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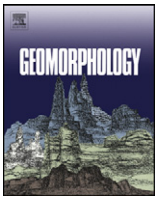

Influence of deep-seated gravitational slope deformations on landslide distributions: A statistical approach

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ABSTRACT

The influence of deep-seated gravitational slope deformations (DSGSDs) on the distribution of translational landslides was analyzed in the Milia basin, Tuscany, Italy. Detailed geomorphological mapping, combined with the analysis of aerial photography, enabled us to build two landslide inventories. One inventory including landslides before 1975 was used to create statistical models, whereas the other inventory including landslides after 1975 was used to validate the models. Geology, slope angle, slope aspect, distance to hydrographic elements, and distance to tectonic lineaments were considered as landslide-predisposing factors. To quantify the importance of DSGSDs as another landslide-predisposing factor, the DSGSD presence/absence map was introduced in the stepwise statistical analysis. The landslide inventory maps and factor maps were processed using a conditional analysis on all possible factor combinations to produce landslide susceptibility maps with five susceptibility classes. The results indicate that the DSGSDs significantly affect landslide distribution.

1. Introduction

Deep-seated gravitational slope deformations (DSGSDs; Dramis and Sorriso-Valvo, 1994) affect large mountain slope areas worldwide, modifying slope morphology (Bovis and Evans, 1996; Julian and Anthony, 1996; Kinakin and Stead, 2005) and bedrock fracture systems (Agliardi et al., 2001; Bachmann et al., 2009; Pánek et al., 2011a). The formation and evolution of DSGSDs could be a nonnegligible landslide-predisposing factor. However, the link between landslides and DSGSDs has rarely been clearly shown (Bisci et al., 1996; Bovis and Evans, 1996; Sorriso-Valvo et al., 1999), although many landslides have occurred in rock masses affected by DSGSDs (Crosta, 1996; Agliardi et al., 2009a,b; Kellerer-Pirklbauer et al., 2010; Pánek et al., 2011a,b). Over the last few decades, various methods have been applied to analyze the gravitational evolution of DSGSDs (Boukharov and Chanda, 1995; Crosta and Agliardi, 2003; Bachmann et al., 2004, 2006; Stead et al., 2006; Jomard et al., 2007). However, the results remain restricted to a relatively short time period of observations, typically several years (El Bedoui et al., 2009).

To provide some clues about the importance of DSGSDs as a landslide-influencing factor, this study employs the concept of unique condition units (UCUs; Carrara et al., 1995). The conditional analysis method is easy to understand even for nonspecialists (Carrara et al., 1995; Chung et al., 1995) and has fewer limitations than other methods of statistical analysis (Clerici et al., 2006, 2010). For example, the bivariate analysis and the logistic regression analysis require independent variables (Cliff and Ord, 1981; Dey et al., 2000; Neuhäuser and Terhorst, 2007), whereas discriminant analysis requires a normal distribution of the covariates (Hosmer and Lemeshow, 1999; Giudici, 2005; Härdle and Simar, 2007). Our landslide susceptibility (LS) analysis has been performed in the Milia basin in Central Tuscany, Italy, where DSGSDs have conditioned the evolution of landforms. The LS analysis did not consider DSGSDs as a landslide-influencing factor at first but then introduced them to evaluate whether the LS best model has improved with statistical significance. It was also considered necessary to perform an LS analysis using two landslide inventories for different periods (Guzzetti et al., 2006; Chung and Fabbri, 2008; Blahut et al., 2010; von Ruette et al., 2011). To validate the model based on the "wait and see" concept (Chung and Fabbri, 1999), data for landslides before 1975 were used to create models, whereas data for landslides after 1975 were used to validate the models.

2. Study area

The study area is the Milia basin in Tuscany, Italy (Fig. 1), with an area of 101 km^2 and elevations from 39 to 913 m above sea level, with an average of 336 m (standard deviation = 167.5 m). The basin is stretched out in a southwest direction and shows a prevalent hilly character. Approximately 80% of the study area is located below the altitude of 503.5 m. Only the eastern side of the Milia basin, where the morphological–structural highland of Poggione Mountain occurs, is higher. Most of the streams of higher orders (Strahler, 1952) show intense vertical erosion in the northeastern part of the basin, whereas lateral erosion dominates in the western sector.

