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Paleotopographic control of landslides in lacustrine deposits (Trièves plateau, French western Alps)

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ABSTRACT

Paleotopography in Quaternary sedimentary environments can be an important factor that controls landslide movement. This study investigates the relation between paleotopography and landslide activity in two adjacent landslides in glaciolacustrine sediments located in the Trièves area (French western Alps). Although both are in slopes underlain by the same lacustrine deposits, the Avignonet and Harmalière landslides exhibit major differences in morphology and displacement rates. Through a combination of geological mapping, airborne light detection and ranging (LiDAR) data, aerial photographs, global positioning system (GPS), and seismic noise measurements, a three-dimensional impression was made of both landslides. The analysis reveals that the difference in kinematics between the two mass movements can be traced back to at least 50 years ago. The results show that the Harmalière slide, which failed catastrophically in 1981, is still much more active than the Avignonet landslide. The fear was that the Avignonet landslide might develop in a similar catastrophic manner, threatening a number of houses constructed on the landslide. A geophysical survey based on ambient noise measurements allowed us to map the base of the lacustrine clays, and the results indicate the presence of a N–S ridge of hard sediments (Jurassic bedrock and/or compact alluvial layers) on the eastern side of the Avignonet landslide. This ridge disappears when approaching the Harmalière landslide and makes a place to what can be interpreted as a NW–SE oriented paleovalley of the river Drac. We proposed that the ridge acts as a buttress that could mechanically prevent the Avignonet landslide from evolving as fast as the Harmalière. Furthermore, the NW–SE paleovalley located under the Harmalière landslide corresponds to the motion direction of the slide. Therefore, the different behaviour of the two landslides is partly controlled by the paleotopographic setting of Lake Trièves during the last Glacial Maximum extension. These results suggest a major influence of the bedrock paleotopography on the kinematics of the landslides.

1. Introduction

Landslide hazard assessment requires a thorough understanding of the internal controlling factors (soil nature and characteristics, fracturing, slope hydrology, vegetation) and of the triggering factors (rainfalls, earthquakes, erosion, and anthropogenic influence). Landslides occurring in recent soft sediments have been regularly reported to be controlled by tectonic features (Bozzano et al., 2008), lithological variations like the presence of smectite-rich layers (Ambers, 2001; Azanon et al., 2010), and hydrogeological drainage (Eilertsen et al., 2008). In several depositional conditions, soft sediments can exhibit significant variations in thickness in relation with an irregular paleotopographic surface existing at the time of deposition. This may be the case in volcanic environments where pre-eruption topography can be buried by volcanic ash or pyroclastic flow materials (Van Westen and Daag, 2005). In marine conditions, after the latest glaciation in Scandinavia and Canada, clay layers were deposited over an irregular surface made of a thin till layer on top of bedrock (Rankka et al., 2005). These areas have been affected by isostatic uplift, leaving the clay deposits located above sea level and subjected to salt leaching. This process generated quick clays that have been involved in numerous large clay slides (Lundström et al., 2009). Also, glaciolacustrine environments are famous for creating irregular clay deposits and favorable conditions for landslides in previously glaciated areas such as the Alps (Giraud et al., 1991; Jongmans et al., 2009) or the Baltic Sea (Kohv et al., 2009). In mountainous areas, intensive erosion by glaciers

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or rivers has created numerous incisions in the topography, which has regularly been covered by soft deposits. In the black marls outcropping in the southwestern Alps (France), Flageollet et al. (2000) identified the role of the buried topography (crests and gullies) on the dynamics of the Super-Sauze earth flow. Recently, Coe et al. (2009), in the San Juan Mountains (Colorado, USA), observed that the location of several ponds in a huge fine-grained landslide, with displacement velocities ranging between 0.1 m/y and 7 m/y, remained stationary for the last 50 years at least. They showed that the position of the ponds and the surface morphology coincided with the presence of irregularities of the basal topographic surface. The spatial variation in thickness of recent clayey sediments and the relation with the topography that existed at the time of deposition can then play an important role on landslide dynamics. However, few publications are still investigating the effect of such old erosional surfaces underneath recent soft deposits.

This study aims to investigate the importance of paleotopographic control of landslides in an area covered by glaciolacustrine sediments in the French Alps, and we attribute significant differences in geometry and kinematics observed between two adjacent landslides to variations in the erosional surface below the soft lake sediments. A combination of geological mapping, airborne light detection and ranging (LiDAR) data analysis, aerial photograph interpretation, global positioning system (GPS) monitoring, and seismic noise measurements were applied to characterize the landslide morphology and the thickness of the soft layer down to the underlying bedrock and to relate this to the different behavior of the landslides. The methods provide a three-dimensional view of the soft formations and allow mapping of the paleotopography that plays a crucial role in explaining the different behavior of the landslides.

