



Earthquake triggered rock falls and their role in the development of a rock slope: The case of Skolis Mountain, Greece

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ABSTRACT

Inventory of pre-earthquake and earthquake triggered landslides is used to provide insight into the interplay between climatic and tectonic forcing in the development of the rock slopes of the Skolis Mountain, in the NW Peloponnese. Aerial photograph analysis and surface mapping indicate that the Skolis Mountain is characterized by long-term climatically and tectonically controlled rock falls forming taluses. Temporally these taluses show a slow progressive inflation in surface area from 1945 to 2007. However, the post-earthquake surface area of the rock falls increased three times. Similarly 75 rock fall sites before the earthquake, increased into 89 after the Movri Mountain earthquake (Mw 6.4). In addition, during the earthquake a series of isolated rock falls descended Skolis slopes causing threat of the Santomerion village and blocking significant part of the dirt roads around it. These boulders are clustered in three areas beyond the base of taluses. The rock slope failures are controlled by a complex array of discontinuities that are conveniently related to rock mass classification following the geological strength index. These discontinuities are associated with joints and faults caused during the formation of the Hellenides fold- and thrust-belt, and/or related tectonic damage. We infer that a dense pattern of fractures in limestone plays a crucial role in the reactivation of movement within the rock falls during the 2008 Movri Mountain earthquake. All these data are used to define two borders, the taluses base and the rock fall hazard border beyond the base of taluses. For defining these borders we use the angle β drawn from the boulders' release zone down its maximal runout points. Our results indicate that the border defined by the $\beta = 33^\circ$ corresponds to the climatically driven rock falls while the $\beta = 24^\circ$ border is defined as the boulders' maximum runout during earthquakes.

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1. Introduction

A strong feedback exists between geological history, tectonics, lithology and geomorphological evolution of slopes (Jaboyedoff et al., 2011); this is the reason why various types of landslides respond in many ways to tectonic processes. In addition most of the slope features can be considered as the result of long-term geomorphologic evolution under climatic forcing and/or in cases of geologically active areas by the tectonic forcing during earthquakes. Otherwise, topography, lithology and rock mass damage appear to promote or control the rock slope failures (Reid and Iverson, 1992; Zêzere et al., 1999; Agliardi et al., 2013).

Landslides are commonly triggered in the epicentral area of earthquakes or in proximity with active faults (Keefer, 1984a,b; Bull et al., 1994; Tibaldi et al., 1995; Burbank and Anderson, 2001; Gallousi and Koukouvelas, 2007). Thus, mapping and analysis of the landslide distribution can be used for hazard assessments (Eisbacher and Clague, 1984; Keefer, 1984a). In addition, landslides in actively deforming areas often

provide key data for understanding the delivering of material from hillslopes into valley bottom occupied by rivers, lakes, gulfs or glaciers (Molin et al., 2004; Korup, 2005a,b; Gallousi and Koukouvelas, 2007).

For the Mediterranean and Greek climatic conditions, the relationships between landslides and extreme rainfall events have been extensively investigated (e.g. Crosta, 1998; Guzzetti et al., 2004; Koukis et al., 2005; Agliardi et al., 2013). However, the role of the earthquakes in landslides is poorly understood in Greece, since a limited number of case studies exist and information from historic data are limited (Koukouvelas et al., 1996; Christaras et al., 1998; Papadopoulos and Plessa, 2000; Ambraseys, 2009). In addition, landslide inventory data are poor for earthquake triggered landslides in terms of their dimensions and it is unlikely that very specific landslide-related parameters, such as material shear strength or phreatic surface levels, are mapped to the detail required for present day landslide susceptibility analysis.

On the 8th of June 2008, a strong earthquake of Mw = 6.4 struck northwestern Peloponnese called hereinafter as the Movri Mountain earthquake (Fig. 1). Northwestern Peloponnese and its surroundings Ionian Islands are located at the most tectonically and seismically active region of Greece (Papazachos and Papazachou, 1997; Ambraseys, 2009; Kokkalas et al., 2013 and references therein). The 2008 event

