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Giant non-catastrophic landslides and the long-term exhumation of the European Alps

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ABSTRACT

Landslides influence local slope morphology, affect sediment flux from hillslopes to rivers, and mass wasting in response to tectonics and climate forcing. However, the links between giant, non-catastrophic landslides known as Deep-Seated Gravitational Slope Deformations (DSGSDs) and the long-term evolution of orogenic landscapes are almost unknown. We explore these links in the European Alps using the first orogen-scale inventory of DSGSDs (> 900 over an area > 10^5 km^2) and a dataset of published apatite fission-track ages (> 1000) that provides an estimate of the long-term exhumation patterns of the orogen. We show that DSGSDs are more widespread than previously considered, and exhibit an orogen-scale distribution not explained by well-known local lithological and structural controls. We test the hypothesis that this orogen-scale distribution correlates to the long-term evolution of the Alps by subdividing the study area into 37 square sub-areas (50×50 km), classified according to combinations of long-term exhumation and mean annual rainfall. On each sub-area we perform a morphometric analysis of topography (hypsometry, relief, slope). Excluding local and regional controls due to rock type and structure, DSGSDs tend to cluster in areas with intermediate exhumation rates (fission-track age between 10 and 40 Ma), where large-scale topography is less dissected and incision is localised along major valleys. Here DSGSD abundance correlates positively with the degree of valley incision and related relief. Instead, DSGSDs lack in areas which underwent either low exhumation rates, resulting in insufficient relief production, or high exhumation rates associated to rapid uplift or higher erosional dissection of topography. Negative correlation between DSGSD abundance and mean annual rainfall suggests that effective hydrological surface processes contribute, on the long-term timescale, to the development of large-scale topography unfavourable to DSGSDs, especially in areas of high exhumation rates. Where DSGSDs are abundant, long-lasting slope deformations effectively adjust post-glacial relief by reducing slope inclination values, and are thus expected to significantly contribute to the long-term denudation of active orogens.

1. Introduction

Competing tectonic and surface processes build and destroy topography in active orogens. Thrusting, crustal thickening and isostatic response result in rock uplift and relief production. Glacial, fluvial, and mass wasting processes erode topography, leading to rock exhumation and sediment redistribution under lithological and climatic controls (England and Molnar, 1990; Burbank and Anderson, 2001). Understanding the relative contributions and possible interplays between different processes which control the long-term evolution of orogenic landscapes is required to validate and improve existing geomorphological models of landscape evolution, outline new research directions, and provide useful hints in a geohazard perspective. While the feedbacks between tectonics and fluvial erosion have been widely studied (Ahnert, 1970; Whipple, 2004), the links between landslides and landscape development in active orogenic belts are much less clear and often neglected in quantitative geomorphological models (Densmore et al., 1997; Korup et al., 2010). The geomorphic role of landslides has only been accounted for in the framework of fluvial systems and processes, with threshold hillslopes rapidly adjusting to changes in incision rates, in turn responding to climate change or tectonic processes (Burbank et al., 1996; Montgomery, 2001). In such framework, landslides affect hillslope and channel profiles, as well as sediment transfer by soil or bedrock landslides and rock avalanches (Hewitt, 1998; Densmore and Hovius, 2000; Montgomery, 2001; Korup, 2006; Korup et al., 2007; Brardinoni et al., 2009). Instead, very little is known about the relationships between giant, non-catastrophic

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landslides known as Deep-Seated Gravitational Slope Deformations (DSGSDs, *sackungen*) and the long-term evolution of topographic relief in active orogens.

In the mid-twentieth century this class of slope instabilities was almost completely unknown and sometimes neglected. Starting from the 1970s, DSGSDs were recognised and classified, but still considered as "outliers" of alpine morphogenesis, rare processes limited to peculiar lithological or structural settings. Today, the increasing availability of local to regional-scale DSGSD datasets (Ambrosi and Crosta, 2006; Agliardi et al., 2009; El Bedoui et al., 2011; Pedrazzini, 2012), extensive geological data and advanced investigation tools allow recognising that DSGSDs are widespread, often active, and long-lasting slope instability phenomena (Crosta et al., 2008; Agliardi et al., 2012). Thus, their potential contribution to landscape evolution deserves to be evaluated and eventually accounted for in geomorphological models. Nevertheless, the dramatic variability of the geological and morphological features, geometry, and mechanisms of DSGSDs has often hampered a sound understanding of the factors controlling their distribution, especially when the spatial scale of entire mountain belts is considered. This points to the need for large DSGSD datasets to investigate the local and regional controls on their distribution, geomorphic significance at orogen scale, and relationships with the long-term geological and topographic evolution of mountain ranges. Such large datasets lack, since most landslide inventories presented in the literature were focused on large, catastrophic landslides occurred in the European Alps (i.e. rockslides/rock avalanches; Montandon, 1933; Abele, 1974; Eisbacher and Clague, 1984; Heim, 1932), but did not account for DSGSDs.

