Complex Interactions of Rock Avalanche Emplacement with Fluvial Sediments: Field Structures at the Tschirgant Deposit, Austria

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Abstract

The Tschirgant rock avalanche in Tyrol, Austria, produced a complex deposit $200–250 \times 10^6$ m^3 in volume and 9.8 km^2 in area. The landslide resulted from deep-seated failure of an intensely deformed carbonate rock mass on the southeast face of a 2370 m-high ridge. The rock mass rapidly fragmented as it moved towards the floor of the Inn River valley. Part of the debris collided with and moved around an opposing bedrock ridge and flowed into the Oetz valley, reaching up to 6.3 km from source. A large volume of mobilized sedimentary gravels and sands occurs beneath, within, and atop the rock avalanche deposit. Within proximal inter-hummock depressions, entrained gravels and sands extend to the deposit surface; elsewhere they are intercalated in narrow bands that dip towards and into flow direction. Some of these sediments were liquefied and mobilized *en route*, whereas others were most likely inherited from the source area. None of them shows signs of fragmentation, suggesting different mechanical behaviour or low fragmentation pressures at the time of entrainment. Generally, exposures of the basal contact of large rock avalanche deposits are rare, but at Tschirgant they are well exposed and reveal substrate injection features (some > 10 m across), thrust and normal faults, entrained sand and gravel rip-up clasts, corrugated basal shear contacts, and disturbed underlying material. Mixing of rock avalanche and substrate material is only observed at the distal margin, suggesting longer travel distances or particular material properties to allow mixing to take place. Ongoing research focuses on these substrate interaction features to reveal details of rock avalanche movement, flow paths, and emplacement.

Keywords

Rock avalanche • Sediment interaction • Runout • European alps

303.1 Introduction

Large ($>10^6$ m^3) rock and debris avalanches resulting from the catastrophic collapse of rock slopes are far less frequent than smaller landslides, yet they are serious hazards in nearly all mountain ranges on Earth. Within the European Alps, deep-seated rock-slope failures are particularly common in areas with steep, high carbonate slopes. These lithologies are associated with the largest volumes of failed mass per event (Abele 1974). Often emplaced into wide valley floors, rock avalanches inevitably encounter and interact with sedimentary materials along their runout paths. These interactions can exert strong positive or negative feedbacks on rock avalanche

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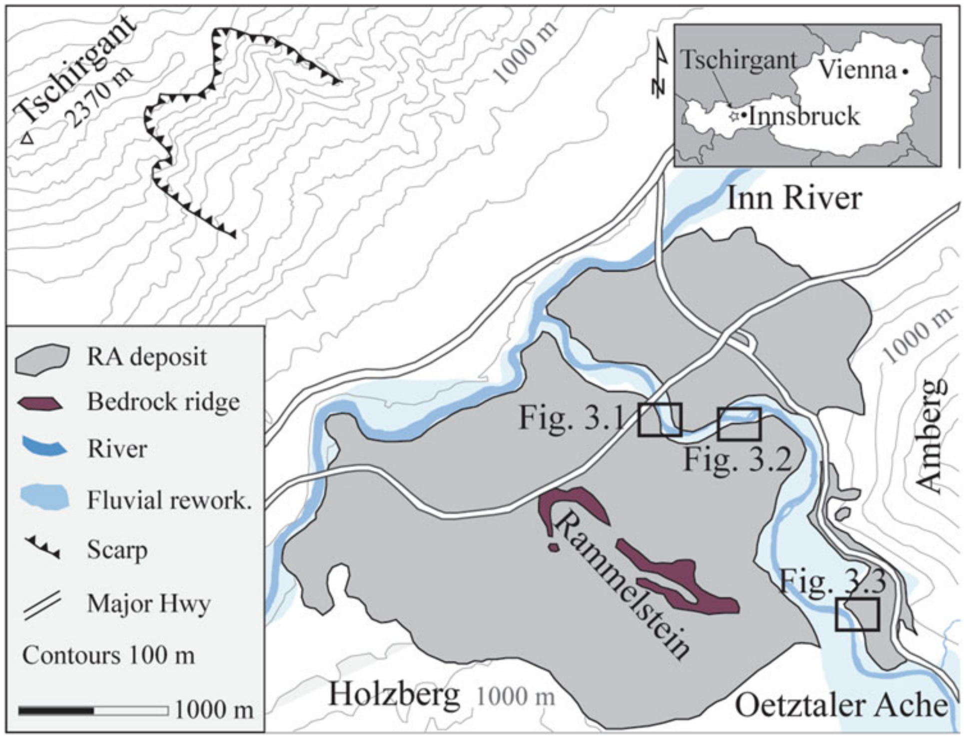

