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Efficiency of frost-cracking processes through space and time: An example from the eastern Italian Alps

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ABSTRACT

It is widely accepted that climate has a strong impact and exerts important feedbacks on erosional processes and sediment transport mechanisms. However, the extent at which climate influences erosion is still a matter of debate. In this paper we test whether frost-cracking processes and related temperature variations can influence the sediment production and surface erosion in a small catchment situated in the eastern Italian Alps. To this extent, we first present a geomorphic map of the region that we complement with published ^{10}Be-based denudation rates. We then apply a preexisting heat-flow model in order to analyze the variations of the frost-cracking intensity (FCI) in the study area, which could have controlled the sediment production in the basin. Finally, we compare the model results with the pattern of denudation rates and Quaternary deposits in the geomorphic map. The model results, combined with field observations, mapping, and quantitative geomorphic analyses, reveal that frost-cracking processes have had a primary role in the production of sediment where the intensity of sediment supply has been dictated and limited by the combined effect of temperature variations and conditions of bedrock preservation. These results highlight the importance of a yet poorly understood process for the production of sediment in mountain areas.

1. Introduction

During the past two decades, the extent at which climate influences erosion and limits the height of mountain ranges has been discussed in a controversial way, highlighting the difficulties in discriminating the effects of climate versus tectonic on denudation rates (Molnar and England, 1990; Raymo and Ruddiman, 1992; Egholm et al., 2009; Koppes and Montgomery, 2009; Thomson et al., 2010; Willenbring and von Blanckenburg, 2010; Egholm, 2013; Herman et al., 2013). More recently, the development of in situ produced, cosmogenic-nuclide techniques has allowed a substantial enrichment of data quantifying denudation rates in different regions of the world and on multisecular to millennial time scales. Still, denudation rate values measured through cosmogenic nuclides include the effects of a series of processes (e.g., physical and chemical weathering, sediment production, etc.) and conditions (e.g., hillslope-channel connectivity, transport capability of streams and rivers, etc.), which could be difficult to disentangle from each other but which influence the landscape's response to environmental changes (Harvey, 2002). This is particularly the case for cold regions and mountain areas not glaciated nowadays, where periglacial processes including frost-cracking have been proposed as a very efficient mechanism of bedrock erosion and sediment production (Anderson, 1998; Hales and Roering, 2005, 2007; Delunel et al., 2010, and references therein). As frost-cracking and related periglacial activities are mostly dependent on temperature-driven ice dynamics and water availability, they are strongly influenced by climatic oscillations. In this context, Anderson (1998) proposed a model in which the relationships between temperature gradients in bedrock and the depth at which frost cracking occurs were addressed. This author proposed that frost-cracking intensities increase at greater depths with decreasing surface temperatures. Hales and Roering (2007) expanded this model by considering hydrologic and heat-flow gradients in order to assess the role of frost-cracking and ice-segregation mechanisms for the conditioning of rockfalls. They suggested that not only the intensity of the frost-cracking increases with depth, but also that the efficiency of the frost-cracking mechanism reaches a maximum where positive mean annual air temperatures (MAATs) of ca. 0 °C prevail. More recently, Anderson et al. (2013) explored the role of regolith production as a function of temperature variations and introduced the concept of limited-water circulation that significantly affects the magnitude of frost-cracking prediction in permafrost environments. They also reported that aspect-related microclimates can influence the transport efficiency on hillslopes via creeping, which partially influences the patterns and rates of denudation. Although these studies indicate an important control of

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temperature variations and frost-cracking processes on the production of sediments, only little research has been carried out to assess the role of these variables in a natural environment (Hales and Roering, 2005, 2009; Matsuoka, 2008; Delunel et al., 2010).

Here, we focus on a formally glaciated catchment, located in the southeastern Alps of Italy, which we use to test whether frost-cracking processes could be invoked to explain the pattern of sediment production and denudation in this basin. To this extent, we present a geomorphic map of the region along with the results of ^{10}Be-based denudation rates that we have published before. We then apply a model that allows us to calculate patterns of frost-cracking intensities in the studied catchment, following the approach proposed by Hales and Roering (2007). In a subsequent step, we reconstruct the temperature variations through the Holocene, based on a compilation of published climatic proxy data (Heiri and Lotter, 2005; Ilyashuk et al., 2011). We use this information to explore how climate changes might have influenced the temporal and spatial patterns of denudation rates in the basin if sediment production would have predominantly been accomplished by frost cracking processes.

2. Settings

We conducted our study in the Zielbach catchment (33.5 km^2) located in the southeastern Alps of Italy (Fig. 1), in which the spatial and temporal distribution of sediment supply was already reconstructed in previous publications (Savi et al., 2014a,b).

