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Landslide susceptibility assessment in the Peloritani Mts. (Sicily, Italy) and clues for tectonic control of relief processes

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Abstract. Many destructive shallow landslides hit villages in the Peloritani Mountains area (Sicily, Italy) on 1 October 2009 after heavy rainfall. The collection of several types of spatial data, together with a landslide inventory, allows the assessment of the landslide susceptibility by applying a statistical technique. The susceptibility model was validated by performing an analysis in a test area using independent landslide information, the results being able to correctly predict more than 70 % of the landslides.

Furthermore, the susceptibility analysis allowed the identification of which combinations of classes, within the different factors, have greater relevance in slope instability, and afterwards associating the most unstable combinations (with a short–medium term incidence) with the endogenic processes acting in the area (huge regional uplift, fault activity). Geological and tectonic history are believed to be key to interpreting morphological processes and landscape evolution. Recent tectonic activity was found to be a very important controlling factor in landscape evolution. A geomorphological model of cyclical relief evolution is proposed in which endogenic processes are directly linked to superficial processes.

The results are relevant both to risk reduction and the understanding of active geological dynamics.

1 Introduction

Shallow landslides are very common in steep mountainous regions where they often constitute a major risk factor for human activities (Glade, 1998; Singh et al., 2005; Claessens et al., 2007; Salciarini et al., 2008; Gullà et al., 2008; Deb and El-Kadi, 2009; Harp et al., 2009). Their occurrence, often triggered by exceptional rainfall or earthquakes, can involve large regions with a huge numbers of events. The simultaneous occurrence of multiple landslides gives the exclusive opportunity to study their distribution in relation to several environmental factors.

On 1 October 2009, more than one thousand shallow landslides occurred in the NE corner of Sicily (Italy) (Maugeri and Motta, 2010). The affected area extended over approximately 30 km^2 and was located on the eastern sector side of the Peloritani mountain ridge. Slope instabilities were triggered by heavy rainfall and affected mainly the lower parts of 14 small catchments directly facing the Ionian Sea (Fig. 1). Landslides caused 35 fatalities, the total devastation of several villages in Messina province, and severe damage to the public heritage and the local economy (Fig. 2). Rainfall was very intense: 223 mm of rain fell in 7 h, with a peak of 10.6 mm in 5 min, on terrain already saturated by precipitation during previous weeks ($\sim$ 400 mm in 14 days) (Maugeri and Motta, 2010).

Here we perform a susceptibility analysis for shallow landslides, by spatial combination of the inventory map of the events with some causative factors. We employ a statistical bivariate method that assigns numerical weight values to each class of causative factors.

The susceptibility assessment yields two main results. Firstly, we are able to identify reliably which areas in this territory are more likely to be involved in future landslides. Secondly, we can investigate the connection between the most landslide-prone conditions and the active geodynamics of the area.

The principal thesis is that geotectonic history is behind the factors controlling landsliding, playing a leading role in

