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Invited research article

Interpretation of recent alpine landscape system evolution using geomorphic mapping and L-band InSAR analyses

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ABSTRACT

Alpine landscapes are typically characterized by inherited features of past glaciations and, for the more recent past, by the interplay of a multitude of types of geomorphic processes, including permafrost creep, rockfalls, debris flows, and landslides. These different processes usually exhibit large spatial and temporal variations in activity and velocity. The understanding of these processes in a wide alpine area is often hindered by difficulties in their surveying. In this study, we attempt to disentangle recent changes in an alpine landscape system using geomorphic mapping and L-band DInSAR analyses (ALOS-PALSAR) in the Zermatt Valley, Swiss Alps. Geomorphic mapping points to a preferential distribution of rock glaciers on north-facing slopes, whereas talus slopes are concentrated on south-facing slopes. Field-based interpretation of ground deformation in rock glaciers and movements in talus slopes correlates well with the ratio of InSAR images showing potential ground deformation. Moraines formed during the Little Ice Age, rock glaciers, and talus slopes on north-facing slopes are more active than landforms on south-facing slopes, implying that the presence of permafrost facilitates the deformation of these geomorphic units. Such deformations of geomorphic units prevail also at the elevation of glacier termini. For rock cliffs, the ratio of images indicating retreat is affected by slope orientation and elevation. Linkages between sediment supply from rock cliffs and sediment transport in torrents are different among tributaries, affected by relative locations between sediment supply areas and the channel network. We conclude that the combined use of field surveys and L-band DInSAR analyses can substantially improve process understanding in steep, high-mountain terrain.

1. Introduction

Alpine landscapes are constantly shaped by a multitude of geomorphic processes with largely differing spatial and temporal activity, such as rockfalls, floods, permafrost creep, debris flows, or landslides (e.g., Haeberli et al., 2006; Korup et al., 2010; Lugon and Stoffel, 2010; Schneuwly-Bollschweiler and Stoffel, 2012; Barboux et al., 2014). Understanding their rates and patterns of activity is usually restricted to field surveys at individual sites, such that studies focusing on larger surface areas have remained relatively scarce. In the past, geomorphic mapping has been based widely on aerial photograph interpretations, analyses of airborne LiDAR (light detection and ranging) data, and field surveys to interpret types of processes occurring in alpine environments (e.g., Ikeda and Matsuoka, 2002; Lugon et al., 2004; Otto et al., 2009). However, and because present landscapes are a result of current and past geomorphic processes, detection of current process activity is often limited in cases where interpretation relies on geomorphic mapping alone. On the other hand, field monitoring and periodical LiDAR surveys provide quantitative data on current geomorphic activity but also require substantial labor and budgets.

The Interferometric Synthetic Aperture Radar (InSAR), by contrast, can be used to detect small deformations of the ground surface (in the order of millimeter to centimeter) and has been used in recent years for the detection of activity of volcanic (Lu et al., 2010; Schaefer et al., 2015), rockfall (Arosio et al., 2009; Rouyet et al., 2017), landslide (Peyret et al., 2008; Jebur et al., 2014; Singleton et al., 2014;

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Nishiguchi et al., 2017), and rock glacier (Liu et al., 2013; Barboux et al., 2014) processes. Recent results are promising, and the approach is thought to greatly improve understanding of geomorphic systems in alpine environments.

The choice of sensors and analysis methods in InSAR-based studies is typically based on land cover, characteristics of the geomorphic processes, and available data. For example, ground based InSAR (GB-InSAR) is frequently used for the detection of rockfall activity in fairly small areas (Arosio et al., 2009; Rouyet et al., 2017) because rockfall source areas are usually on subvertical slopes in which space-borne InSAR analyses repeatedly fail because of the problem of layover (Bamler and Hartl, 1998). In contrast, space-borne SAR images are usually used for the detection of ground surface deformation in those areas where topography is more gentle (Saroli et al., 2005; Liu et al., 2010). Permanent Scatter Interferometric Synthetic Aperture Radars (PSInSAR) are usually employed in areas with artificial structures (Strzelczyk et al., 2009), as the latter can be used as stable radar targets (or as so-called PS points). Finally, differential InSAR (DInSAR) approaches using L-band images are applicable in those areas covered by deep forests, lacking artificial structures that could be used as PS points (Roering et al., 2009; Barboux et al., 2014; Nishiguchi et al., 2017).

Interestingly, a large array of published work focused on a very specific geomorphic process, such that only very few studies have attempted to understand entire geomorphic systems by single InSAR analysis so far (Barboux et al., 2014). As a consequence, a clear need exists for analytical procedures that are able to detect activity of various mass transfer processes and therefore can enhance our understanding of larger, and often complex, geomorphic systems.

