated any features of a possible glacial inheritance. Therefore, we suggest that glacial processes do not explain the contrasts between eastern and western valley flanks, i.e. the predominance of landslides with little evidence of channelized processes versus highly dissected landscapes where large landslides are absent. We thus consider that the contrasts between hillslope stabilities on the east- and west-facing valley flanks have resulted in differences in the relative importance between hillslope and channelized processes, which, in turn, has controlled the overall topographic evolution of the study area according to theoretical concepts (van der Beek & Braun 1998; Simpson & Schlunegger 2003). The litho-tectonic setting of this region in turn, controls the processes and possible feedback mechanisms operating in the hillslope-channel system. As a consequence, we consider that enhanced slip rates affecting an entire slope, as it is the case for the Lumnezia landslide, results in the formation of a smooth topography superimposed by an unstable channel network. The constant and long- term movements appear to have inhibited the formation of valleys. On the other eastern side of the valley, episodic processes operating at local scales have affected the landscape. In addition, the geomorphologic map shows that routing of sediment into the channel network has occurred as sediment cascade operating from small scales to successively larger scales. This testifies again the supply-limited nature of sediment discharge (see above). Such a situation represents a prerequisite for a channel network to establish and to deeply incise into the landscape, resulting in a high topographic roughness (van der Beek & Braun 1998; Simpson & Schlunegger 2003). However, this does not mean that this particular landscape with a high roughness and thus a high potential energy is an important sediment source for geomorphic time scales. Our study shows that the opposite can be the case.

Comparison with other mountainous catchments

An example where hillslope mass wasting has exerted a significant control on the topographic evolution was presented by Hovius et al. (1998). These authors found that in the pre-steady state Finisterre Mountains, Papua New Guinea, the mode and rate of drainage basin modification is governed to a significant extent by hillslope mass wasting at the channel heads. The results of the Hovius et al. study imply that in this mountain belt, hillslope processes rather than fluvial erosion potentially dictate the evolution of a landscape for a limited time interval. Similarly, Hewitt (1989) found that in the Karakoram Himalaya, large rock avalanches released up to 10^{10} m^3 of sediment which caused damming of the trunk stream and temporary sediment storage either upstream (i.e. backwater aggradation), downstream (steep debris fans from catastrophic outburst flooding), or within the landslide-dam deposit. Similarly, Korup (2005, 2006) emphasizes that deep-seated landslides that often involve an area of several tens of km^2 have to be considered as controls on local relief and the pattern of low-order drainages. In this regard, the presumably most impressive example of deep-seated landslide and gravitational faulting that affects low-order drainages is the Lluta Collapse, Chile (Fig. 7), which is one of the largest ($V \sim 2.6 \times 10^{10}$ m^3) and oldest giant landslides in a terrestrial environment (García & Hérail 2005, Strasser & Schlunegger 2005; Zeilinger et al. 2005). This particular example illustrates that mass failure may influence the development of landscapes even in arid/hyperarid environments.

