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Mid-Holocene cluster of large-scale landslides revealed in the Southwestern Alps by ^{36}Cl dating. Insight on an Alpine-scale landslide activity

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ABSTRACT

Although it is generally assumed that the internal structure of a slope (e.g. lithology and rock mass properties, inherited faults and heterogeneities, etc.) is preponderant for the progressive development of large-scale landslides, the ability to identify triggering factors responsible for final slope failures such as glacial debuttressing, seismic activities or climatic changes, especially when considering landslide cluster at an orogen-scale, is still debated. Highlighting in this study the spatial and temporal concordant clustering of deep-seated slope failures in the external Southwestern Alps, we discuss and review the possible causes for such wide-spread slope instabilities at both local and larger (Alpine) scale.

High resolution field mapping coupled with electrical resistivity tomography first allows establishing an inventory of large landslides in the Southwestern Alps, determining their structural model, precising their depth limit (100–200 m) as well as the involved rock volumes ($>10^7$ m^3). We show that they developed in the same geostructural context of thick mudstone layers overlain by faulted limestone and followed a block-spread model of deformation that could evolve in rock-collapse events.

Cosmic ray exposure dating (CRE), using both ^{36}Cl and ^{10}Be in coexisting limestone and chert, respectively, has been carried out from the main scarps of six Deep Seated Landslides (DSL) and leads to landslide-failure CRE ages ranging from 3.7 to 4.7 ka. They highlighted: (i) mainly single and fast ruptures and (ii) a possible concomitant initiation with a main peak of activity between 3.3 and 5.1 ka, centered at ca 4.2 ka.

Because this region was not affected by historical glaciations events, landslide triggering by glacial unloading can be excluded. The presented data combined with field observations preferentially suggest that these failures were climatically driven and were most likely controlled by high pressure changes in the karstic medium. In effect, the chronicle of failure-ages is concomitant to a well-known climatic pulse, the "4.2 ka" climate event characterized by intense hydrological perturbations associated to the heaviest rainfall period of the entire Holocene. Despite requiring further investigations and discussions, the dating of numerous events across the entire Alps during the middle Holocene period suggests a potential synchronous triggering of several large-scale gravitational-failures induced by the mid-Holocene climatic transition.

1. Introduction

Large-scale ($>10^6$ m^3) landslides play first order roles in dismantling mountain ranges (Korup et al., 2010; Larsen and Montgomery, 2012), limiting relief growth (Larsen and Montgomery, 2012; Roering, 2012), controlling long term denudation rates and associated sediment flux (Zech et al., 2009; Hsieh and Chyi, 2010), modifying topography and landscape environment (Hewitt, 2009; Korup and Clague, 2009), and, last but not least, generating strong hazards and thus associated risk for human activities (Kilburn and Pasuto, 2003; Eeckhaut and Hervás, 2012). The recent review published in a special issue of *Geomorphology* edited by Crosta and Clague (2009) pointed out however that, mainly due

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to the fact that they evolve on time scales (>10^4 yrs) hampering their study (Larsen and Montgomery, 2012; Roering, 2012), several mechanisms leading to the occurrence of large-scale landslides still remain misunderstood.

Numerous studies (Martino et al., 2004; Pollet, 2004; Prager et al., 2008; El Bedoui et al., 2009; Le Roux et al., 2009) have established that large-scale slope failures do not evolve temporally linearly but can be separated in distinct phases of temporal evolution. There is firstly a progressive pre-failure phase evolving on time scale up to 10^4 years characterized by slow sliding rates ranging from few mm yr^{-1} to cm yr^{-1} and related to the chemical and mechanical weathering rates of the rock slope continually submitted to gravity and external solicitations. It broadly results in the progressive development of cracks and possible changes in the hydrological properties of the slope which ultimately affect its equilibrium. Then, either the slope still evolves progressively and slowly, generating shallow landslides and progressive dismantling or, once the general properties of the slope are weakened, the effect of a highly energetic solicitation of the landscape, called triggering factor, could drastically modify the stability conditions and cause the final slope collapse.

Understanding the factors and mechanisms leading to the transition from a progressive failure toward a sudden and rapid event is the challenge for a better risk management (Hewitt et al., 2008). Whilst the triggering factors currently evoked are paraglacial slope processes (see a review in McColl, 2012), climatic changes (Bookhagen et al., 2005; Borgatti and Soldati, 2010), or tectonic activity (Jibson et al., 2004; Antinao and Gosse, 2009; Lebourg et al., 2009, 2014), substantial debates are still ongoing to clearly point out which one is the most influencing and controlling factor (Crosta and Clague, 2009). Especially in the Alps, many visions oppose. While few studies suggested a primary control by tectonic activities (Persaud and Pfiffner, 2004; Ambrosi and Crosta, 2006; Hippolyte et al., 2006; Sanchez et al., 2009), a link between past climate variations and landslide occurrences was also often suggested, but this has been rarely demonstrated on the basis of convincing evidence (Le Roux et al., 2009; Borgatti and Soldati, 2010).

