Geomorphology 275 (2016) 46–57

Contents lists available at ScienceDirect

Geomorphology

journal homepage: www.elsevier.com/locate/geomorph

Quantitative reconstruction of late Holocene surface evolution on an alpine debris-flow fan

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ARTICLE INFO

Article history:
Received 11 March 2016
Received in revised form 2 September 2016
Accepted 9 September 2016
Available online 10 September 2016

Keywords:
Fans
Lobes
Avulsion
Debris flows
Switzerland
Cosmogenic radionuclide dating

ABSTRACT

Debris-flow fans form a ubiquitous record of past debris-flow activity in mountainous areas, and may be useful for inferring past flow characteristics and consequent future hazard. Extracting information on past debris flows from fan records, however, requires an understanding of debris-flow deposition and fan surface evolution; field-scale studies of these processes have been very limited. In this paper, we document the patterns and timing of debris-flow deposition on the surface of the large and exceptionally active Illgraben fan in southwestern Switzerland. We use terrain analysis, radiocarbon dating of sediment fill in the Illgraben catchment, and cosmogenic ^{10}Be and ^{36}Cl exposure dating of debris-flow deposits on the fan to constrain the temporal evolution of the sediment routing system in the catchment and on the fan during the past 3200 years. We show that the fan surface preserves a set of debris-flow lobes that were predominantly deposited after the occurrence of a large rock avalanche near the fan apex at about 3200 years ago. This rock avalanche shifted the apex of the fan and impounded sediment within the Illgraben catchment. Subsequent evolution of the fan surface has been governed by both lateral and radial shifts in the active depositional lobe, revealed by the cosmogenic radionuclide dates and by cross-cutting geometrical relationships on the fan surface. This pattern of frequent avulsion and fan surface occupation provides field-scale evidence of the type of large-scale compensatory behavior observed in experimental sediment routing systems.

1. Introduction

Debris flows are a ubiquitous process in mountain environments around the world, and represent a major physical hazard to populations and infrastructure. Deposition of sediment by repeated flows results in the construction of debris-flow fans that can potentially record information on past flow size, timing, composition, and depositional pattern (Schumm et al., 1987; Harvey, 2011). Such fans are therefore a potentially powerful archive of debris-flow processes (e.g., Whipple and Dunne, 1992; Dühnforth et al., 2007; d'Arcy et al., 2015; de Haas et al., 2015a, 2015b), hazard (e.g., Hubert and Filipov, 1989; Helsen et al., 2002; Stoffel et al., 2008a; Arattano et al., 2010; de Scally et al., 2010), and sediment supply (e.g., McDonald et al., 2003; Dühnforth et al., 2008; Hornung et al., 2010; Savi et al., 2014). Reading that archive, however, and extracting quantitative information about past debris flows, requires that we understand the pattern and timing of debris flow deposition on fans so that the evolution of the fan can be reconstructed.

Much recent work on fluvial fans and fan deltas has shown that they grow and evolve by a sequence of autogenic avulsion, fan-head incision or trenching, and backfilling (e.g., Kim and Muto, 2007; Nicholas and Quine, 2007; Powell et al., 2012; Reitz and Jerolmack, 2012; van Dijk et al., 2009, 2012), leading to migration of the active locus of deposition in space and time and filling of the available accommodation (Straub et al., 2009). This autogenic sequence can be modified or overprinted by allogenic forcing of fan development caused for example by large landslides or rock avalanches that drive external variations in sediment supply (e.g., Davies and Korup, 2007; Korup et al., 2010). By comparison, there has been little work on whether fans built by debris flows share this evolutionary model, or how they are affected by external events such as large landslides. Debris-flow fans are known to occupy different depositional lobes over time (Suwa and Okuda, 1983; Blair and McPherson, 1994; Stoffel et al., 2005; Dühnforth et al., 2007; Ventra and Nichols, 2014; d'Arcy et al., 2015), and switching between lobes has been linked to internal and external controls on fan development

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http://dx.doi.org/10.1016/j.geomorph.2016.09.020
0169-555X/

(Dühnforth et al., 2008; Ventra and Nichols, 2014). Schumm et al. (1987) and de Haas et al. (2016) documented cyclic alternations of avulsion, channelization, and backstepping of the active depocenter on experimental debris-flow fans, and de Haas et al. (2016) argued that debris-flow fans are therefore likely governed by the same large-scale compensatory behavior as fluvial fans and fan deltas, albeit via different physical processes. To date, however, there are very few well-documented and well-dated examples of this behavior on active field-scale debris-flow fans.

Studies of debris-flow fan surface evolution to date have tended to focus on arid environments such as the western USA, where vegetation and post-emplacement sediment reworking are minimized and primary debris-flow depositional features are more easily preserved (e.g., Whipple and Dunne, 1992; Kim and Lowe, 2004; Staley et al., 2006; Frankel and Dolan, 2007; Dühnforth et al., 2007). Despite the frequency of debris flows in more humid environments such as the Swiss Alps (Hürlimann et al., 2003; Schlunegger et al., 2009), quantitative reconstruction of the timing and patterns of deposition on alpine debris-flow fans remains fairly limited. A number of studies have used dendrochronology to establish the timing and magnitude of debris flows on fans in the Swiss Alps (e.g., Stoffel et al., 2005, 2008a, 2008b, 2014; Bollschweiler and Stoffel, 2010; Stoffel, 2010; Arbellay et al., 2010). This approach typically is limited to the last few hundred years (Bollschweiler and Stoffel, 2010) and cannot therefore capture the evolution of the fan surface over Holocene time scales. It is therefore not clear whether alpine debris-flow fans record similar patterns of avulsion, channelization, and backstepping, nor what time scales are required to completely resurface a large fan in these settings.