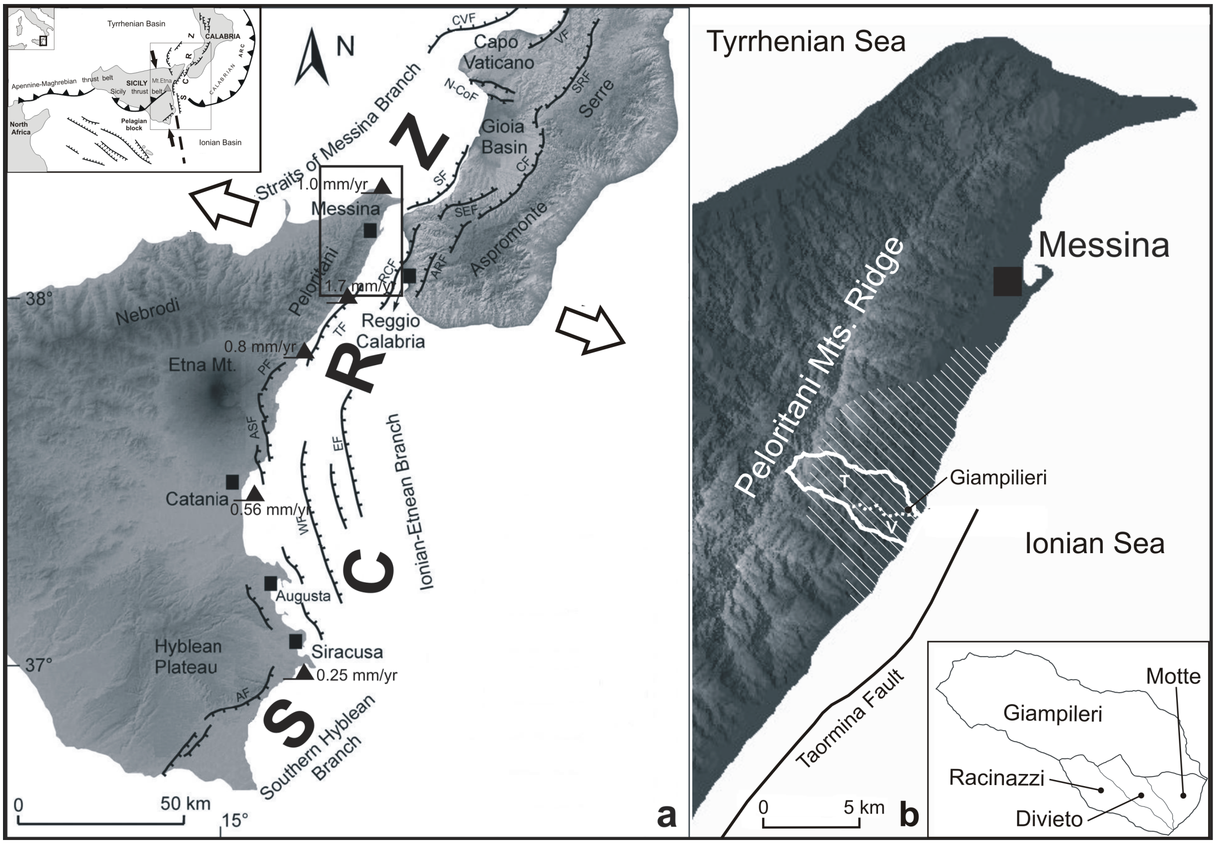

Fig. 1. (a) Tectonic map of eastern Sicily and southern Calabria showing the Siculo–Calabrian Rift Zone (SCRZ), modified from Catalano et al. (2008). Arrows indicate the regional extension direction and triangles the uplift rates given by Catalano et al. (2003) and Catalano and De Guidi (2003); RIF: Rosolini–Ispica faults; AV: Avola fault; WF: western Ionian fault; EF: eastern Ionian fault; ASF: Acireale–S.Alfio faults; PF: Piedimonte fault; TF: Taormina fault; RCF: Reggio Calabria fault; AF: Armo fault; SF: Scilla fault; SEF: S.Eufemia fault; CF: Cittanova fault; SRF: Serre fault; VF: Vibo fault; CVF: Capo Vaticano fault; N-CoF: Nicotera–Coccorino faults. **(b)** the hatched zone represents the area affected by landslides on the 1st October 2009; the continuous white line indicates the study area; training area (T) and validation area (V) of the landslide susceptibility analysis are showed.

the slow but inexorable process of transformation of the morphological structure of this area. In fact eastern Sicily and southern Calabria are among the most tectonically active areas in the Mediterranean. Since the Middle Pleistocene, the entire Calabrian arc has undergone strong tectonic uplift (Montenat et al., 1991; Westaway, 1993; Tortorici et al., 1995; Rust and Kershaw, 2000), accompanied by activity of a normal fault belt since 700 ka BP (Fig. 1). Present-day activity is testified by the strong historical seismicity (Monaco et al., 1997; Monaco and Tortorici, 2000; Catalano et al., 2008).

Several papers have highlighted the relationship between tectonics and the evolving landscape (Burbank and Pinter, 1999 and reference therein; Montgomery and Brandon, 2002; Snyder et al., 2002, 2003; Korup et al., 2007; Agliardi et al., 2009; Goswami et al., 2011). Similarly, we investigate the role of tectonics on surface processes with respect to geological, climatic and environmental factors.