More generally, it remains difficult to study these movements on time scales on the order of thousands of years and consequently first order questions still remain unsolved or partly answered. For example: does a time of recurrence exist for large-scale landslide failures when considering a mountain range scale, or are large landslides purely stochastic geomorphic processes?

To elucidate such questions, temporal and spatial inventories up to the mountain range scale are crucial to assess the random or clustered trends of the landslide distribution (Hewitt et al., 2008; Korup et al., 2010; Ostermann and Sanders, 2011). Furthermore, comparing chronologically clustered landsliding with the chronology of past climate variations and other significant events (such as paleoseismicity chronicles, glacier retreat phases, etc.) chronology may also lead to a broader knowledge of landslides triggering (McColl, 2012). At a mountain-range scale, performing such analysis is a long and fastidious task that however progressively derives from several studies.

During the last ten years, several studies using Cosmic Ray Exposure (CRE) dating and other absolute dating methods succeeded in reconstructing landslide inventories on the Holocene scale in different mountain ranges such as the New Zealand Alps (Hancox and Perrin, 2009), the Himalayas (Dortch et al., 2009), the Nanga Parbat-Haramosh Massif (northern Pakistan) (Hewitt, 2009) and the Chilean Andes (Antinao and Gosse, 2009).

Regarding the European Alps, the numerous studies dealing with the timing of large landslide failures published over the last ten years have provided a large dataset, a pre-requisite necessary to better understand the driving mechanisms and rates of large Holocene landsliding in that region. However, up to now, no comprehensive study has tried to review these dated events at the scale of the mountain belt and to cross-correlated them to eventually evidence any potential trends.

To address parts of these substantial issues, the chronological development of several large landslides recently discovered in the southwest external part of the European Alps (Fig. 1) was investigated using the CRE dating method. In addition to geomorphological investigations, the landslide causes and their failure mechanisms using more than thirty absolute CRE ages were analyzed. The obtained results allow us to discuss the Holocene triggering of the studied landslides according to recently evidenced constraints on past climate variations and to demonstrate, for the first time in the European Alps, a clear relationship between the temporally grouped collapse of these landslides and the so-called 4.2 ka event (Magny et al., 2009, 2012; Simonneau et al., 2012; Walker et al., 2012 and reference therein), a severe paleohydrological pulse. Furthermore, a thorough review of the database constituted from the published large-scale landslide chronicles throughout the Alps strongly suggests a period of synchronous gravitational failures at larger scale, which could be linked to this climatic event.

2. Geo-structural and geomorphological settings of the study area

The study area is located in the southeast of France, roughly 15 km north of the Mediterranean coastline, close to Cannes and Nice (Alpes Maritimes). Morphologically, it is a moderately elevated mountain range whose altitudes range from 200 to 1200 m. Geologically, this area is on the first southern forefront of the southern Subalpine chains bounded to the north by the elevated crystalline massif of the Argentera (external massifs), and, to the south, by the Ligurian oceanic domain and its steep and narrow margin (e.g. Calais et al., 2000). Interestingly, the study area has not been affected by any glaciations during the last thousands of years (Darnault et al., 2012 and reference therein), allowing to reject glacial debuttressing as a possible control factor on the gravitational processes, and thus simplifying the discussion of the landslide triggering.

The southern Subalpine chains, better known as the Castellane and the Nice arcs, consist in a series of S to SW-verging thrusts and folds involving Mesozoic to Paleogene sedimentary cover (Fig. 1). This sedimentary cover, previously deposited above the crystalline basement of the Argentera-Taneron-Esterell on the northern Tethyan margin (De Graciansky et al., 1989), was globally pulled out above a basal decollement zone within the upper Triassic gypsum and mudstones (Laurent et al., 2000). This southward thrusting occurred mainly during the Miocene as a result of the successive NS compressional phases related to the exhumation of the crystalline massif of Argentera at the end of the Alps orogenesis (Giannerini et al., 2011; Sanchez et al., 2011) that pursued during the Pliocene and the Quaternary under similar stress fields (Larroque et al., 2011). Nowadays, these deformations have given rise to a superimposition of fractured Jurassic limestone units, bounded by major N40° and N160° strike slip faults, and overlying highly tamped and thickened Triassic soft rocks (Spini, 1978) which constitute a geological context highly prone to landslide events. From a hydrological standpoint, several deep karstic aquifers develop within each limestone unit, overlying the thick impervious level of Triassic mudstone. Because bedding planes, and thus the contact between karstified limestone and mudstone level (aquiclude), typically dips (15–30°) toward the slope interior, groundwater reserves are permanent.