Geomorphology 208 (2014) 1–10

Contents lists available at ScienceDirect

Geomorphology

journal homepage: www.elsevier.com/locate/geomorph

A Late Holocene deep-seated landslide in the northern French Pyrenees

T. Lebourg [a,*], S. Zerathe [a], R. Fabre [b], J. Giuliano [a,c], M. Vidal [a]

[a] Univ. Nice Sophia Antipolis, CNRS, IRD, Observatoire de la Côte d'Azur, Géoazur UMR 7329, 250 rue Albert Einstein, Sophia Antipolis 06560 Valbonne, France
[b] UMR 5295, I2M-GCE, Avenue des facultés, 33405 Talence, France
[c] Aix-Marseille Université, CNRS-IRD-Collège de France, UM 34 CEREGE, Technopôle de l'Environnement Arbois-Méditerranée, BP80, 13545 Aix-en-Provence, France

ARTICLE INFO

Article history:
Received 23 July 2012
Received in revised form 1 October 2013
Accepted 11 November 2013
Available online 23 November 2013

Keywords:
Deep-seated landslide
Pyrenees
Cosmic ray exposure dating
Climate change
Coseismic triggering

ABSTRACT

A very large deep-seated landslide (DSL) in the northern Pyrenees with over ~1.4 × 10^9 m^3 was mapped and dated based on sedimentation rates and ^{10}Be terrestrial cosmogenic radionuclide surface exposure (CRE) dating. Our analysis on the landslide reveals the role of inherited structures in the landslide process, and highlighted typical gravitational morpho-structures and a small lake trapped at the toe of the landslide head scarp. The rate of lake sedimentation (0.86 ± 0.57 mm yr^{-1}) also provided us with the approximate age of the landslide: 1106 ± 540 yr. The CRE dating result highlights two main slope destabilization phases. Then we discussed the history of DSL activity and its controlling factors. Information related to historic markers and the absence of particular climate markers and changes during the Medieval Dark Ages point to a single event in AD 1380 due to a major seismic event (Lavedan earthquake).

1. Introduction

Over the past decade, many researchers of gravitational mass movements have developed and improved the methods of morphological characterization, observation of dynamics, kinematic modeling, and geochronological dating, to better understand landslide processes. In mountain areas, large-scale landslide structures known as "deep-seated landslides" (DSLs) or "deep-seated gravitational slope deformations" (DSGSDs) often take place. DSGSDs are gravity-induced processes which evolve over a very long time and usually affect entire slopes, displacing rock volumes up to the order of 10^8 m^3 over areas of several km^2 with thicknesses of several 10^1 m. The main feature of these processes is the absence of a continuous surface of rupture and the presence of a deep zone where displacement takes place mostly through rock micro-fracturing (Radbruch-Hall, 1978). DSGSDs, defined by Malgot (1977), have been documented almost everywhere in the world but with different terms such as sackung, gravity faulting, deep-reaching gravitational deformation, deep-seated creep deformation, gravitational block-type movement, gravitational spreading and gravitational creep. In spite of the variety of terms used, the most frequently used terms are sackung and lateral spreading. Sackung can be described as a sagging of a slope due to visco-plastic deformations at depth which affect high and steep slopes made up of rocks with brittle behavior (Zischinsky, 1969; Crosta, 1996). Lateral spreading is the lateral expansion of a rock masse along shear or tensile fractures. Two main types of rock spreading, under different geological situations, can be distinguished: (1) affecting brittle formations overlying ductile units, often due to the deformation of the underlying material, and (2) in homogeneous rock masses (usually brittle) without a well-defined basal shear surface or a zone of visco-plastic flow (Pasuto and Soldati, 1996). Triggering and causal mechanisms of DSGSDs and DSLs (Gutiérrez et al., 2008; Agliardi et al., 2009) include: (1) postglacial debuttressing of oversteepened slopes and associated changes in groundwater flow (Bovis, 1982; Agliardi et al., 2001; Ballantyne, 2002), (2) topographic stresses (Radbruch-Hall, 1978; Varnes et al., 1989), (3) regional tectonic or locked-in stresses (Miller and Dunne, 1996), (4) earthquake ground shaking or co-seismic slip along faults (e.g. Beck, 1968; Harp and Jibson, 1996; McCalpin and Hart, 2003; Gutiérrez-Santolalla et al., 2005; Hippolyte et al., 2006; Guttiérrez et al., 2008), and (5) fluvial erosion of the toe of slopes (Crosta and Zanchi, 2000).

