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# Time-dependent evolution of rock slopes by a multi-modelling approach

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ABSTRACT

This paper presents a multi-modelling approach that incorporates contributions from morpho-evolutionary modelling, detailed engineering-geological modelling and time-dependent stress-strain numerical modelling to analyse the rheological evolution of a river valley slope over approximately $10^2$ kyr. The slope is located in a transient, tectonically active landscape in southwestern Tyrrhenian Calabria (Italy), where gravitational processes drive failures in rock slopes. Constraints on the valley profile development were provided by a morpho-evolutionary model based on the correlation of marine and river strath terraces. Rock mass classes were identified through geomechanical parameters that were derived from engineering-geological surveys and outputs of a multi-sensor slope monitoring system. The rock mass classes were associated to lithotechnical units to obtain a high-resolution engineering-geological model along a cross section of the valley. Time-dependent stress-strain numerical modelling reproduced the main morpho-evolutionary stages of the valley slopes. The findings demonstrate that a complex combination of eustatism, uplift and Mass Rock Creep (MRC) deformations can lead to first-time failures of rock slopes when unstable conditions are encountered up to the generation of stress-controlled shear zones. The multi-modelling approach enabled us to determine that such complex combinations may have been sufficient for the first-time failure of the S. Giovanni slope at approximately 140 ka (MIS 7), even without invoking any trigger. Conversely, further reactivations of the landslide must be related to triggers such as earthquakes, rainfall and anthropogenic activities. This failure involved a portion of the slope where a plasticity zone resulted from mass rock creep that evolved with a maximum strain rate of 40% per thousand years, after the formation of a river strath terrace. This study demonstrates that the multi-modelling approach presented herein is a useful tool for estimating the progressive development of slope failures because it can highlight time-dependent continuous deformations as the major processes that drive rocky slopes to failure. This type of approach can be devoted to the best selection of risk mitigation strategies with respect to both human life and anthropic infrastructure.



## 1. Introduction

Landslides in rock or soil (Hutchinson, 1988; Cruden and Varnes, 1996; Hungr et al., 2001) are an important landscape-shaping process (Petley, 2010) that depends on the environment as they release sediment/rock from hillslopes and deliver them to the fluvial system. Transient, tectonically active mountain landscapes are widely affected by landslides in response to gravitational disequilibrium on hillslopes (Larsen and Montgomery, 2012). Earthquake-induced landslides are widely recognized to play an important role in the hillslope evolution of such landscapes (e.g., Keefer, 1996; Malamud et al., 2004; Owen et al., 2008; Parker et al., 2011; Hovius et al., 2011; Li et al., 2014). Furthermore, Mass Rock Creep (MRC) processes (Chigira, 1992) may become a primary factor for deteriorating rock masses on slopes and also lead to failures when rock slopes are subjected to gravity over a long period. In this regard, MRC is significantly related to the timing of landscape evolution (Bozzano et al., 2012). Nonetheless, the contribution of MRC to landsliding is less well understood. The strain rate associated with MRC depends primary on rock mass mechanical properties (Apuani et al., 2007; Bozzano et al., 2012; Hou et al., 2014) but also on the presence of discontinuities that drive rock mass deformations, slope topography and groundwater pressures (Asef and Reddish, 2002; Bretschneider et al., 2013; Bozzano et al., 2013a). In the evolution of mountain slopes, MRC processes can evolve to (and successively be re-activated as) rapid failures (Xu et al., 2014) in response to external forces such as earthquakes or human actions.

In this paper we evaluate landslide hazards related to the geomorphological evolution of a transient, tectonically active landscape. We selected a study area in southern Italy that encompasses two major coastal river valleys shaped in metamorphic rock commonly affected by gravitational slope deformations. We developed sequential interlocking models. First, we provided a time constrained morpho-evolutionary model of the steep valley-slopes. Based on those constraints, a sequential slope evolution model was derived and used for the stress-strain numerical modelling of the MRC process that affected the valley slopes as a

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consequence of river incision. For that purpose, a time-dependent rheology was considered in the numerical modelling to simulate the strain effects induced in the rock mass by the gravitational force. According to such a rheology, strain effects can be induced by the stress field, which is strictly related to the topography and to the mechanical properties of the rock mass. The rock mechanical properties were based on previously surveyed geomechanical data and were optimally tuned by taking into account available data from in-hole strain measurements and monitoring (Bozzano et al., 2013b).

## 2. Regional geology

Our study area is located in the core of the Calabrian Arc, which is one of the most active tectonic areas of the Italian peninsula. The region is affected by high Quaternary uplift rates (~1 mm/a; Ferranti et al., 2008, and references therein) and seismicity that is among the strongest in the entire western Mediterranean region (Mattei et al., 2007; and references therein), with fairly well-documented historical earthquakes (at least 34 having intensity of VIII–XI on the MCS scale, among which, those that occurred in 1638, 1693, 1905 and 1908 had estimated Mw values ≥7; Bozzano et al., 2011; and references therein).