2.1. Background

The Zielbach catchment can be divided into two distinct subbasins based on the main mechanism of sediment transfer (Savi et al., 2014a). In particular, a debris flow tributary is located in the southeastern margin of the basin and covers an area of ca. 2.3 km^2. Basinwide denudation rates reported for this tributary average at ~1.6 mm/year, though highly variable in space (variance of 1.3). In contrast, the Zielbach main catchment (25.5 km^2), representing >90% of the whole basin's area, is characterized by the predominant occurrence of alluvial and fluvial processes that have primarily reworked glaciogenic material, which has been previously accumulated on the slopes. Averaged

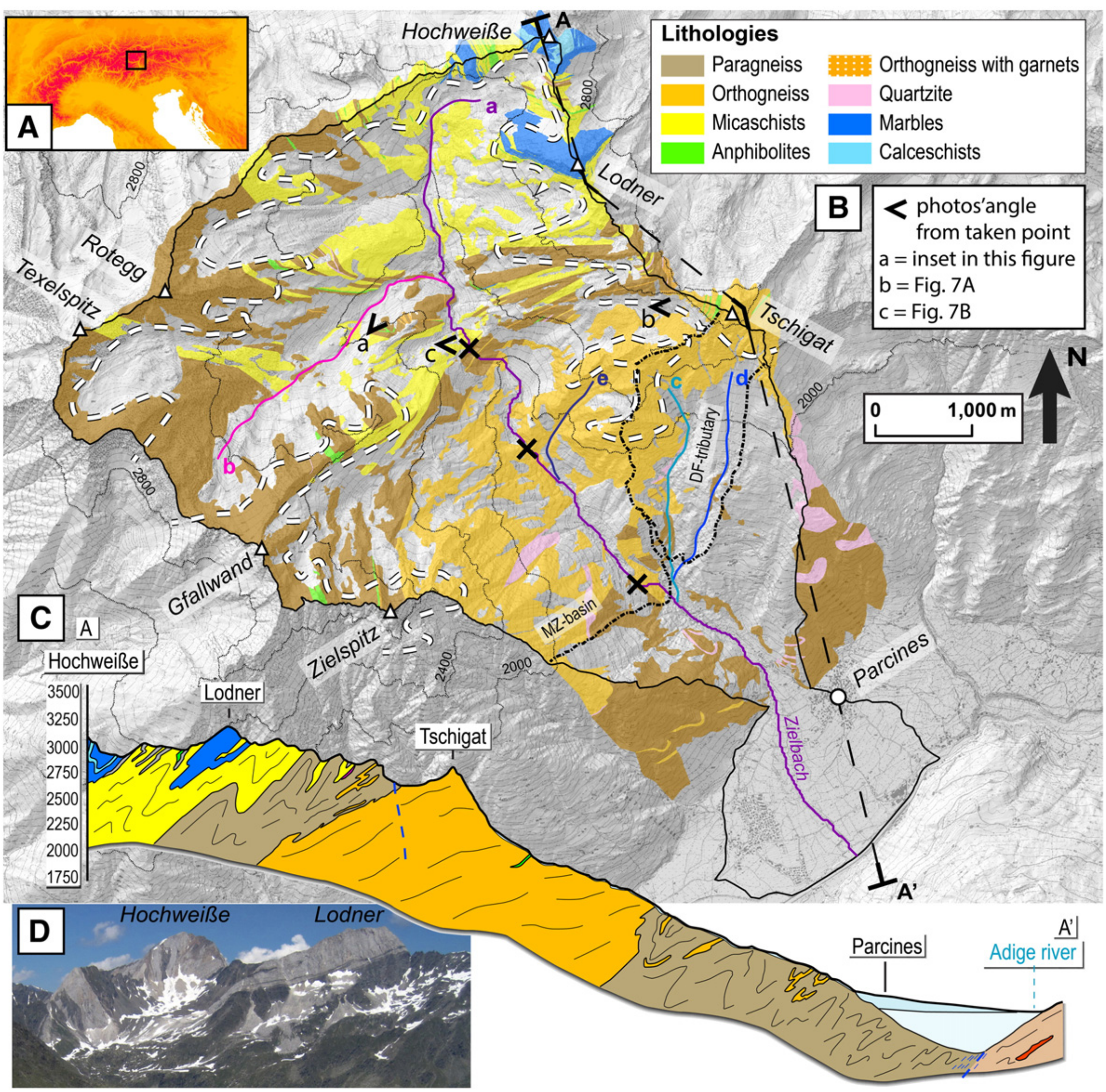

Fig. 1. Zielbach catchment. (A) Inset showing the location of the study area in the eastern European Alps. (B) Lithological units cropping out in the catchment with indication of the major peaks' name. White dashed line delineates the nunataks and ridges above the maximum ice altitude, based on recognition on the field of trimline and glacial landforms. Dotted black lines delineate the watershed divide of the main Zielbach catchment (MZ-basin) and debris flow tributary (DF-tributary). The color and code on the channels is visualized in Fig. 2. Black crosses along the main channel indicate the location of the major knickzones. (C) Cross section of the A–A′ profile shown in (B) (modified from Bargossi et al., 2010). (D) Picture showing the marble outcrops on the Hochweiße and Lodner peaks.