2 Morphostructural setting

The study area is part of the Peloritani mountain range belonging geologically to the Calabrian arc and representing the inner chain of the Apennine–Maghrebian mountain belt (Amodio Morelli et al., 1976; Bonardi et al., 1982). The mountain ridge extends longitudinally for about 50 km, with a SW–NE orientation (Fig. 1), resulting in peaks higher than 1200 m that shelve toward the Tyrrhenian and Ionian seas (NW and E respectively).

2.1 Tectonic outline

The Calabrian arc has a long and complex geological history. In fact, it has been involved in two orogenic cycles since late Palaeozoic times and many other Neogene deformation events. More recently (Middle Pleistocene), the entire Calabrian arc underwent strong tectonic uplift (Montenat et al., 1991; Westaway, 1993; Tortorici et al., 1995), with rates greater than 1.0 mm yr^{-1}, accompanied since 700 ka

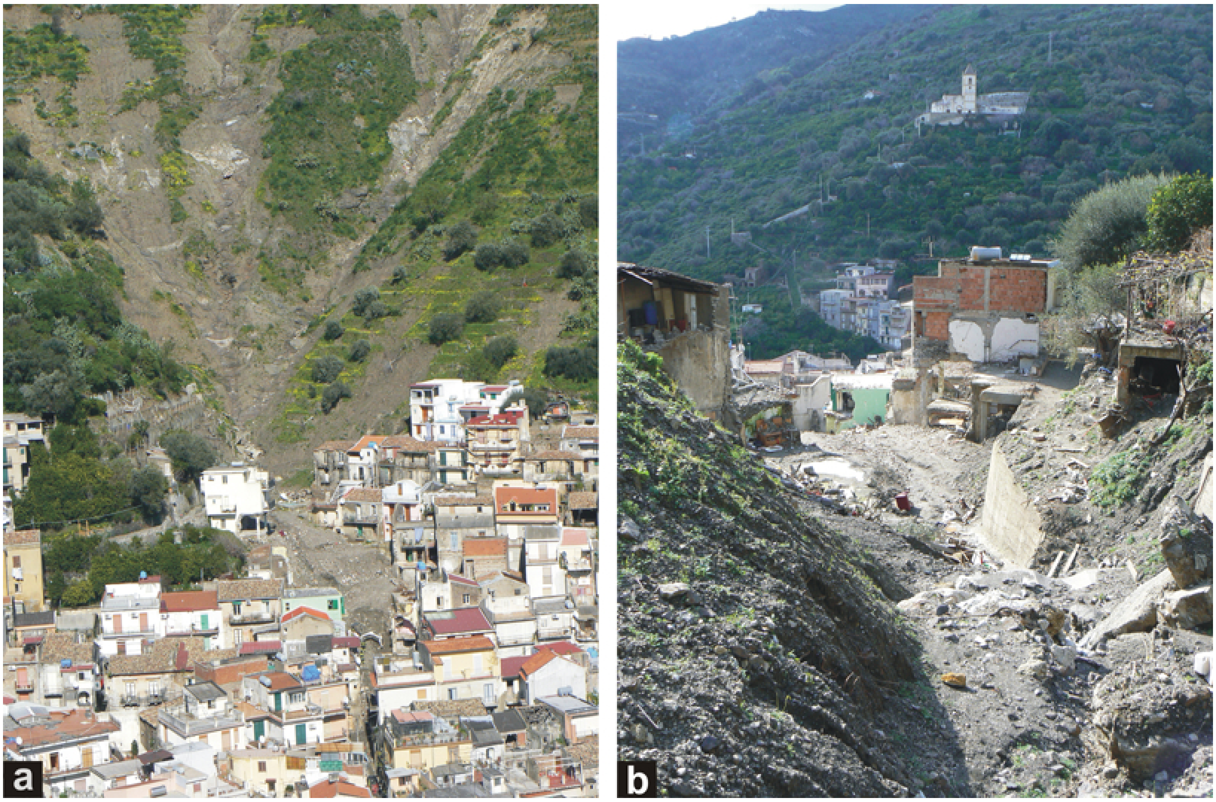

Fig. 2. Examples of some shallow landslides triggered by October 1st 2009 rainfall event in Giampilieri village: **(a)** front view; **(b)** downslope view.