The data used in this study was generated by a phased array type L-band Synthetic Aperture Radar (PALSAR), which was mounted on the Advanced Land Observing Satellite (ALOS). The device is classified as an L-band SAR and was launched on 24 January 2006. The wavelength of PALSAR is longer than the X-band radar (typified by COSMO-SkyMed and TerraSAR-X) and the C-band radar (typified by Envisat and RADARSAT-2), which have been widely used in Europe and North America in the past. Although the resolution of the X- and C-band SARs are higher than that of the L-band SAR, PSInSAR, a widely used technique for the analysis of X- and C-band SAR images, requires PS points (Strzelczyk et al., 2009; Oliveira et al., 2015). Therefore, any DInSAR analyses using PALSAR images will have clear advantages in the detection of any ground surface deformation in areas lacking artificial structures (Strozzi et al., 2005; Roering et al., 2009). In addition, coherence of InSAR analysis using short wavelength images (i.e., C-band SAR) has been demonstrated to be generally low for long observation periods (>100 days) between images, mainly because of changes in ground surface conditions (Zebker and Villasenor, 1992). By contrast, past studies based on L-band SAR have shown clearly that image pairs with longer observation periods can be used without major problems (Wei and Sandwell, 2010; García-Davalillo et al., 2014) and that L-band SAR seems ideal for the detection of moderate ground surface deformations (Nishiguchi et al., 2017).

The purpose of this paper is to understand geomorphic process activity and changes over time in an alpine high-relief landscape system of the Swiss Alps by coupling field-based geomorphic mapping with L-band DInSAR analysis based on PALSAR images. The DInSAR analysis was used to interpret the spatial variability of geomorphic processes over a wide alpine area, which is too large to be covered by field surveys alone. Results of DInSAR analysis were cross-validated by field surveys in order to avoid misinterpretation affected by topography, atmosphere, and noise (Roering et al., 2009; García-Davalillo et al., 2014). By doing so, we interpret recent activity of various types of geomorphic processes, including movements of rock glaciers, rockfalls, landslides, and deformation of talus slopes and moraines, in the Zermatt Valley (also referred to in the literature as Mattertal or Matter Valley). We selected ALOS/PALSAR material rather than images from the currently working sensors (e.g., ALOS-2/PALSAR-2). This choice was motivated by the fact that the number of image pairs observed by the new L-band sensors is not yet large enough for the analyses of geomorphic processes in the study area. Although ALOS has already retired, our findings using PALSAR images are considered to be beneficial for the analysis of other L-band sensors as well.

2. Study area

The study was conducted on the east-facing slopes of the Zermatt Valley, a very deep and narrow glaciated valley; the study area is located in the southern Swiss Alps and is 10 km wide and 3 km deep and has a surface of 99 km^2 (Fig. 1). Geomorphology in the Zermatt Valley is characterized by a large array of mass transfer processes, including permafrost creep (Lugon and Stoffel, 2010; Wirz et al., 2016), rockfalls (Stoffel et al., 2005), landslides and rockslides (Willenberg et al., 2008b; Stoffel and Huggel, 2012), and debris flows (e.g., Bollschweiler and Stoffel, 2010; Schneuwly-Bollschweiler and Stoffel, 2012; Stoffel et al., 2014). The basement rock in this area, mainly Permian gneiss and quartzite, is hard when intact but becomes highly deformed and fractured by folding, gravitational creep, and periglacial processes (Willenberg et al., 2008b).

The western tributaries of the Mattervispa River cut the steep slopes of the Zermatt Valley and are aligned in a north-south direction in the study area. Above treeline, locally at about 2200 m asl, alpine grasslands spread over previously glaciated, gentle terrains between 2400 and 2600 m asl and are surrounded by steep and high mountains, the summits of which range from 3100 to 4505 m asl (Fig. 1B). Many of the slopes underneath these summits are underlain by permafrost (Gruber and Hoelzle, 2001). Rock glaciers and talus slopes, composed of rock debris derived from outcrops of these mountains, are distributed near the boundaries between these high mountains and the gentle terrains (Fig. 1B). Vegetation cover is very limited on mountains and on most of the rock glaciers and talus slopes. Glaciers are widespread at the highest elevations of the large tributaries (>2800 m asl) but have retreated significantly since the end of the Little Ice Age (LIA) around 1850 CE (Joerin et al., 2006).

Sub-vertical, glaciated rock cliffs (40°–80°) are exposed at elevations ranging from 1000 to 2400 m asl along the Mattervispa River (Fig. 1C). In April and May 1991, a series of rockslides with a total volume of 30 million m^3 severely altered the landscape around Randa (Willenberg et al., 2008a, 2008b). A number of smaller slope failures (with areas <10,000 m^2) have occurred on other rock cliffs. Between these rock cliffs, conifer trees grow in tiny flat spaces. Farther down, debris flow fans occur at the confluence of tributaries with the Mattervispa River, whereas talus slopes can be found mostly at the base of rock cliffs.

On the sparsely wooded surfaces around 1800 m asl, annual average precipitation is estimated to be 660 mm (Stoffel et al., 2005). Precipitation is highest between August and November when persistent rain from low-pressure masses in the Mediterranean Sea may penetrate into this inner-alpine valley. At elevations above 2400 m asl, snow usually covers the slope from autumn to spring. Snow covers some portion of the study area above 2900 m asl even in summer, especially on north-facing slopes (where avalanche deposits may sometimes persist for several years). Snow accumulation is much more limited on the steep rock cliffs at elevations of 1000 to 2400 m asl, even in winter. Mean annual air temperature in Zermatt (1638 m asl), 18 km south of St. Niklaus, is 3.9 °C (1900–2008) (Stoffel et al., 2013). Using a temperature lapse rate of 5 °C km^{-1}, mean annual air temperature at 2400 m asl is estimated to be −0.1 °C.

3. Material and methods

3.1. Mapping of geomorphic units

The spatial distribution of seven major geomorphic units was mapped in a geographical information system (GIS) using digital