Fig. 303.1 Rock avalanche deposit and scarp locations

(RA) runout, alter emplacement processes, and change RA deposit morphology. Preserved interaction features highlight structures within the RA mass, thereby providing important insights into RA emplacement processes that might not otherwise be discernible (e.g. in rock avalanches that lack lithological contrasts). In this paper, we describe structures resulting from the interaction of the Tschirgant rock avalanche with runout path materials that provide insights into emplacement processes and factors that could more generally contribute to the complexities of rock avalanches.

303.2 Study Area

Situated at the southern margin of the Northern Calcareous Alps, a major Austroalpine thrust complex, the Tschirgant ridge comprises a stacked nappe pile of Lower to Upper Triassic carbonates. The well-exposed rock avalanche scarp is characterized by massive to thick bedded, intensively fractured dolostones and limestones of the Wetterstein Formation. Lower sections of the slope comprise less competent sequences of claystones, dolostones, and evaporates of the Raibl Group (Brandner 1980; Pagliarini 2008). The lithology and structure of the scarp area indicate that the failure and the block sizes in the rock avalanche deposit are controlled by a network of fracture sets. The slope collapse was mechanically favoured by the presence of the weak Raibl beds at the toe of the slope. These ochre-coloured evaporates (Rauhwacken) are marker beds for reconstruction of the preserved source stratigraphy in the deposit.

The Tschirgant rock avalanche is one of a spatial and temporal cluster of large landslides that occurred between 4200 and 3000 B.P. (Prager et al. 2008). It has been dated to 3700–3500 years B.P., with a second event at the same site sometime between 3200 and 3000 years ago (Patzelt 2012).

The fragmented carbonate rock mass of the Tschirgant rock avalanche dominates the landscape of the Inntal valley at its confluence with the Oetztaler Ache River, covers an area of 9.8 km^2 and is well exposed in river bluffs (Fig. 303.1). After a drop of 1480 m from the Tschirgant ridge, the rock mass crossed the Inn River valley (today at an elevation of 680–700 m), overtopped and spread around both sides of a 150–200 m-high bedrock ridge (Rammelstein), collided with valley walls at Holzberg and Amberg at the mouth of the Oetztal Valley, and travelled another kilometre up this valley. The total travel distance is at least 6.3 km. Most of the rock mass was deposited north of the bedrock ridge, and the largest hummocks are found there. Associated with these are megablock accumulations that are rare elsewhere on the deposit. Boreholes show that the thickness of the rock avalanche debris ranges from a few metres to several tens of metres, with finely ground and low-permeable silt-sized attrition debris in the lower parts of the deposit (Hartleitner 1993; Patzelt and Poscher 1993).