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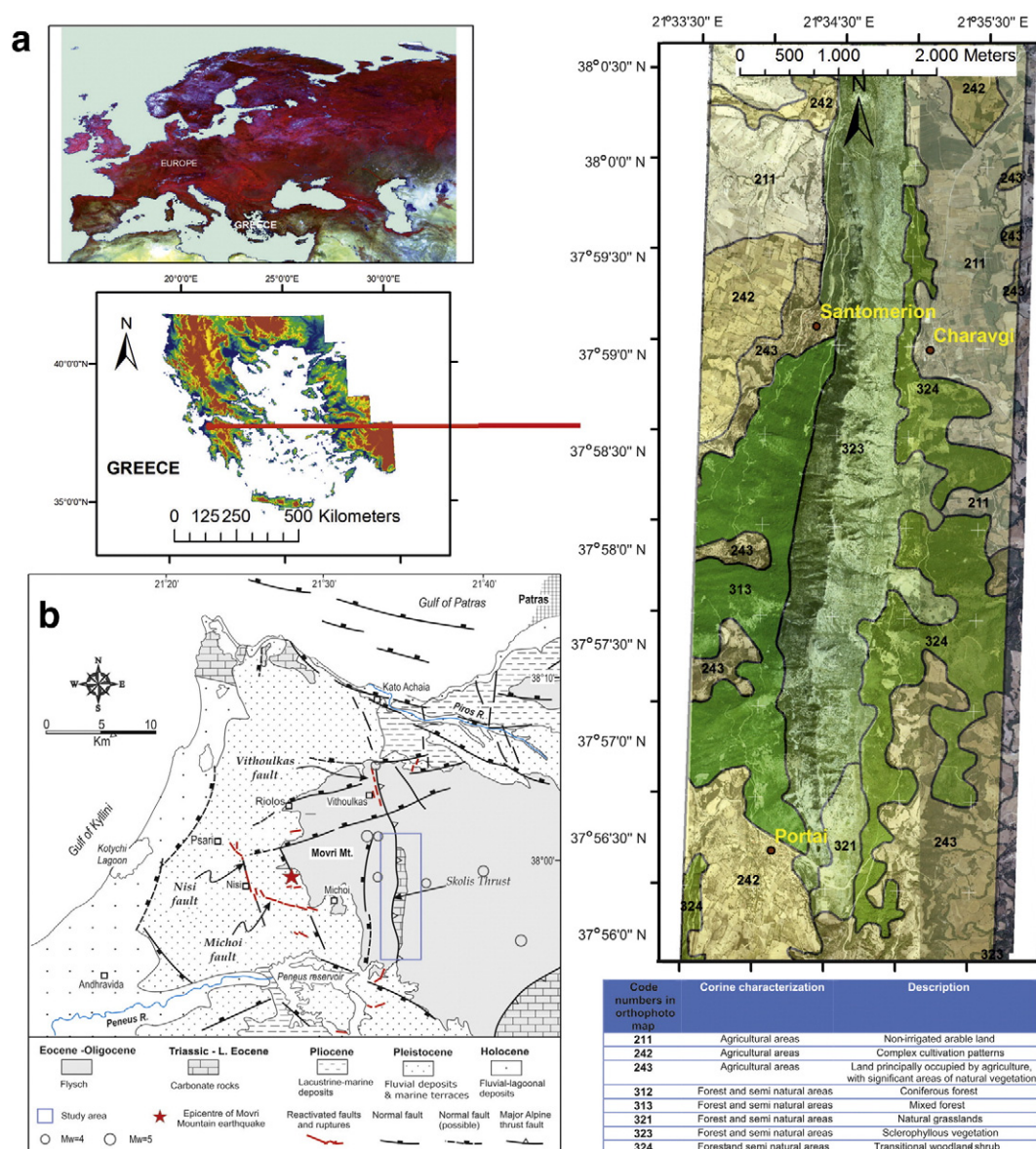


Fig. 1. (a) Location maps of the study area. The land use map as reproduced from CORINE project, is superposed on an aerial orthophoto of the Skolis Mountain. The orthophoto map has a 25 cm spatial resolution as extracted from ©Google Earth. (b) Geological map of the NW Peloponnese showing lithology, active faulting and the surface ruptures that appeared during the Movri Mountain earthquake. The star indicates the epicenter of the 2008 earthquake and open circles represent the historical seismicity of the study area as reproduced from www.gein.noa.gr. The box in the geological map shows the study area and the location of Fig. 2. The geological map is modified from Koukouvelas et al., 2010.

was the largest earthquake to occur in northwestern Peloponnese during the past 30 years (Koukouvelas et al., 2010). The earthquake toppled primarily old buildings in the epicentral area and less reinforced houses and reinforced concrete buildings in the villages and communities nearby its epicenter (unpublished data of our laboratory). The secondary effects that were caused by the $M_w = 6.4$ earthquake, were landslides, and liquefaction phenomena near the epicentral area (Kokkalas et al., 2008; Koukouvelas, 2008; Pavlides et al., 2008; Koukouvelas et al., 2010; Papadopoulos et al., 2008; Papathanassiou, 2012). Santomerion village suffered by far the most damage due to its proximity to the steep slopes and its high elevation (Fig. 1). As a result, the largest volume of landslide materials, consisting of rock falls and boulders, hit the village. Due to this the Civil Protection Authorities temporarily evacuated the villages in order to avoid casualties and injuries in case of landslide reactivation during strong aftershocks.

The study of Skolis Mountain landslides supports a subdivision of slope failures into two principal types: (a) primarily rock falls and

(b) minor rock slides sensu Varnes (1978). Additionally, we estimated rock falls related to seasonal rainfall, and we tried to test if the shadow angle (angle β) of 33° , 27.5° and 24° are applicable in our study area (sensu Evans and Hung, 1993; Dorren, 2003). The angle β is defined by an imaginary line drawn from the release point down to the maximal runout point of the block. The angles $\beta = 33^\circ$ and $\beta = 24^\circ$ correspond with the maximum runout beyond the talus slope and the point where the boulders stop on the slope (Dorren, 2003 and references therein).

In this paper we investigate the distribution of rock falls and isolated rock falls over the period from 1945 until 2008 (63 years) across the Skolis Mountain and how these were modified during the Movri Mountain earthquake. Note that our study area is characterized primarily as forest and semi natural and thus human activity is rather limited (Fig. 1). Thus, the Skolis Mountain is a key example of earthquake triggered mass movements overlapping in time onto identical type of mass movements caused by climatic forcing. Phreatic surface is too deep in the area to have any impact on mass movements and thus this paper

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