The area is part of the geodynamic Calabrian–Peloritane Domain (Fig. 1), which is mostly composed of exhumed Hercynian and Alpine polymetamorphic rocks that are overlain by Mesozoic marine sedimentary units. The Neogene and Quaternary evolution of the Calabrian Arc was driven by the southeastward retreat of the narrow and steeply dipping Ionian slab (Malinverno and Ryan, 1986; Selvaggi and Chiarabba, 1995; Wortel and Spakman, 2000; Faccenna et al., 2001; Piromallo and Morelli, 2003). The retreat caused the opening of several extensional back-arc basins on the Tyrrhenian side of the arc (Ghisetti, 1979, 1981), where Miocene to Pleistocene marine sediments were deposited unconformably. In the Calabria-Peloritane Domain, relatively rapid block rotation caused a tight arc with structural fragmentation, which led to the formation of tectonically–confined extensional basins that were oriented transverse to the arc and likely developed as tidal straits (Longhitano, 2013), such as the Messina, Siderno and Catanzaro straits (Fig. 1).

The presence of several seismogenic sources capable of producing earthquakes with magnitude values Mw ≥7 in our study region is well documented (CPTI04, http://emidius.mi.ingv.it/CPTI04/; ITHACA, http://www.apat.gov.it/site/it-IT/Progetti/ITHACA), although the seismotectonic setting is still debated, especially concerning the location and magnitude of tectonic events from the Middle to Late Pleistocene (Valensise and Pantosti, 1992; Tortorici et al., 1995), as well as the sources of historical earthquakes such as the famous Messina earthquake that occurred on December 28, 1908 (Monaco and Tortorici, 2000; Pino et al., 2009; Doglioni et al., 2012; Ridente et al., 2014), which was one of the strongest (Mw 7.1) ever recorded in Italy.

Extensional faulting and mantle circulation linked to the slab retreat dynamics have been widely invoked as major causes for the strong

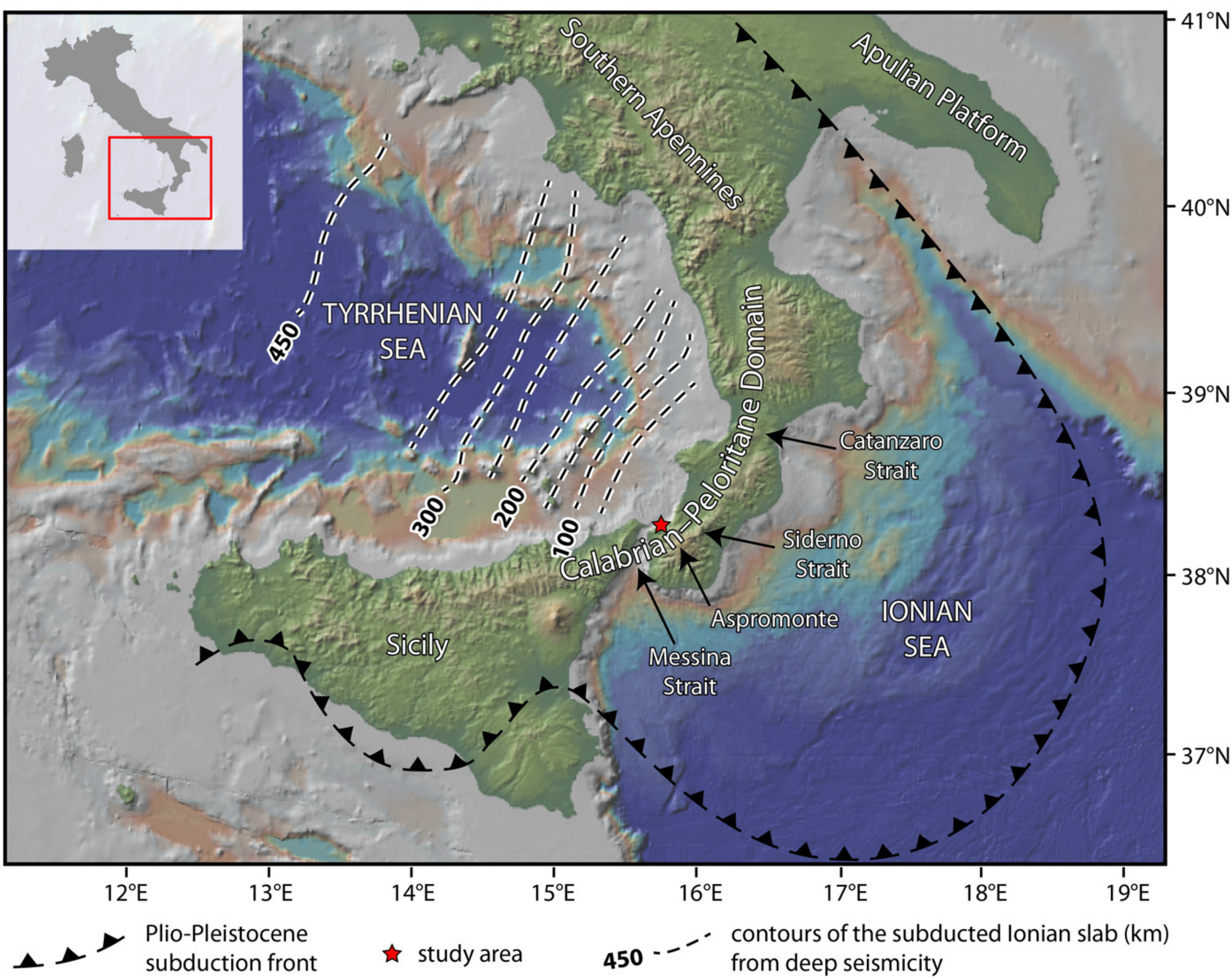


**Fig. 1.** Geodynamic map of Southern Italy and the location of the study area in the Calabria-Peloritane Domain (modified after Cifelli et al., 2007).