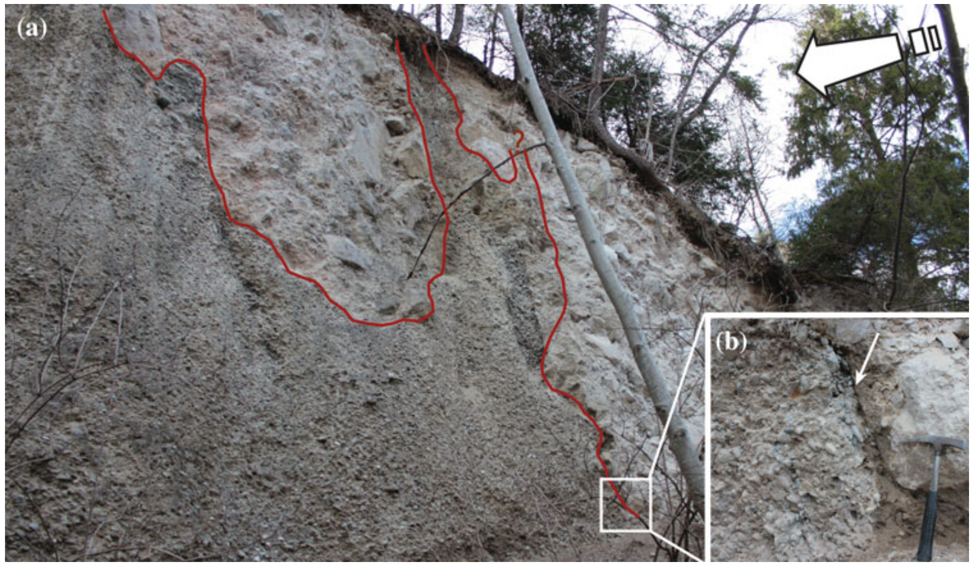

Fig. 303.2 **a** Entrained polymict gravels (outlined) in the rock avalanche deposit exposed along the Oetztaler Ache River (large white arrow indicates the direction of RA movement). **b** Sharp contact (small arrow) of entrained gravels and RA material. See Fig. 303.1 for location of exposure

In the hummocky landscape, geometrically partially complex structures, featuring carbonate rockslide debris associated with polymict clast-supported gravels, and sands are encountered (Patzelt and Poscher 1993; Abele 1997; Prager 2010). However, this situation has not been investigated in detail yet.

303.3 Rock Avalanche: Substrate Interactions

Fluvio-glacial gravels are found on top of hummocks in the proximal zone of the deposit. These cover-rocks, and presumably also a few allochthonous plants found atop the carbonate rockslide deposits, indicate that both were transported piggy-back from the scarp area, where remnants of old fluvial deposits are present at elevations up to about 2200 m and sporadically even higher. This evidence suggests that mechanically the "Bergsturz" (rock fall) event was characterized predominantly by laminar flow processes (Prager 2010).

Of particular note are large exposures of clast-supported polymict gravels incorporated into the rock avalanche from the valley floor. Sections of gravels ranging from several meters to more than 10 m in length are present at several sites along the Oetztaler Ache River (Fig. 303.1). In some cases, i.e. between hummocks, the gravels extend upward to the top of the deposit (Fig. 303.2a). They are not mixed with rock avalanche material, but rather the two are separated by very sharp boundaries (arrow in Fig. 303.2b). Individual elongate gravel clasts are oriented parallel to contact, supporting the inference that they were injected into the rock avalanche mass from below without further disruption by flow processes.

Farther from the source, the highly fragmented RA mass lies on disrupted sands; again the contact is very sharp, with no indication of mixing (Fig. 303.3). The sands appear to be sheared and they fine towards the RA contact. Whether this is primary or a result of rock avalanche emplacement is currently under investigation. The larger structures at outcrop scale suggest bulldozing of the sand sequence. Concurrent with this feature are compressional ridges when the rock avalanche ran up against the Amberg Ridge (background in Fig. 303.3). A few metres below the contact, gravels and sands retain their depositional layering.

The base of the rock avalanche is again exposed at the distal limit of the deposit, along with evidence for different stages of substrate interaction (Fig. 303.4). In this area, rock avalanche and substrate materials are thoroughly mixed in the lowest part of the RA deposit (I in Fig. 303.4), in contrast to the sharp basal contact without mixing in the more proximal area. The rock avalanche also entrained clasts of unconsolidated coarse sand that did not disintegrate (II in Fig. 303.4). Finally, the rock avalanche came to rest on *in situ* rust-coloured sands and gravels. It faulted (III in Fig. 303.4) and ductily deformed (IV in Fig. 303.4) them, with little or no mixing; faulting here is extensional. Some substrate material was injected into the RA debris over distances of several metres along extensional faults.

303.4 Preliminary Conclusions and Research Outlook

The outcrops at Tschirgant reveal extensive substrate involvement in the rock avalanche and provide a more complete picture of emplacement processes. (1) Large amounts of polymict gravels are found where tensile failure

