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Patterns and controls of sediment production, transfer and yield in the Illgraben

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ABSTRACT

Quantification of the volumes of sediment removed by rock–slope failure and debris flows and identification of their coupling and controls are pertinent to understanding mountain basin sediment yield and landscape evolution. This study captures a multi-decadal period of hillslope erosion and channel change following an extreme rock avalanche in 1961 in the Illgraben, a catchment prone to debris flows in the Swiss Alps. We analyzed photogrammetrically-derived datasets of hillslope and channel erosion and deposition along with climatic and seismic variables for a 43 year period from 1963 to 2005. Based on these analyses we identify and discuss (1) patterns of hillslope production, channel transfer and catchment sediment yield, (2) their dominant interactions with climatic and seismic variables, and (3) the nature of hillslope–channel coupling and implications for sediment yield and landscape evolution in this mountain basin.

Our results show an increase in the mean hillslope erosion rate in the 1980s from 0.24 ± 0.01 m yr^{-1} to 0.42 ± 0.03 m yr^{-1} that coincided with a significant increase in air temperature and decrease in snow cover depth and duration, which we presume led to an increase in the exposure of the slopes to thermal weathering processes. The combination of highly fractured slopes close to the threshold angle for failure, and multiple potential triggering mechanisms, means that it is difficult to identify an individual control on slope failure. On the other hand, the rate of channel change was strongly related to variables influencing runoff. A period of particularly high channel erosion rate of 0.74 ± 0.02 m yr^{-1} (1992–1998) coincided with an increase in the frequency and magnitude of intense rainfall events.

Hillslope erosion exceeded channel erosion on average, indicative of a downslope-directed coupling relationship between hillslope and channel, and demonstrating the first order control of rock–slope failure on catchment sediment yield and landscape evolution.

1. Introduction

Rock–slope failures are a critical process in mountain basins. They are a key source of sediment, removing large portions of hillslopes and delivering substantial quantities of sediment to the heads of mountain channels (e.g. Hovius et al., 1997, 2000; Korup et al., 2004; Korup, 2006, 2010; Bennett et al., 2012). In many mountain basins, debris flows subsequently transport much of this sediment, and deliver it to the downstream fluvial system (e.g. Dietrich and Dunne, 1978; Haeberli et al., 1990; Zimmermann and Haeberli, 1992; Rebetez et al., 1997; Bovis and Jakob, 1999; Marchi et al., 2002; Hürlimann et al., 2003; Jomelli et al., 2004; Jakob et al., 2005; Berger et al., 2011a; Brardinoni et al., 2012). Debris flows are also important land-forming agents (Stock and Dietrich, 2006) and hazards (Jakob and Hungr, 2005). Quantification of the volumes of sediment removed by rock–slope failure and transferred by debris flows, and identification of their coupling and controls (Harvey, 2001, 2002, 2012) are pertinent to understanding landscape evolution in mountain basins and mountain basin sediment yield (Korup et al., 2010, Brardinoni et al., 2012).

Geomorphic hillslope–channel coupling, defined as the exchange of mass and energy between hillslopes and channels (Korup and Schlunegger, 2007), is important for identifying the factors that influence hillslope and channel erosion. The dominant view in geomorphology is that channel incision into bedrock in active mountain belts sets the base level for hillslope erosion (Burbank et al., 1996; Whipple, 2004). In this situation, frequent landsliding on threshold hillslopes is thought to rapidly adjust relief created by fluvial bedrock incision (Burbank et al., 1996) and may be referred to as a bottom-up process (Bishop, 2007). The direction of coupling is from channel to hillslope, in the upslope direction (Harvey, 2001, 2002, 2012). However, as Korup et al. (2010) point out, this concept is at odds with widespread landsliding that occurs independently of fluvial slope undercutting, apparently in response to environmental controls. There are many examples of large rock–slope failures aggrading and even

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blocking channels and consequently reducing or even preventing channel bedrock incision. Thus a downslope-directed coupling relation in which hillslope erosion controls landscape evolution and sediment yield may be more common than is currently thought (Schlunegger et al., in press). Studies that quantify relative rates of hillslope and channel erosion are needed to assess the prevalence of a downslope directed coupling relationship in the landscape.

Potential environmental controls on hillslope sediment production include rainfall (e.g. Crozier, 2010; Rossi et al., 2010) and seismic activity (e.g. Keefer, 1984; Korup, 2010). In addition, a link between an increase in air temperature and frequency of slope failures in high mountain regions is gaining support in the literature (e.g. Gruber et al., 2004; Fischer et al., 2012). Alpine permafrost has warmed by 0.5–0.8 °C in the upper tens of meters during the last century (Harris et al., 2003), potentially reducing the stability of hillslopes by the melting of ice along potential failure surfaces (Haeberli et al., 1997). Conversely, higher mean temperatures may also increase slope stability and reduce the rate of sediment supply to debris flow channels by vegetation establishment on slopes and an increase in the length of the growing period (Schwab et al., 2009). Additionally, higher temperatures may decrease the occurrence of thermal weathering by processes of freeze–thaw (e.g. Matsuoka and Sakai, 1999) and frost cracking/ice-segregation (e.g. Hales and Roering, 2007). The combination of all of these effects means that in some settings it is difficult to detect an individual control on slope failure. For example, Allen et al. (2011) were not able to detect the dominance of any one particular factor of many possible influencing factors of slope failure in the Southern Alps of New Zealand, including climatic and tectonic factors. More research and good datasets are needed over longer timescales to decipher the environmental controls, particularly thermal controls, on slope failure.