Here, we begin to address these knowledge gaps by documenting the evolution of the Illgraben fan, in southwestern Switzerland, as recorded by the debris-flow deposits that are visible on the fan surface. The Illgraben is one of the largest fans in the Swiss Alps and is exceptionally active, with an average of 3–5 debris flows per year (Hürlimann et al., 2003; McArdell et al., 2007; Schlunegger et al., 2009). The characteristics, morphology, and patterns and mechanisms of erosion and deposition in these flows have been very well documented (McArdell et al., 2007; Berger et al., 2011; Schürch et al., 2011), as have their contributions to catchment-scale sediment transfer (Schlunegger et al., 2009; Bennett et al., 2013, 2014; Burtin et al., 2014). Previous studies of the fan, however, are limited to quantification of the near-surface stratigraphy (Franke et al., 2014) and short-term evolution of the fan surface as recorded by dendrochronology (Stoffel et al., 2008a; Arbellay et al., 2010). To understand the longer-term development of the entire fan surface, we combine geomorphic mapping and analysis of the fan surface, using high-resolution digital topographic data, with the first systematic study of post-glacial depositional ages using in situ cosmogenic radionuclide exposure dating on an alpine debris-flow fan. While these techniques have previously been combined and applied to arid-region fans (e.g., Dühnforth et al., 2007), this is (to our knowledge) the first application to a fan in a more geomorphically active setting such as the Alps.

2. Field site

The Illgraben catchment (Fig. 1) is located on the southern flank of the Rhone Valley, within the canton of Wallis in southwestern Switzerland. The catchment covers an area of ca. 9.5 km^2 and feeds a debris-flow fan with a radius of ~2 km that has developed on the floor of the Rhone Valley. Two bedrock units of different lithologies, both highly fractured, dominate the catchment (Gabus et al., 2008): the northwestern (left) bank of the Illgraben is underlain by Upper Triassic dolomites and marbles, whilst the southeastern (right) bank is mainly underlain by Lower Triassic quartzites (Fig. 1). Both units are steeply dipping to the southeast.

Sediment is supplied to the Illgraben catchment-fan system by frequent landslides and debris flows within the catchment, as documented by Schlunegger et al. (2009) and Bennett et al. (2012). This material accumulates within the trunk channel of the Illgraben and is re-entrained in debris flows that reach the fan (Bennett et al., 2013) and in most cases the Rhone River (Schlunegger et al., 2009; Berger et al., 2011; Schürch et al., 2011). Bennett et al. (2014) showed that episodicity in sediment delivery to the fan, at least on decadal time scales, can be understood as a product of stochastic variations in sediment supply and of a critical runoff necessary for debris-flow generation. Delivery of sediment to the fan is complicated by the presence of at least two large rock avalanche

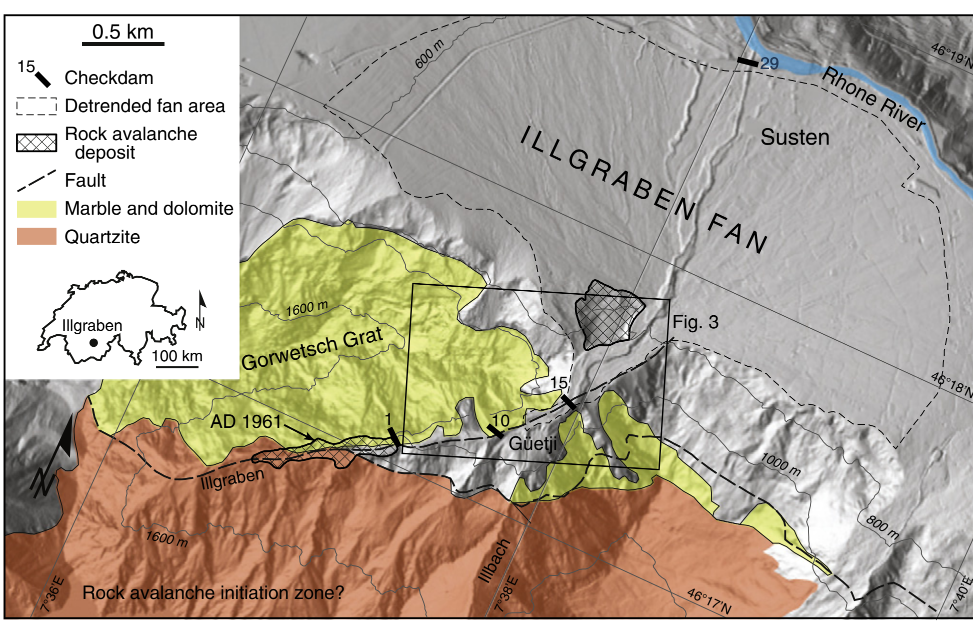

Fig. 1. Overview of Illgraben catchment and fan system. Inset shows Illgraben location in southwestern Switzerland. Background hillshade image is derived from Swisstopo DTM-AV digital elevation model, with 2-m cell size. Extent of rock avalanche deposits in the Illgraben catchment (emplaced in 1961) and at the head of the Illgraben fan (analyzed here) are shown in the cross-hatched pattern. Colors indicate extents of marble/dolomite and quartzite within the catchment, separated by an inactive fault; geology is simplified from Gabus et al. (2008). Selected checkdams, and their numbers, are shown by short black lines. Box shows location of Fig. 3.