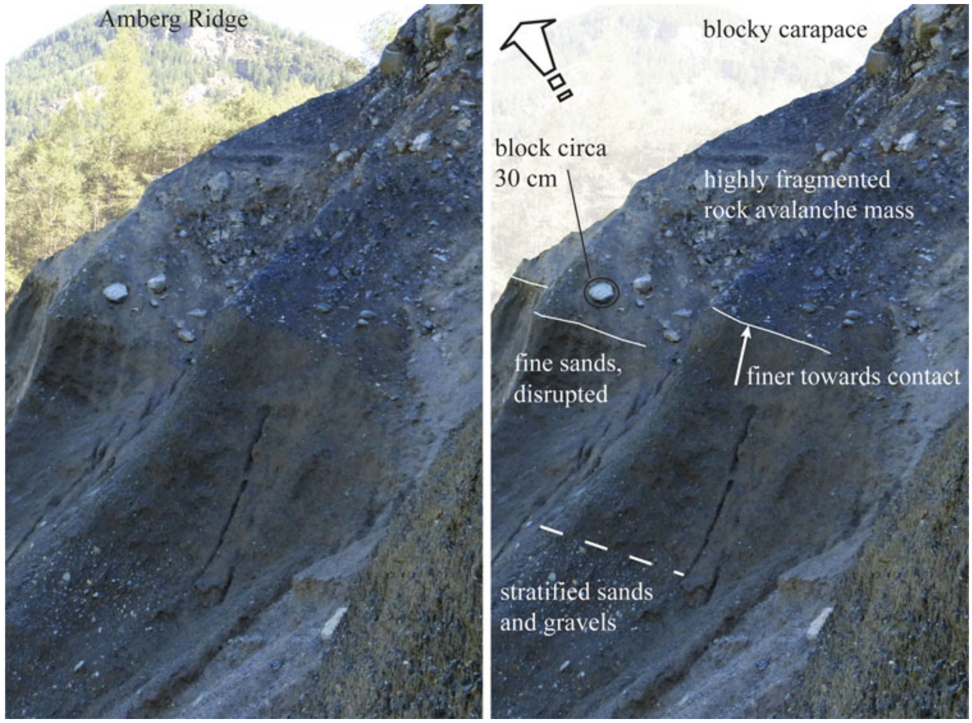

Fig. 303.3 Sharp contact of rock avalanche debris with underlying sands and gravels

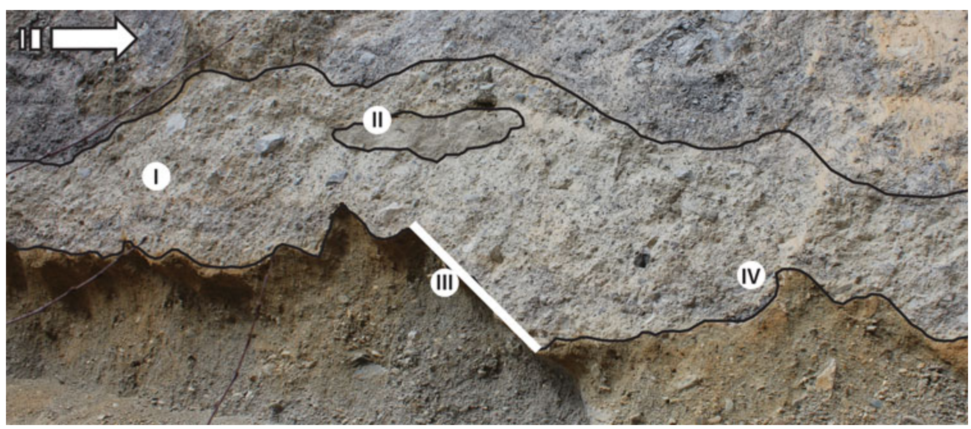

Fig. 303.4 Rock avalanche-substrate interaction at very distal sections of the rock avalanche deposit (after Dufresne, in press); see text for explanations. *Arrow* shows direction of rock movement; the section is about 4 m long

or horizontal separation of rock avalanche units (e.g. between hummocks) allowed the upward movement of substrate material into the rock avalanche mass. Incorporation of gravel into the rock avalanche most likely occurred towards the end of emplacement, therefore not contributing to runout dynamics. (2) Differential motion between rock avalanche units is evident from shearing and brittle offsets of entrained substrate. (3) Sharp contacts, lack of mixing and lack of crushing of entrained gravels generally characterize RA-substrate interaction features. The substrate may have behaved mechanically different from the fragmenting rock avalanche debris, or alternatively, fragmentation pressures may have been low at the time of their entrainment. (4) Only the distal section exhibits RA-substrate mixing in a narrow basal zone, suggesting a requirement for longer travel distances or particular substrate and/or RA properties to allow mixing.

Future research involves characterization of deposit morphology, substrate interaction, degree of fragmentation, grain size distribution, deposit fabric, distribution of lithological units, and topographic runout interference. We intend to compare these characteristics with those of other rock avalanche deposits to better understand processes that operate within, and particularly at the base, of rock avalanches and that contribute to runout behaviour.

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