by the activity of a normal fault system called the Siculo–Calabrian Rift Zone (SCRZ) (Monaco et al., 1997; Monaco and Tortorici, 2000; Catalano et al., 2008) (Fig. 1). The corresponding regional tensional stress is oriented $N \sim 115\,\mathrm{E}$ (D'Agostino and Selvaggi, 2004; Catalano et al., 2008) and is partially accommodated by deformation on the various fault segments. The study area is located at the footwall of one of these active normal faults (Taormina fault) (De Guidi et al., 2003). Taking into account the vertical deformation induced by its activity, the total tectonic uplift rate for the last 125 ka reaches a maximum value of $1.7\,\mathrm{mm\,yr^{-1}}$ (Catalano and De Guidi, 2003; Catalano et al., 2003) across all of eastern Sicily.

Holocene uplift rates are even greater, and, in fact, this is one of the areas that incurred the highest uplift in this period for the entire Italian peninsula (Lambeck et al., 2004). Vertical rates measured in the area of the Peloritani Mts. peak at between 1.4 and $2.4\,\mathrm{mm\,yr^{-1}}$ for the last 5000–6000 yr (Stewart et al., 1997; Rust and Kershaw, 2000; Antonioli et al., 2003; De Guidi et al., 2003; Antonioli et al., 2009), although the true uplift with respect to base level (Ionian Sea level) is lower, because in the same period sea level rose at an average rate of about $1\,\mathrm{mm\,yr^{-1}}$ (Lambeck et al., 2004). However, the increase in the topographic gradient of the Peloritani Mts. is very notable.

2.2 Morphological features

The landscape of the Peloritani Mts. reflects the tectonic setting of the area, in particular the intense recent dynamics. Vertical movements of base level during the late Quaternary, caused by interaction between vertical tectonic deformation and eustatic sea level changes, controlled the shaping of the landforms. This resulted in a poly-cyclical evolution of the coastal slopes that shows imprinting of many sequential cycles of rejuvenation during Late Pleistocene and Holocene times (Montenat et al., 1991; Rust and Kershaw, 2000; Catalano and De Guidi, 2003; Catalano et al., 2003; De Guidi et al., 2003).

One of the most prominent aspects is represented by a consequent drainage system, developed on both the northwestern and eastern slopes of the Peloritani mountain ridge. Other morphological features are represented by the remnants of marine terraces located at various elevations on the coastal slopes, and deep V-shaped valleys, typical of recent erosional stage, which cut pre-existing peneplaned surfaces.

In particular, different fluvial landforms characterize the northwestern and eastern sectors of the Peloritani Mts. In the former, low-energy fluvial landforms mark the landscape; river valleys with smooth longitudinal profiles separate wide north–south elongated surfaces dipping toward

