Rockfalls change the runout and frequency of debris flows at Punta Nera (Eastern Italian Alps).

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Abstract. In the Dolomitic region, many debris flow basins have headwaters characterized by extremely steep slopes of bare outcropping rock. Cliffs are commonly incised by multiple chutes which rapidly deliver runoff at their base where the channels incise scree deposits. Debris flows mobilize and transport sediment along such ephemeral channels following intense summer convective rainstorms. In the debris flow basin of Punta Nera, a series of rockfalls, which occurred in the upper part of the headwater between 2013 and 2016, caused dramatic changes in the debris flow dynamics. Starting from the summer of 2014, the runout of debris flow events increased so much that it reached the national road, which runs at the toe of the debris flow fan, attracting media attention and prompting the adoption of protective measures. Here, we use newspaper reports, direct observations, aerial and terrestrial photograph, monitoring data and topographic surveys to document the rockfalls and the debris flow activity. The sudden increase in sediment availability changed the magnitude of events, their runout and the critical conditions for debris-flow occurrence.

1 Introduction

The source of sediment that can be mobilized to generate a debris flow can derive from landslides [1], progressive bulking of sediment operated by runoff along steep mountain torrent [2] or en-masse failure of channel bed sediment [3]. The total debris flow volume is largely controlled by the volume of material entrained in the debris flow channel [4]. Consequently, the volume of a new debris flow depends on the amount of available loose material stored in channels.

Debris flow basins may be supply-limited or transport-limited depending on the availability of loose mobilizable debris in relation to climate forcing [5]. Sediment production is important in supply-limited systems because it has strong influence on debris flow frequency and magnitude. The process of channel recharge is very often relevant for debris flow initiation. In fact, the likelihood that a debris flow will be triggered depends on the availability of sufficient precipitation and mobilizable sediment [6]. The second condition depends on progressive time-dependent mechanisms of sediment accumulation (dry ravel processes, channel-bank failures, bed load, [2, 7]) or sudden episodes that can produce a large amount of sediment (upstream mass failures and rock falls, [8]). The remobilization of landslide and rockfall deposits can feed debris flows for many years, as documented in the case of catastrophic earthquakes-induced mass failures [9]. Many studies have reported that debris flow frequency and magnitude dramatically increases following upstream mass failures and progressively decay toward background rates within a decade [10].

When sediment availability also changes the critical conditions for debris-flow occurrence may change. Debris flow-triggering rainfall thresholds may lower significantly whereas more frequent and destructive debris flows may occur [11, 12].

Research efforts to include the availability of sediment and/or channel recharge rate in the prediction of debris flow magnitude and frequency have appeared in recent years [13, 14] but challenges and limitations are still relevant for practical applications, therefore direct observations are still in great need.

This short communication describes the abrupt changes affecting the sediment transport dynamics in a small Alpine debris flow basin, during the last decade. We document how a series of rockfalls occurred in the headwater of a debris flow basin produced significant changes to the magnitude and frequency of debris flow events. The sudden increase in sediment availability changed the critical conditions for the occurrence of debris flows and resulted in an increase in their runout sufficient to repeatedly inundate the national road at the toe of the fan.

2 The Punta Nera debris flow basin

The Punta Nera debris flow basin is located on the western slope of Mount Sorapiss (3205 m a.s.l.) in the dolomitic region of the eastern Italian Alps. Steep

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bedrock cliffs dominate the steep headwater whose area measures 0.5 km^2 approximately.

Debris flows represent the main sediment transport mechanism for the basin, whereas torrential activity is mostly absent. Debris flows are triggered by the surface water runoff that steep rocky slopes concentrate into the headwater [15]. Scree deposits drape the base of the dolomite walls. Here, at the fan apex, the debris flow channel is incised into scree deposits while further downstream its proneness to avulsions is demonstrated by the considerable size of the fan.

Channel-bed material accumulates along the channel due to rockfall from dolomite cliffs and dry ravel from steep channel banks, promoted by drying and wetting cycles. Debris flow activity evacuates accumulated sediment, erodes the channel and underscours its bank, causing frequent localized bank failures feeding the cyclic process of channel refilling. Triggering rainfalls consist of short and intense rainfalls typically produced during the summer season by convective rainstorms [15, 16].

