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Sediment storage and transfer on a periglacial mountain slope (Corvatsch, Switzerland)

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ABSTRACT

High mountain geomorphology is mostly characterized by high elevation, steep gradients, rocky terrain, the presence of snow and ice and the related processes occurring in a high energy environment. Large sources of sediment and sediment storages often exist within high mountain systems and are controlled by the processes occurring within this setting. The purpose of this study is to describe sediment paths on a periglacial mountain slope and quantify geomorphic work within one example year in order to analyze and compare sediment budgets in high mountain geosystems. This energy-related approach helps to characterize a periglacial slope on account of the effectiveness of its geomorphological processes and might help to understand the complex dynamic behavior of its constituent subsystems.

A periglacial mountain slope is investigated in Eastern Switzerland (Corvatsch). The environment is characterized by a typical coarse debris cascade: rock wall → rock fall → talus slope → permafrost creep → rockglacier. Rockglaciers are considered to be sediment traps of the coarse debris system, reflecting the erosion history of the corresponding catchment. Headwall recession and creep processes of the talus slopes and rockglaciers are quantified by a multi-method-approach combining remote sensing and terrestrial methods. Multitemporal DEMs of the last two decades enabled the quantification of sediment transfer of the slow moving landforms (frozen talus slopes and rockglaciers). Sediment input from the rock wall is quantified by repeated laser scanning over the last 4 years. With the introduced cascading approach it is possible to assess dynamics within the coarse debris system. The mountain slope is divided into three subsystems (headwall, talus cone and rockglacier) and their dynamics are analyzed individually but also in relation to the entire mountain slope on a yearly base. A backweathering rate of 2 mm can be derived for the headwall and an energy transfer of 29.8 GJ from the headwall to the slope, 4 GJ from the talus slope to rockglacier where 1.44 GJ of geomorphic work are released by the downwards creep of the landform. This study is the first to include an analysis of the geomorphic work generated on the basis of vertically differentiated sediment production and transport processes.

1. Introduction

High mountain geomorphology is characterized by high elevation, steep gradients, rocky terrain, the presence of snow and ice and the resulting processes, forming a high energy environment (Barsch and Caine, 1984). Therefore, mountains deserve special attention within geomorphology, since environmental changes may occur on shorter time-scales and with lasting consequences and thus reflect the sensitivity of complex environmental systems. In a periglacial high mountain environment, it is assumed that changes in the temperature regime lead to respective changes in geomorphological processes such as weathering rates and transport rates. The outstanding landforms in such systems evolve over millennia and are related to constant temperature regimes during these periods, but we expect certain changes related to climate change to occur on shorter time scales; thus influencing the related processes. In most mountain ranges the topography is dominated by major erosional landforms (e.g., cirques) reflecting former dynamics, superimposed by more contemporary meso-relief-forms (e.g. moraines, talus cones), reflecting diverse process domains (Roer, 2007). Periglacial slopes are characterized by rockglaciers, ice-cored moraines or solifluction lobes and are often in close connection to glacial and gravitational landforms. All of these landforms are considered as significant indicators for changes within the system. The dynamic behavior of rockglaciers especially has been assessed in relation to regional climatic influences (Delaloye et al., 2010) but some rockglaciers still show erratic rheologies which cannot be accounted for by climatic drivers (Roer et al., 2008; Springman et al., 2013). An energy-based approach might help to understand the behavior of

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the rockglacier as a result of the state of the entire slope system. In order to describe sediment transfer in high mountain environments in a systematic context, Caine (1974) developed a conceptual model of alpine sediment cascades. This model describes the logical, cascade-like sequence of processes, based on an idealized slope profile. This approach has been adapted and applied within this study in order to assess an entire periglacial mountain slope.

Geomorphic work, energy fluxes and sediment transfer rates are among the main components in characterizing and comparing the potential energy of geomorphological systems (e.g., Reid and Dunne, 1996; Beylich and Warburton, 2007). The energy-based approach establishing geomorphic work as a measure for erosion intensity (Caine, 1976) allows the direct comparison of environmental systems and geomorphic processes on different spatial and temporal scales. Process rates and their changes can be analyzed by using energy fluxes and geomorphic work as indicators for their effectiveness. Based on the sediment budget approach, geomorphic work, energy fluxes and sediment transfer rates are often assessed for entire mountain ranges (e.g., Church and Slaymaker, 1989) or single gravitational processes (e.g. Krautblatter et al., 2012) but have rarely been used on a scale in between. Barsch and Caine (1984) pointed out that the sedimentary features such as talus cones and rockglaciers receive a lot of scientific attention whereas information on the source area, the rockwall and its connection to the cascading sediment system is lacking. Up to now, deficits exist in the knowledge of temporal and spatial coupling of nested geomorphological processes and complex interactions of different sediment storages (Dietrich and Dunne, 1978; Caine and Swanson, 1989; Schrott et al., 2003). Connectivity studies such as Fryirs et al. (2007) and Heckmann and Schwanghart (2013) have assessed the linkage of landforms and coupling between systemic entities. These connectivity approaches allow accounting for the discrepancy between erosion/mobilization of material and the sediment yield at the outlet of the system compartment which has been challenging to sediment budget studies (Caine and Swanson, 1989; Hooke, 2003; Fryirs et al., 2007).