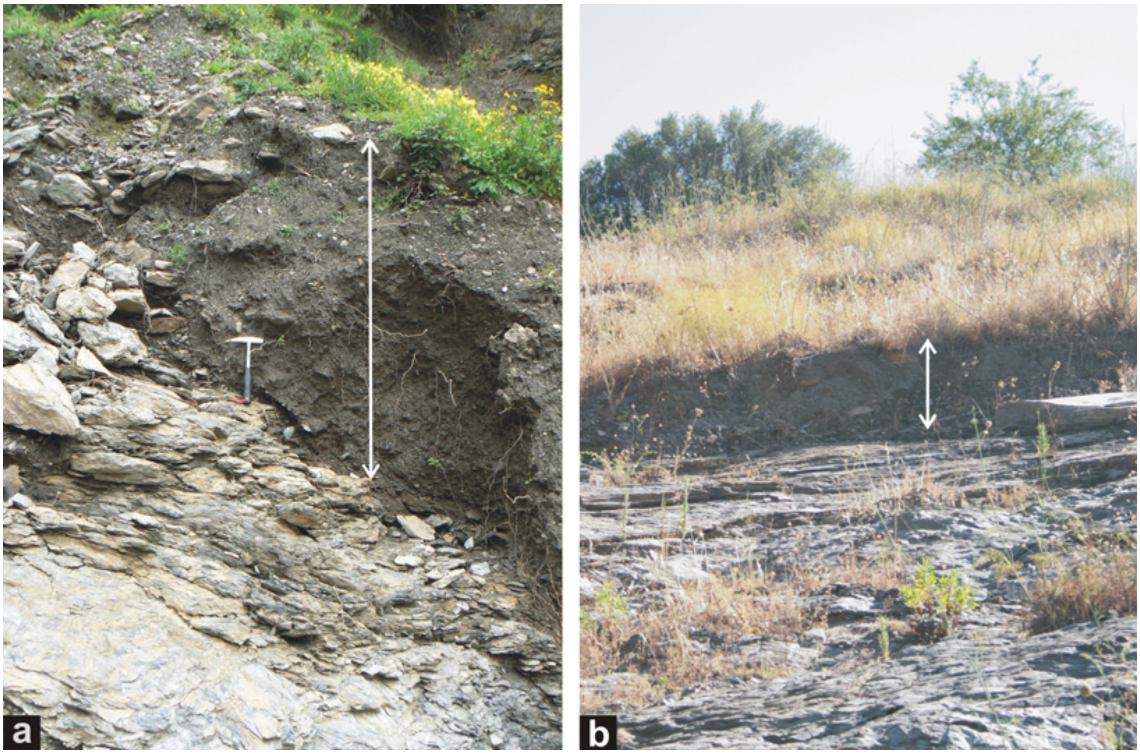

Fig. 3. Landslides scars: lateral **(a)** and frontal **(b)** view. Note the sharp contact between the colluvium (approximately 1.0 m thick) and the bedrock.

the Tyrrhenian Sea. In the latter the landscape exhibits more the results of its poly-cyclical evolution: deeply incised valleys separate interfluves constituted by remnants of marine terrace surfaces (APAT, 2008 and 2010). The longitudinal-profiles show several steady knickpoints due to stages of relative stability of the base level (Goswami et al., 2012). The most recent knickpoint is active and steadily migrates upslope while the steep flanks of the river valleys are affected by headward erosion.

Several streams characterized by high gradient and short length, fed by intermittent and torrential rainfall, drain the Peloritani Mts., in particular the eastern (i.e. Ionian) sector. The local name for this kind of river is *fiumara*. The precipitation regime controls their activity, and therefore sudden, heavy floods usually interrupt longer period of inactivity. The morphostructural framework also influences flow regime, with active tectonic uplift being one of the main controlling features (Sabato and Tropeano, 2004).

The overall topography is uneven with steep slopes ranging between 25° and 70°, but flat areas may also occur where remnants of Quaternary marine terraces are preserved; they originated through the interplay between tectonic uplift and the sea level high stands (Catalano and De Guidi, 2003; Antonioli et al., 2006).

3 Landslide susceptibility assessment

The landslide susceptibility for a given landslide typology is the spatial probability that an event may occur in a given area considering a given selection of geo-environmental factors (van Westen at al., 2006; Fell et al., 2008). Susceptibility can be evaluated using many different approaches according to the aims of the susceptibility assessment itself and to the scale of the analysis. There are heuristic or empirical models, statistical analyses, deterministic models and probabilistic methods (Guzzetti et al., 1999; Brenning, 2005; van Westen et al., 2008; Cascini, 2008). Many of these have been developed in conjunction with geographic information systems (GIS) (Carrara et al., 1991; van Westen et al., 1997; Carrara et al., 1999). In particular, susceptibility assessment for shallow landslides recently has been evaluated using methods belonging to all four groups (Dai and Lee, 2003; Guzzetti et al., 2005; Singh et al, 2005; Deb and El-Kadi, 2009; Godt et al., 2008; Gullà et al., 2008; Salciarini et al., 2008; Günther and Thiel, 2009; Piacentini et al., 2012).

All of the methods entail some basic assumptions (Guzzetti et al., 1999 and references therein): (i) each landslide leaves on the terrain some features that are recognizable and can be mapped in the field or remotely; (ii) slope failures obey mechanical laws, and the collection of instability factors leading to the failures allows assessment of the susceptibility models; (iii) future landslides will occur under the same condition that caused past failures; (iv) it is possible to infer the spatial and temporal occurrence of failures through the analysis of the geo-environmental factors. Thus, a given territory can be classified according to different landsliding probability.