The National Road SS151 is located at the toe of the fan and was repeatedly inundated during the years 2015 and 2016 before massive defensive structures were progressively built (completion in 2019).

From 2015 to 2018, we maintained a low-cost monitoring station along the debris flow channel at an elevation of 1520 m. Here the channel is steep (about 30°) and debris flow initiation occurs due to entrainment of the channel bed material. The aim of the monitoring was to gain knowledge of the channel runoff and debris flow initiation by recording videos of the channel during and after intense rainfalls. Measured parameters also include rainfall and wind speed and direction. Whenever a rainfall intensity threshold (0.3mm/min) was exceeded, the system powered the two cameras and acquired high-frequency data (5s).

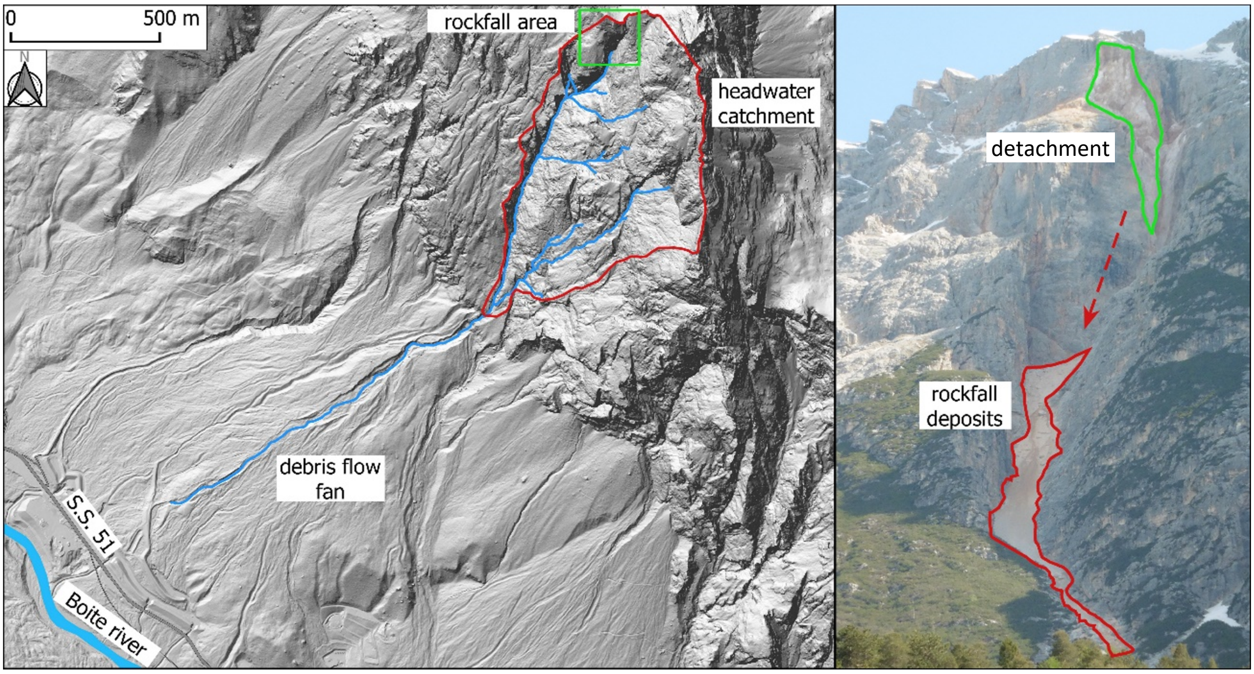

Fig. 1. Hillshade of the Punta Nera debris flow basin (left) derived from a 2015 lidar-derived DEM (1 m) and photograph (right) taken shortly after the occurrence of the main rockfall event on May 20th, 2016.

3 Rockfalls in the headwater

The first evidence of rockfall occurring in the Punta Nera basin dates back to October 2013. Similar events occurred between October and November of the following year. All rockfalls involved the dolomite walls in the upper western part of the headwater (Figure 1). Based on terrestrial photographs and direct observations, we estimate volumes in the order of a few tens of thousands of m^3, although even the mapping in the 2015 aerial photographs is problematic due to extreme steepness (>60°) causing shadowing.