2. Study area

Two adjacent landslides, called the Avignonet and Harmalière landslides, were selected for this study. They are located in the Trièves area, 40 km south of the city of Grenoble in the French western Alps (Fig. 1). From the available data (Jongmans et al., 2009) and following Cruden and Varnes (1996), the Avignonet and Harmallière landslides can be classified as “active, very slow, wet, translational earthslide” and “complex, active, slow earth slide-earth flow”, respectively. The region with a maximum altitude of 800 m above sea level (asl) corresponds to a large depression of about 300 km^2 drained by the Drac River and its tributaries (Fig. 1). Geologically, this area is characterized by the widespread occurrence of Quaternary glaciolacustrine clays, which are highly prone to landslides (Lorier and Desvarreux, 2004). These clay landslides can develop over several slip surfaces ranging from superficial (5 to 15 m) to deep (>50 m) (Blanchet, 1988; Jongmans et al., 2009). Slide velocities are generally low (a few cm/y) but can reach several meters per year in certain places. In some cases, generally after a long wet period accompanied by quick snowmelt, the slides can evolve into mudflows and velocities can reach several meters per hour. This leads to dramatic events such as the failures that occurred in Harmalière in 1981 (Moulin and Robert, 2004) and in La-Salle-en-Beaumont in 1994 (Moulin and Chapeau, 2004; see location in Fig. 1). The morphology of the Trièves area was controlled by several Quaternary glacier fluctuations, which resulted in alternating deposition and erosion phases. Fig. 2A presents a general view of the area, looking to the west. The Quaternary deposits are underlain by early Jurassic carbonate strata (Fig. 2B) that were folded and faulted during the Alpine orogenesis. Ancient glacial (Riss) and interglacial phases (Riss–Würm) carved the substratum and generated valleys partly filled with Riss–Würm alluvial deposits (Fig. 2C). This led to an irregular shape of the basement prior to the last glacial phase (Würm; −80 to −12 ky BP). During the last glacial maximum extension, which occurred between 22,000 and 18,000 BP (Clark et al., 2009), the Isère glacier that came from the North blocked the torrential flows from the Drac River and its tributaries, generating a large ice-dammed lake (Monjuvent, 1973) (Fig. 1). This lake was progressively filled during thousands of years by rythmic alternations of clay and silt layers originating from nearby Mesozoic marls and crystalline massifs (Huff, 1974). These laminated clays (Fig. 2D) rest either on carbonate rocks or on locally cemented, compact alluvial layers from the interglacial Riss–Würm period. The irregular shape of the basement induces strong lateral thickness variations of the paleolake infill, from 0 to more than 250 m (Fig. 3) (Monjuvent, 1973; Antoine et al., 1981). The top of the clay is generally found at an elevation of about 750 m asl (Antoine et al., 1981). Morainic deposits, which cap the clays found as far as the south of the village of Sinard, are evidence that the Würmian glacier has partly overridden the lacustrine materials (Figs. 1 and 3). In the study area, the thickness of the morainic deposits varies from 50 m around Sinard to a few meters in the east. At the end of the last glacial maximum, the Isère glacier withdrew, allowing the rivers to cut deeply into the glaciolacustrine deposits. This last erosion phase created the actual Drac River valley. This favoured the conditions for landslide development in the clay with a general eastward motion in the study area (Fig. 3) (Brocard et al., 2003; Jongmans et al., 2009).

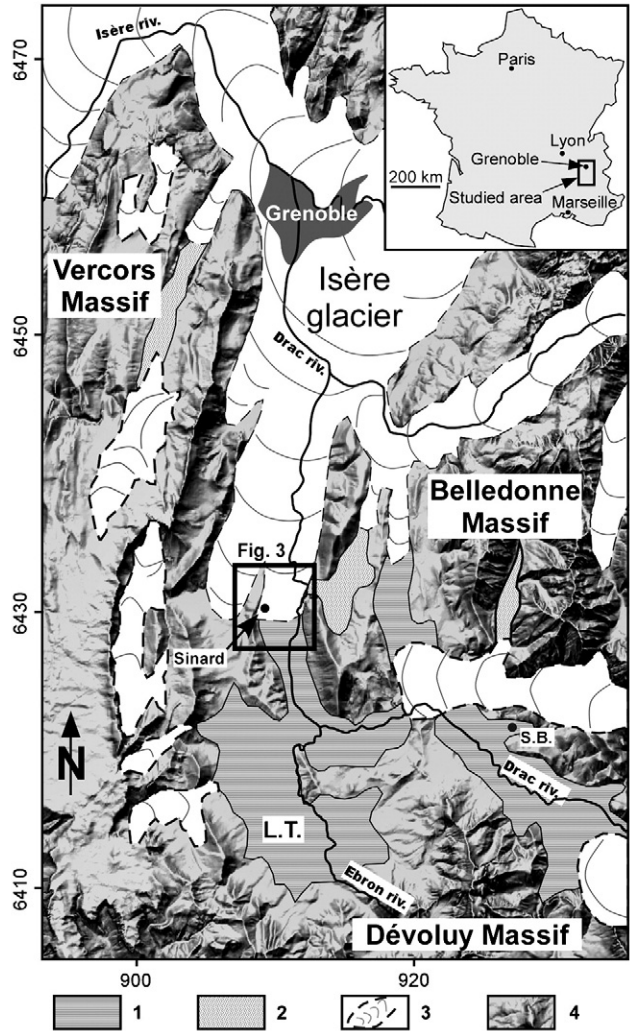

Fig. 1. Location of the area and paleogeographical map at the end of the Würm age (adapted from Monjuvent, 1973). Coordinates are in kilometers using the French system Lambert-93. The thick black box shows the location of the study area and the extent of Fig. 2. 1: Laminated clay deposits in the Trièves area; 2: fluvioglacial deposits; 3: extension of the Isère Glacier at the end of the Würm age; 4: present-day topography; L.T.: Lake Trièves; S.B.: La Salle-en Beaumont.

The geological map and the cross section of Fig. 3 show the presence of two paleovalleys (v1 and v2) formed during pre-Würm interglacial incision phases. Paleovalley v1 is the oldest (Monjuvent,