Significant climatic change has been observed across the European Alps in the past century, with potential implications for sediment production and transfer in mountain basins. Air temperature has increased across the Alps, with a significant acceleration in the 1980s (e.g. Casty et al., 2005). An increase in precipitation and runoff has been observed in many mountain basins (e.g., Beniston et al., 1994; Rebetez et al., 1997; Frei and Schar, 2001; Birsan et al., 2005).

Changes in runoff are generally stronger than changes in precipitation, especially in the winter and spring, and they coincide with a significant warming in these seasons (Birsan et al., 2005). Several studies have noted an increase in debris-flow activity associated with both increasing temperatures and intense precipitation events (Haeberli et al., 1990; Zimmermann and Haeberli, 1992; Rebetez et al., 1997; Jomelli et al., 2004). Triggering of debris flows is most often linked to rainfall events of a certain intensity and duration (e.g. Caine, 1980; Rebetez et al., 1997; Jomelli et al., 2004; Badoux et al., 2009). Conversely, the impact of increasing temperature on debris-flow activity is less clear. Increasing temperatures are thought to increase debris-flow activity by increasing the sediment supply for debris-flow generation through permafrost degradation of contributing hillslopes (Haeberli et al., 1990, 1993, 1997; Zimmermann and Haeberli, 1992). In other catchments, sediment supply has often been identified as a limiting factor in debris flow occurrence (Zimmermann and Haeberli, 1992; Bovis and Jakob, 1999; Marchi et al., 2002; Jomelli et al., 2004; Jakob et al., 2005). Thus hillslope sediment production processes and their influencing factors need to be considered in order to fully understand debris-flow activity.

With an exceptional hillslope erosion rate by rock–slope failure of 0.39 ± 0.03 m yr^{-1} (Bennett et al., 2012) and a large and well-monitored annual sediment yield of about 100,000 m^3 yr^{-1} by debris flows (McArdell et al., 2007; McArdell and Graf, 2009, Schlunegger et al., 2009), the Illgraben in the Swiss Alps is an ideal mountain basin in which to study the combined impact of rock–slope failure and debris-flow dominated channel sediment-transfer on mountain basin sediment yield. We present an analysis of a dataset of sediment production, transfer and yield in the Illgraben spanning 1963–2005. The differentiation of sediment yield into hillslope and channel sources in different sub-periods enables the identification of their independent potential influencing factors and of hillslope–channel coupling on a decadal scale. In order to study the climatic and seismic controls on these hillslope and channel processes and ultimately on sediment yield, we conduct an analysis of precipitation, temperature, snow depth and seismic data for the study period. The ultimate objectives are to identify (1) patterns of hillslope sediment production, channel transfer and catchment sediment yield, (2) their dominant interactions with climatic and seismic variables, and (3) the nature of hillslope–channel coupling and implications for landscape evolution in this mountain basin.

This study extends those of Schlunegger et al. (2009) and Berger et al. (2011b). Schlunegger et al. (2009) assessed rates of hillslope activity in the catchment and provided some initial estimates of hillslope erosion rates. Berger et al (2011b) identified patterns of hillslope sediment production and channel transfer in the upper Illgraben catchment over a period of 2 years. They observed accumulation of sediment from slope failure in the upper channel in the spring and its removal during the summer.

2. Study site

Located in western Switzerland, the Illgraben contributes disproportionally more sediment than water into the Rhône River (Fig. 1). The entire Illgraben basin is ~9.5 km^2 in area, consisting of two tributary basins: the Illgraben (~4.6 km^2), which outputs several debris flows each year into the Rhône River, and the Illbach (~4.9 km^2), which contributes very little to sediment output due to the construction of the Illsee dam in 1923 (Berger, 2010). In this study we focus on the active Illgraben sub-catchment, referred to hereafter as the Illgraben.

The Illgraben experiences a temperate–humid climate with a relatively low mean annual precipitation ranging from 700 mm in the lower part (610 m a.s.l) to 1700 mm at its summit (2716 m a.s.l). The rainfall occurs mainly during intense summer rainstorms in which rainfall intensity may reach more than 70 mm h^{-1} (Berger, 2010). Mean annual air temperature (MAT) is about 4 °C based on temperature data at stations within the basin (Fig. 1).

The Illgraben is underlain by Triassic metasedimentary rocks. The trunk channel follows a SW–NE striking fault that dissects the axial plane of a large anticline (Schlunegger et al., 2009). To the south and at the head of the channel and making up the study slope (Fig. 2), slopes expose highly fractured white and light-green sericitic quartzites with interbedded dolomites and schists, all of which dip steeply to the south-east. Slopes to the north of the channel are underlain by a succession of limestones and dolomites that also dip steeply to the south east. About 44% of the Illgraben is exposed bedrock and loose sediment cover, 42% is covered by forest and 14% by grassland (Schlunegger et al., 2009). The debris fan, with a radius of ~2 km, area of ~9 km^2 and volume of ~500×10^6 m^3 (Badoux et al., 2009), is large by Alpine standards and is indicative of past high rates of sediment output (Schürch et al., 2011).

Schlunegger et al. (2009) quantified hillslope erosion in the Illgraben and identified slopes within the study slope as the most actively eroding in the catchment between 1959 and 2004, with regions of up to 60 m of vertical erosion over the period. In contrast, the slopes to the north of the channel of predominantly dolomites experienced less than 10 m of erosion in the same period. Much of the slopes to the south of the main channel and northeast of the study slope are disconnected from the main channel due to dense vegetation cover (Schlunegger et al., 2009) and sediment supply to the main channel from these slopes is negligible. Berger et al. (2011b) made similar findings concerning catchment hillslope activity. They documented eight rockfall events and two landslides from aerial imagery in 2008 and