In order to describe and quantify sediment transfer rates and to derive energy fluxes, information on geometrical changes within the system is required. Remote sensing data and geodetic measurements are frequently used to assess geometrical changes in periglacial high mountain areas (e.g. Campbell and Church, 2003; Roer et al., 2005; Avian et al., 2009; Bodin et al., 2009). These observations deliver information on ongoing processes and process changes and have so far not been applied for the investigation on energy fluxes on an entire slope. The study presented here combines three different methods to derive landform parameters for the analysis of sediment transfer rates and the calculation of geomorphic work. The study focuses on the sediment and energy transfer within one example year where the multitemporal data have been averaged. The process rates of old landforms (rockglaciers) are also quantified to fit a one year period. Beside DEM analyses derived from digital photogrammetry and geodetic field survey, terrestrial laser scanning (TLS) is applied in order to achieve a better understanding of geometry changes in the steep parts of the slope (upper talus slope and headwall). Sediment transfer paths of the rockglaciers have already been described by combining movement rates and sediment volumes (Gärtner-Roer and Nyenhuis, 2010; Gärtner-Roer, 2012).

The purpose of this study is to assess and quantify sediment transfer sediment paths on a periglacial and mountain slope and quantify geomorphic work in order to analyze and compare sediment budgets in high mountain geosystems.

2. Murtèl/Corvatsch Cirque

The field site is the well-studied Murtèl cirque situated below the northern face of Piz Corvatsch (3300 m a.s.l.) in Grison, which lies in the south-eastern part of Switzerland (at about 46 26′N/9 49′E) and expands over an area of 0.48 km^2. The lithology mainly consists of granite, granodiorite and greenschist. The density of the in-situ rock types is assumed to correspond with the values given in the literature with a density of 2.65–2.8 g/cm^3 (Tarbuck and Lutgens, 2011). The climate is characterized by air masses from the south-west. The annual precipitation averages 800 mm in the valley and 1000–2000 mm in higher altitudes. Gubler et al. (2011) show the distribution of ground surface temperatures within the entire Corvatsch area by using an extensive network of randomly distributed temperature loggers. Their temperature data show that the entire slope is situated within the permafrost belt as the existing rockglaciers (Murtèl and Marmugnun) already suggest. Due to the fact of easy accessibility the Murtèl site is one of the best investigated permafrost sites and numerous datasets (such as borehole, ground surface temperatures and kinematics) are available, especially from the rockglacier sites (Hoelzle et al., 2002; Schneider et al., 2012). Based on several studies it is known that the entire slope, down to an altitude of 2620 m a.s.l. (rockglacier front) is situated in discontinuous permafrost.

The north slope of Piz Corvatsch gives a typical periglacial mountain slope with a sequence of characteristic landforms: headwall, talus slopes or cones and rockglaciers. The Murtèl rockwall, the northern face of Piz Corvatsch, comprises the headwall of an ice-free cirque in which the Murtèl rockglacier has formed. The headwall consists of heavily shattered crystalline rocks and has been part of a more detailed analysis on frost weathering and rockwall erosion by Matsuoka (2008) which identified heavy shattering of the headwall with a mean crack width of 2 mm. The headwall supplies coarse bouldery debris to the entire cirque which has developed into the talus cone and two rockglaciers during the Holocene (Barsch, 1996; Haeberli et al., 1998; Matsuoka, 2008). The rockwall can be divided into two source areas supplying the rockglaciers with sediment. The entire headwall has a mean slope of 45° but most bedrock outcrops are 80°–90°. Small ledges within the headwall are covered with debris which developed into small debris cones. These cones lessen the overall steepness of the headwall. The talus cone is characterized by linear transport processes originating in the headwall. It serves as the subsequent sedimentary body to the headwall and consists of heterogeneous loose material. A sudden change in slope and the absence of bedrock identify the talus cone in the geomorphological setting. Permafrost creep and snow avalanches are considered to be processes responsible for sediment transport within the talus cone and on-/into the rockglacier. The Murtèl rockglacier has been identified as a talus derived rockglacier (Haeberli et al., 2006) where the buildup of subsurface ice (segregation ice and the incorporation of perennial snow banks and avalanche snow (Isaksen et al., 2000; Humlum et al., 2007)) within talus slope has led the material to behave fluidly and creep downwards. Therefore the talus slopes supply sediment by permafrost creep and secondary transport by avalanches and debris flows to the rockglacier. The Murtèl rockglacier can be identified by its well developed furrow and ridge topography and the outstanding rheological features. Despite the topographical differences between the landforms, their boundaries are often not detectable as clear lines but can be depicted as transition zones (see Figs. 1 and 2).

3. Concept, methods & data

3.1. Cascading concept

The periglacial high mountain system at hand can be interpreted as a closed system concerning coarse debris (Barsch and Caine, 1984) in the sense of Chorley and Kennedy (1971). The boundaries of the coarse debris system are clearly defined by the ridge of the headwall and the bottom of the rockglacier. There is no possible input of clastic material from outside the system and within this approach it can be assumed that there is no loss of sediment since only the coarse debris system is assessed. Suspended material and material in solution within the drainage water are of course existent but will not be assessed (Barsch and Caine, 1984; Jordan and Slaymaker, 1991). Sediment transfer rates and