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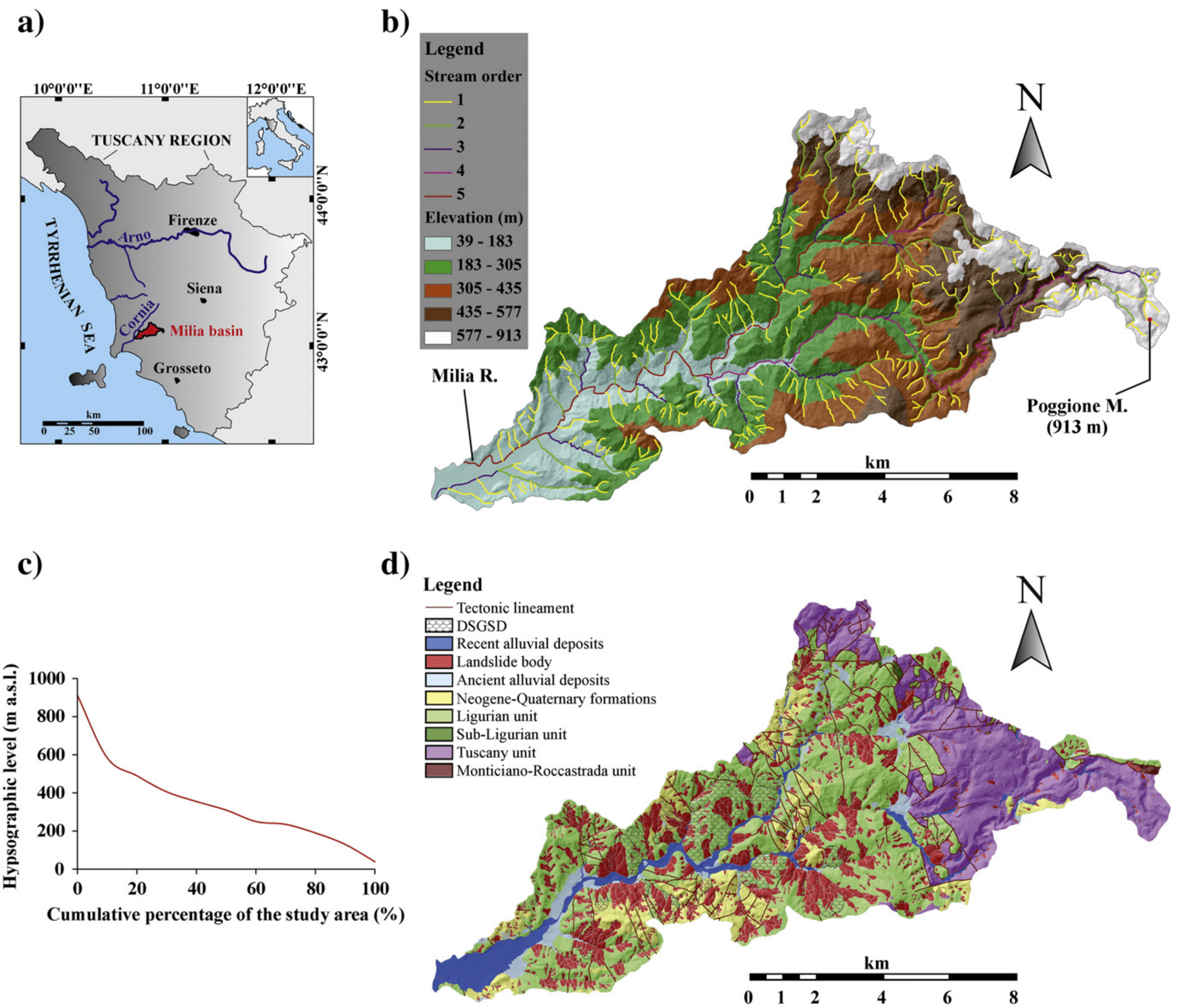

Fig. 1. The study area (Milia Basin). (a) Location. (b) Hydrography. (c) Hypsograph. (d) Geology. Streams in panel b are ordered according to Strahler (1952).

In the Milia basin, compressional events before and during the collisional Apennine episode provided a complex sheet stack where the Ligurian and sub-Ligurian units have been placed above the Tuscan Domain (Costantini et al., 2000, 2002; Fig. 1). These allochthonous units are characteristic of distal turbiditic and hemipelagic environments and are composed by altering siltitic, argillitic, and fine arenitic formations and argillitic formations with interbedded limestone. The Tuscany units are represented prevalently by the Mesozoic carbonate succession, associated with minor outcrops of the Cretaceous–Tertiary turbiditic and hemipelagic sequence. The Tuscany units are overthrust above the Monticiano–Roccastrada unit, which represents the outcrop of the "Autochthon" metamorphic unit. The Monticiano–Roccastrada Unit outcrops only in the eastern part of the basin and is characterized by alternating phyllites and marbles. Neogene–Quaternary formations, representative of continental and coastal–marine environments, are characterized by sandy clays and sandy conglomerates.

All tectonic units underwent a complex deformation history related to the pre- and post-collisional events. Post-collisional deformations since the Middle Miocene have been extensional and caused the partial collapse of the Apennines (Carmignani et al., 1994). The Pleistocene tectonic evolution was followed by a rapid downcutting of the hydrographic network, as suggested by numerous fluvial terraces at different altitudes.

The morphology of the study area is also conditioned by numerous mass movements, including translational slides, rotational slides, and flows (Cruden and Varnes, 1996). DSGSDs are also present (Fig. 1), and their evolution appears related to the Pleistocene tectonic evolution and the base level lowering. Their morphologies are similar to those described elsewhere (e.g., Zischinsky, 1969; Agliardi et al., 2001; Agliardi et al., 2009a,b). The DSGSDs in the Milia basin have sizes comparable to the whole slope, relatively small displacements, and evident morphological features such as doubled ridges, scarps, counterscarps, trenches, and toe bulging. For these phenomena, deformation can be considered as a large oblique "sagging" along a deep, perhaps confined, sliding surface. In this regard, the scarps and counterscarps of the DSGSDs could be considered as surface expressions of shear surfaces, as observed in many previous works (e.g., Agliardi et al., 2001, 2009a,b; Bachmann et al., 2009; El Bedoui et al., 2009). Overall, 23 DSGSDs occur in the Milia basin, with each extending 0.2 to 1.2 km^2, with a total area of 6.2 km^2 (6.1% of the study area). Approximately 87% of the DSGSDs occur in