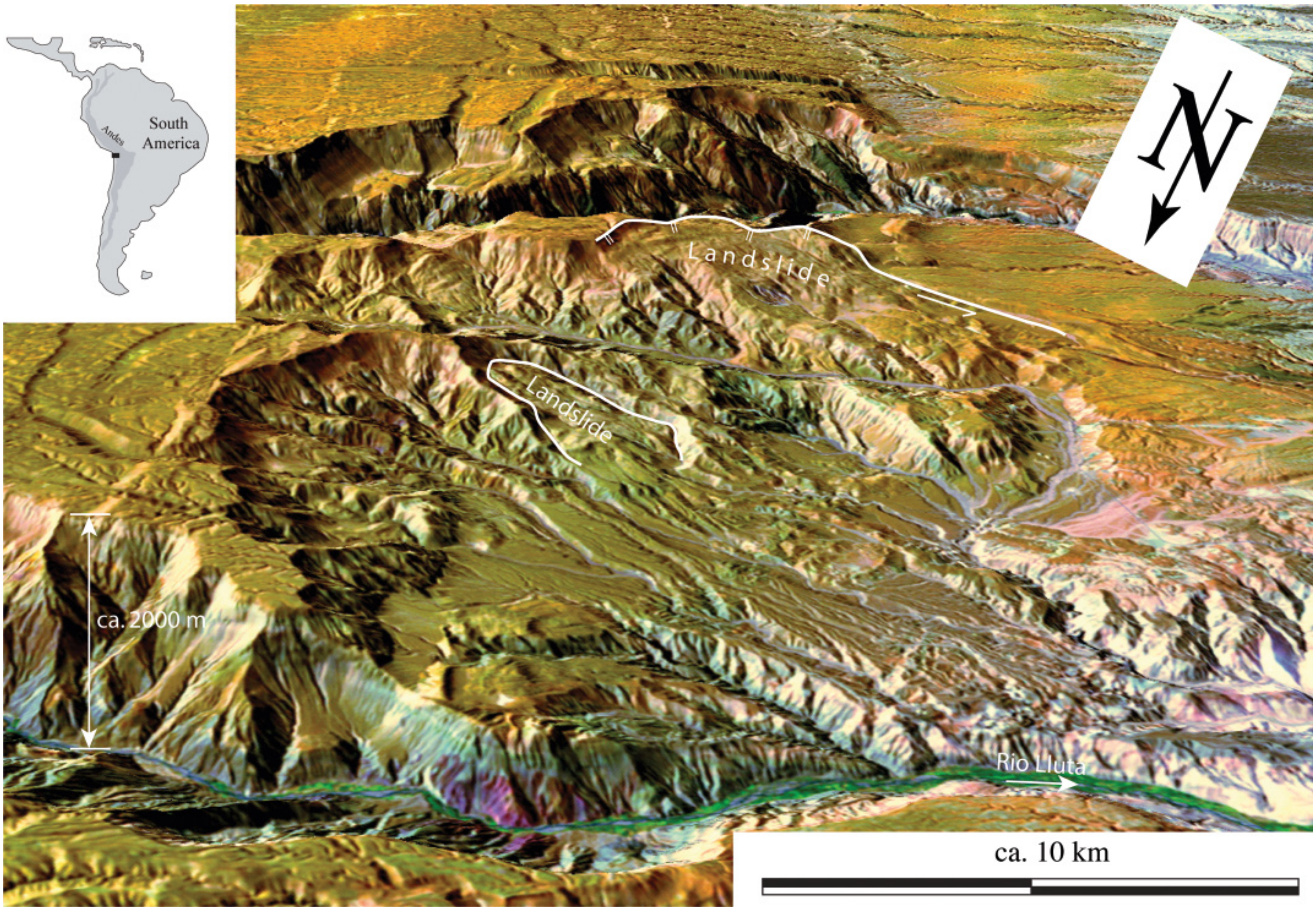


Fig. 7. Example of a landscape in northern Chile where landsliding has inhibited the establishment of a channel network. The Lluta collapse evolved as response to initial landsliding that removed a total of 26 km^3 of mass (Strasser & Schlunegger 2005). Subsequence modification of the landslide scar occurred by headward erosion, resulting in the establishment of a dendritic drainage network and the removal of an additional 24 km^3 of mass. The age of the initial landslide is >2.5 Ma (Schlunegger et al. 2006).

Conclusion

The Glogn valley presents an Alpine case where inferred high erosion rates and sediment discharge on hillslopes inhibits the formation of a stable channel network and largely controls the overall evolution of the landscape. This contrasts to the general notion that channelized processes exert the first-order control on landscape evolution and formation of relief, and thus limit process rates on the adjacent hillslopes. Such a situation was indeed interpreted for the eastern tributaries of the Glogn River where sediment discharge has been supply limited. Under these circumstances, rates of landscape change and growth of local relief are considered to have been controlled by channelized erosion. On the western valley flank, the dip-slope situation of bedrock results in high slip rates of hillslopes and in a situation where sediment discharge is transport limited. In that case, the overall development of the landscape might be largely driven by the ratio between sediment discharge on hillslopes and in channels in general, and by hillslope processes in particular. This issue needs to be considered when analyzing further drainage basins in the Alps and in other mountain belts.

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