In this work, we exploit the first orogen-scale inventory of DSGSDs (Crosta et al., 2008; Agliardi et al., 2012) prepared for the European Alps, one of the most studied orogenic belts worldwide. The inventory includes more than 900 individual DSGSD, mapped in different lithological, structural and morphological settings across the whole belt. We analyse the spatial distribution of DSGSDs and their relationships with lithology and topography, and outline different types of spatial clustering of these phenomena. Here we test the hypotheses that (1) distribution of DSGSDs at the orogen scale correlates to the patterns of long-term evolution of the belt; and that (2) DSGSD has a significant impact on topographic relief.

2. Distribution of DSGSD in the European Alps

DSGSD is a class of mass movement involving entire high slopes from their toes to or beyond the ridges, characterised by relatively low displacement rates (few to tens of mm/a; Varnes et al., 1990; Ambrosi and Crosta, 2006; Agliardi et al., 2012) but large cumulative displacements testifying non-catastrophic, long-term activity. Typical morpho-structural expressions of DSGSD include multiple ridges, trenches, scarps, counterscarps, and half-grabens which dominate in the upper slope sectors, while bulging, buckling folds, enhanced rock fracturing, and secondary, potentially catastrophic rockslides may occur in the lower slope sectors (Fig. 1). The kinematic interpretation of individual morpho-structural features and their associations allows reconstructing the geometry and mechanisms of DSGSD, especially when subsurface site investigation data are lacking. DSGSDs with typical morpho-structural expressions usually involve areas exceeding 10 km^2, whereas smaller phenomena show features transitional to those of typical large landslides (Agliardi et al., 2012).

Several possible triggers of DSGSD have been proposed. Interacting topographic and tectonic stresses in both isotropic and anisotropic rock masses induce shear stress concentrations at slope toes and extensive tensile damage along ridges. These effects scale with topographic relief and may induce large scale instability depending on rock mass strength and local structural controls (Varnes et al., 1989; Miller and Dunne, 1996; Kinakin and Stead, 2005; Ambrosi and Crosta, 2011). In alpine areas, the deglaciation of high, oversteepened valley sides carved by Pleistocene glaciers caused slope debuttressing, increased stress concentrations, fracture unloading and damage, and changes in slope hydrology (Augustinus, 1995; Crosta, 1996; Ballantyne, 2002). Fluvial erosion has also been suggested as a DSGSD trigger in layered sedimentary rocks (Crosta and Zanchi, 2000), whereas ground shaking and coseismic displacements during moderate to strong earthquakes have been suggested to contribute to ongoing DSGSD (Moro et al., 2007).

DSGSD distribution and morpho-structural features on local to regional scale reflect significant structural controls, pointed out at several study sites thanks to structural field data and numerical modelling (Hippolyte et al., 2006; Agliardi et al., 2009). Inherited tectonic features control (at least passively) DSGSD on three different scales. At the outcrop scale, rock fabric and structure influence rock mass strength, deformability and kinematic degrees of freedom. At slope scale, master fractures constrain the occurrence, type, and geometry of major morpho-structures, and thus the localisation and kinematics of DSGSD (Agliardi et al., 2001). At regional scale, major features including nappe boundaries and regional faults act either as loci of preferential linear clustering of DSGSD (e.g. low-angle regional faults and related rocks; Agliardi et al., 2009) or as geometrical barriers (e.g. juxtaposition of different lithological domains along subvertical faults; Ambrosi and Crosta, 2006).

Our DSGSD inventory extends over an area exceeding 10^5 km^2 across Italy, France, Switzerland, and Austria, and encompasses most of the European Alps (Fig. 2a and supplementary Fig. S1). It is based on interpretation of satellite imagery, cross-validated by literature data, aerial photos (both stereo and orthophotos, nominal scales ranging between 1:10,000 and 1:30,000), high-resolution LIDAR topography, and local field surveys. DSGSDs were initially mapped in GoogleEarth™ and then incorporated into a GIS platform for further processing. To avoid operator biases, DSGSDs were mapped as polygons by a single expert without using *a priori* geological or historical information. DSGSDs were recognised and distinguished from either tectonic features or large landslides *s.s.* using diagnostic criteria including: involvement of entire valley slopes and ridge splitting by laterally-continuous upper limiting scarps; occurrence of gravitational morpho-structures reactivating inherited tectonic features (but mostly less persistent and rectilinear); large displacements localised along individual morpho-structures (up to tens of metres); dislocation of slope toes and changes in valley cross profiles, but limited evacuation of unstable masses from the slope (typical feature of landslides s.s.); evidence of controls on local drainage networks (ponding, lakes, captures) and Quaternary landforms and deposits, especially related to glacial and periglacial environments. Inventory sub-samples were cross-validated by comparison with existing local inventories, compiled with different techniques (i.e. historical data collection, aerial photo-interpretation, field surveys) on local to regional scales (Mortara and Sorzana, 1987; APAT, 2008; Ambrosi and Crosta, 2006; Agliardi et al., 2009; Korup and Schlunegger, 2009; El Bedoui et al., 2011; Pedrazzini, 2012).

Rock type control on DSGSD distribution was evaluated by contrasting the inventory map with a regional lithological map, obtained by combining 1:500,000 geological maps available for Switzerland and Italy (Swisstopo, 2007; Bigi et al., 1983; available over 82,500 km^2, 725 DSGSDs covered). The lithological map was