All of the 2013 and 2014 events are likely precursors of the main rockfall occurred on May 20th, 2016 in the same area. In this case, aerial photographs and videos taken from the helicopter on the following day, allowed precise mapping of the area (4,000 m^2 approx.) of the detachment (Figure 1). The deposits spread along the main chute cutting through the headwater, covering an area of about 14,000 m^2. In this case, pre- and post-event photographic documents indicate the detachment of a thick pinnacle of dolomite. Assuming an average thickness of 30 m, we obtained a total volume exceeding 100,000 m^3, which is likely an underestimate.

4 Debris flow events

Before 2014, the debris flow catchment of Punta Nera was not known by authorities and practitioners as an hazardous debris flow basins. The neighbouring Acquabona basin was better known for its debris flow activity [17] as shown by the retention basin that protects the national road SS51. Although the frequency of events at that time at Punta Nera is unknown, there is no evidence of debris flows inundating the national road below. The analysis of aerial photographs demonstrate that the active channel was confined to the upper middle part of the fan (Figure 2) while a dense coniferous forest covered the lower fan.

After the end of the 2014 summer season, on October 13th, a debris flow event reportedly caused some flooding of the national road. After a few weeks another similar event was recorded and, during the following two summer seasons, more debris flows caused traffic disruption due to roadway inundation with debris (Figure 3). Fortunately, there were no victims or major accidents. Relevant authorities intervened by excavating ditches and building retention structures aimed to protect the road. These were already partly operating at the beginning of summer 2016. It was that summer, following the May rockfall, that the highest number of events (Figure 3) and the largest volumes were recorded. Debris flow events repeatedly filled the retention basins and inundated the road. Associated volumes were estimated by the road authority, based on earthmoving works, and the largest event of mid-June event reached about 80,000 m^3.

By comparing aerial photographs (2012, 2015, 2017, 2018, 2020) and lidar surveys (2010, 2011, 2015, 2020) we identified how the runout of debris flow events increased abruptly during the years 2015 and 2016. The path of the debris flow channel remained relatively unchanged in the upper part of the fan while multiple avulsions occurred further downstream with creation of new channels reaching the national road and several lobes of debris deposited in the lower fan (Figure 2).

During recent years (2017-21), the debris flow activity at Punta Nera gradually returned to earlier levels (i.e., no active channel in the lower part of the fan). No traffic disruptions were recorded thanks to the retention basin but also because debris flow activity retreated in the middle part of the fan (Figure 2). No subsequent flow showed the mobility, nor the magnitude, of the large events that occurred during 2015 and 2016.

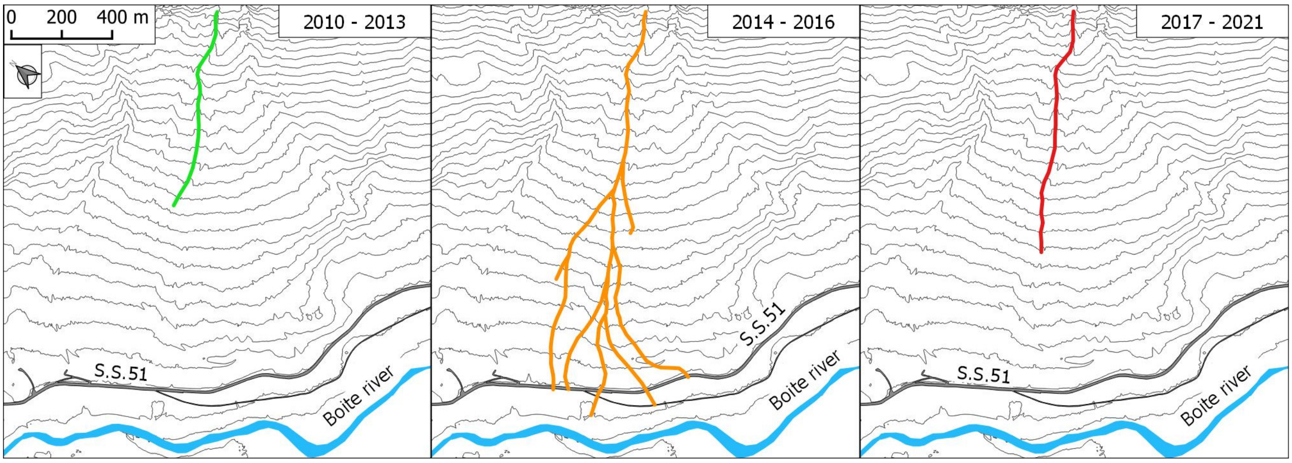

Fig. 2. Active debris flow channels on the Punta Nera fan during the summer seasons preceding the rockfalls (left), following the rockfalls (centre) and following the evacuation of the rockfall deposits from the headwater (right). Channel mapping derives from aerial photographs and lidar surveys.