Recent studies on gravitational instabilities in the Southern European Alps (Mercantour–Argentera Massif and Subalpine chains) have allowed us to highlight large deep-seated landslides with specific morphologies and their relationships with geology (Jomard, 2006; El Bedoui et al., 2009; Zerathe and Lebourg, 2012). These studies have indicated that geological structures and weathering processes significantly affect the development of the deep-seated landslides. However, the triggering factors of such large-scale instabilities often remain unknown, especially for those occurred in the Late or Middle Holocene (Zerathe and Lebourg, 2012).

Most of the time large landslides undergo progressive rock degradation, but sometimes affected by extreme events such as earthquakes, ice melt, and heavy precipitation (Crozier et al., 1995). This study aims to identify such triggering factors of a large landslide in the Pyrenees

* Corresponding author. Tel.: +33 4 83 61 86 70; fax: +33 4 83 61 86 10.
E-mail address: lebourg@geoazur.unice.fr (T. Lebourg).

0169-555X/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.geomorph.2013.11.008

based on cosmic ray exposure (CRE) dating, sediment analysis, and geomorphological observations.

Only a few DSLs or DSGSDs have been identified in the Pyrenean mountain chains (Gutiérrez-Santolalla et al., 2005; Hürlimann et al., 2006; Gutiérrez et al., 2008), although the Pyrenees are broad steep areas with active tectonics (Barnolas and Chiron, 1996) and erosion that would promote gravitational processes. In the northern French Pyrenees, previous studies identified some shallow rockslides (Fabre et al., 2001, 2002; Lebourg et al., 2003a,b), and a few DSGSDs were also reported there (Gutiérrez et al., 2012) as well as in the central Spanish Pyrenees (Gutiérrez-Santolalla et al., 2005; Hürlimann et al., 2006; Gutiérrez et al., 2008).

In the present study, we focus on the recognition and characterization of the largest deep-seated landslide ever identified in the French Pyrenees (Gutiérrez et al., 2012) located in the Aspe Valley (Atlantic Pyrenees). This Cristallere DSL involved 1.2–1.6 × 10^9 m^3 of rock in a complex geological setting of various lithologies, affected by faults and folds, past glacial processes, and surrounding steep slopes (Figs. 1B and 2A). To constrain the age of the Cristallere DSL, we applied CRE dating and studied the sediment deposits of a small lake trapped within a large gravitational morpho-structure associated with the landslide. We also discuss the triggering factors of the DSL.

2. Geological setting

The study area is located in the Aspe Valley (Fig. 1), which is an old glacial valley of the Atlantic Pyrenees. We have been studying this valley for 15 years mainly in relation not only to numerous shallow landslides developed in tills but also to the Cristallere DSL. Since the beginning of the 20th century when railway tracks were installed, there have been numerous signs of active deformation, particularly on railway tracks, tunnels and houses.

The Aspe Valley was heavily affected by the Last Glaciation, as shown by numerous morphological markers along the entire valley (Debourle and Deloffre, 1977; Lebourg et al., 2004). On about 40% of the outcrops, we have found the deposits of glacial moraines, unsorted and heterogeneous materials of "till". These formations are older than 10 kyr BP (Taillefer, 1969), and their deformations occurred in the Holocene. After the glacier retreat, the Aspe River cut the glacial valley through by about 200 m (Fabre et al., 2002), leaving an alluvial terrace at the base of the Cristallere slope.