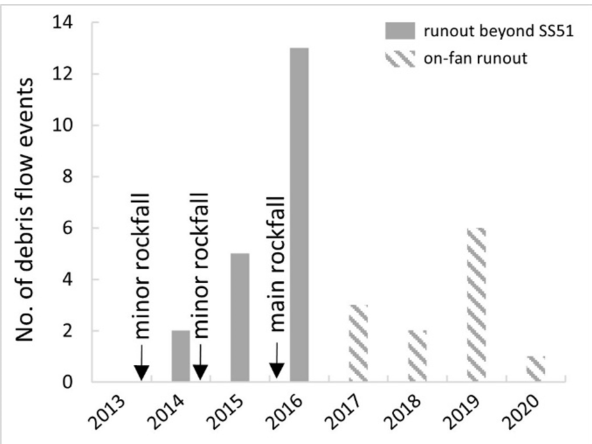

Fig. 3. Number of recorded debris flow events per year and rockfall episodes.

5 Discussion

Previous research has described the cycle of channel filling, debris flows, and channel reloading [5, 6]. In steep alpine landscapes with abundant exposed bedrock, the seasonal competition between winter/spring channel filling from rock weathering and summer debris flow sediment transport determines the amount of debris available along the drainage network [6, 18]. Drainages, with their low slope relative to the surrounding hillslopes and rock slopes, act as a reservoir to retain sediment until debris flow transport [18].

Sediment production and transport processes in a debris flow basin may proceed relatively steady through time or change dramatically their rate in response to a catastrophic event. Most of the documentation of these events describes the effects of large earthquakes and their consequences to sediment transport processes over large areas [9-11]. In the case of Punta Nera, the scale of our observation is very different but the effects on a small alpine debris flow basin appear similar. A series of rockfalls in the very upper part of the headwater produced a dramatic increase in the downslope sediment transported by debris flows. In our interpretation, one of the key elements of such abrupt change is that the rockfall deposited along the main chute of the channel network present in the rocky headwater. This enhances connectivity between the hillslope process (rockfall) and the channel process (debris flow). Also, the slope of the chute (40 to 45°) plays an important role. On one side, the slopes are gentle enough to accommodate the rockfall deposits, initially preventing further downslope propagation. On the other, the slopes are extremely high for the loose debris that could be rapidly destabilized and eroded by water runoff. Our preliminary observations, indicate that debris flows were extremely efficient in evacuating the sediment along low-order drainages where exposed bedrock normally dominates. The resulting debris flows showed strong erosive nature in the downstream fan, and mobilized overall volumes that were never recorded in recent times at Punta Nera. Higher flow magnitudes corresponded to longer runouts and caused many problems to the national road at the toe of the fan. This geologic hazard may become more frequent in the near future due to the expected increase in rockfall frequency in the alpine regions due to climate change [19].

In addition to an increase of magnitude, the years 2015 and 2016 saw a notable increase in debris flow frequency, because of the rockfalls. This indicates a change in the critical conditions required for debris flow initiation. Although anomalies in rainstorm frequency may also have played a role, we believe that debris availability was the primary factor responsible for the increase in frequency and volume of events observed during the two-year period. Ongoing rainfall data analysis is expected to reveal a temporary rainfall intensity/duration ID threshold modification. Results of previous research [14] support the use of rainfall ID thresholds across a range of decreasing sediment supply conditions. In other cases [12] rainfall thresholds showed substantial changes following a dramatic increase of sediment availability across the landscape.

Future developments of the present study will include the analysis of available digital terrain models to document the landscape changes that occurred following the rockfalls and subsequent debris flows.

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