Geologically the Aspe Valley belongs to the Pyrenean Axial Zone (Barnolas and Chiron, 1996) composed of Palaeozoic rocks (Fig. 2A) that have been folded and faulted during the Variscan and the Alpine orogeny. On the slope with the Cristallere DSL, the fold axes are oriented from 90°N to 140°N. These are recumbent folds that are overturned to the south (Lebourg et al., 2003a), with their axes oriented east to west, with low westward axial plunge. The Cristallere slope consists of three Palaeozoic units (Ternet et al., 2004). From top to bottom:

(i) The Devonian units characterized by limestone, forming a glacial rock bar near the Baralet Peak. These constitute an anticline fold with a 120°N axis that is bounded by two 130°N sub-vertical faults;
(ii) The Carboniferous units characterized by alternating black shale and blue-gray sandstone. This lithology constitutes the major part of the Cristallere slope, occupying between 700 and 1400 m a.s.l., and;
(iii) The Permian units characterized by alternating sandstone and red shale. They outcrop at the top of the Cristallere slope (1854 m a.s.l.). The upper part of the units consists of limestone with siliceous breccias and conglomerates. We collected the hydro-thermal quartz used for ^{10}Be dating from this formation.

3. Materials and methods

Our study began with an analysis of high-resolution satellite images to identify lineaments and typical topographic anomalies. This was followed by field surveys and geological analysis. During the field investigations, we performed structural measurements of faults, fractures and bedding planes, together with a precise analysis and mapping of gravitational morpho-structures, to reveal the role of inherited structures in landsliding (Margielewski, 2006). We paid particular attention to gravitational morpho-structures to identify landslide boundaries. To constrain the timing of landsliding and to understand its kinematics, we used two dating methods: analysis of lake deposits and CRE dating using ^{10}Be.

3.1. Lake sediment analysis

Lake sediments have recorded climatic events (Appleby, 2000). Lakes may be formed after a glacial retreat or a landslide, leading to sedimentation (Wojciech, 2004). Analysis of lake sediments including the estimation of sedimentation rates may indicate when the lake was formed. Table 1 gives some examples of sedimentation rates obtained for European and Canadian mountain lakes. For lakes close to

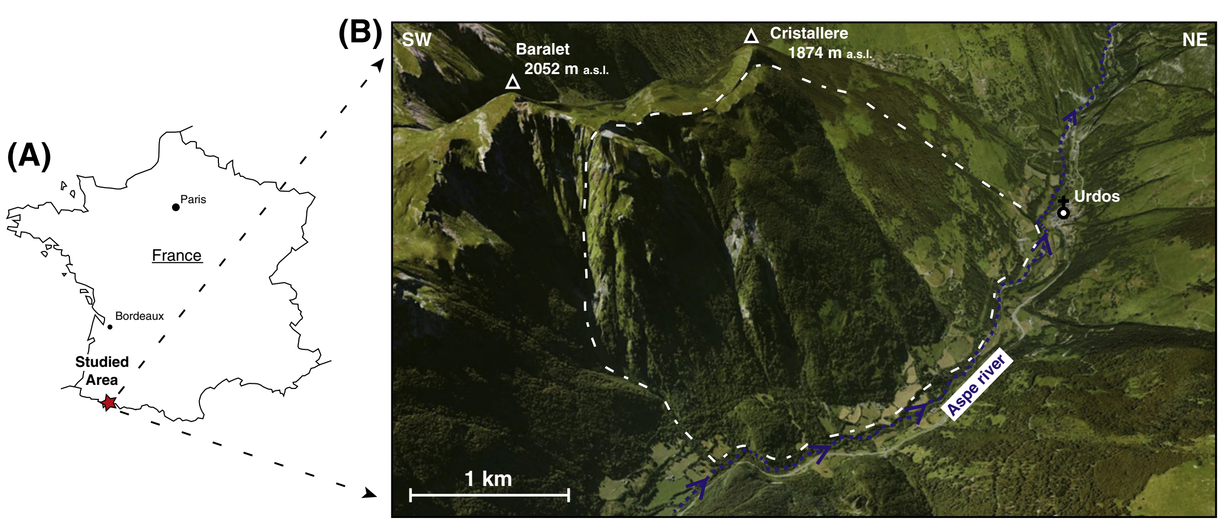

Fig. 1. Location of the studied area. (A) Location of the Aspe Valley in France. (B) Three-dimensional view of the Cristallere slope (from Google Earth). White dashed line corresponds to the boundary of the deep-seated landslide.