We performed the susceptibility assessment with various different statistical models, but here we present only the most effective one. The model was performed in four small catchments of the eastern sector: Giampilieri, Divieto, Racinazzi and Motte (Fig. 1). These catchments were selected because they form the core of the area of landslides, where we have at our disposal the largest amount of data (Scudero and De Guidi, 2011) The basins extend over a $\sim 13\,\text{km}^2$ area within the eastern flank of the mountain range, directly facing the Ionian Sea. Moreover, the study area was subdivided into a "training area" where the analysis was performed, and a "validation area" where the effectiveness of the results was tested.

3.1 Landslide characteristics and inventory

Shallow landslides constitute the main geological hazard in the Peloritani Mts., even though some larger and more complex landslides are present. The latter are mainly induced by the downcutting of stream beds consequent to the overall rejuvenation process, but they were not considered in this study.

All of the landslides took place within the patchy layer of loose, heterogeneous and often weathered material of variable thickness (1–3 m) covering the majority of the slopes *(colluvium)* (Fig. 3). This deposit is characterized by a high coarse fraction (gravel content more than 50 %) and a clay content that is often scarce. Its friction angle can reach more than 35 °, allowing the material to remain, under normal conditions, on the steep slopes of the catchments. According to Lacerda (2007), the term *colluvium* refers to soil material that underwent little transport or derives from large landslides with sudden transport.

The landslides are usually triggered by the detachment of small boulders from natural scarps, rocky cliffs or ancient retaining walls used for terracing the slopes for agricultural purposes, over a saturated portion of colluvium (Agnesi et al., 2009). Another mechanism is the sudden fluidification of the colluvial material due to superficial or subsuperficial water currents or temporary springs rising from the bedrock where contrasts of hydraulic properties with the colluvial layer may occur (Agnesi et al., 2009). The volume of single events is relatively constant, usually comprising between 10^3 and $10^4\,\text{m}^3$ (Falconi et al., 2011).

The flows usually developed downslope, even though they can also enlarge laterally and migrate upslope. The material often canalized following the natural drainage, eroding and sometimes exhuming buried gullies. During their movement downwards, the flows eroded the base or the lateral edges of their channels, gaining further material and increasing their volume, until they stopped in the zone of accumulation, usually located at the foots of the slopes. The villages involved were located at the bases of large, steep slopes and were party swept away by the mobilized material.

Even though different triggering mechanisms induced the failures, all of the events shared the same general geo-environmental arrangement at the source points before the failure occurred. Therefore, we ascribe the failure mechanism to very local conditions and we will treat the instabilities as being a unique typology.

The landslide inventory map of the Regional Civil Defence (Basile, 2010) was verified through field reconnaissance surveys and integrated with missing data to ensure accuracy in the presence and location of the landslides. A total of 397 landslides have been mapped in the entire study area.

The inventory map of Basile (2010) distinguishes, for each landslide, an area mainly characterized by erosion, and the fan, where the accumulation of transported material dominates. Within the areas experiencing loss of material, the source area and the channel have not been considered separately. For the susceptibility assessment of this type of landslide, we have to consider only the area where the first detachment originated. For this reason we considered as source areas for the shallow landslides a circle of 25 m in diameter comprising the initiation point and the upper part of each event (Salciarini et al., 2006). This value is congruent with the scale of our analysis (Hengl, 2006), and with the spatial variability of the causative factor observed in the field.

3.2 Spatial variables

Many factors can influence the occurrence of landslides, and understanding the determinant factors requires a good knowledge of the study area, of the phenomena and an assessment of the scale of analysis and the methodology (van Westen et al., 2006, 2008; Cascini, 2008). The experience gained during field activities (Scudero and De Guidi, 2011) allowed us to recognize six different controlling factors: lithology, geomechanical classification, geomorphology, distance to stream, slope angle, and aspect.

Many other geo-environmental factors have been recognized to have a role in instabilities (van Westen et al., 2008), but these have been excluded from our analysis for the following reasons: (i) if they act evenly, or almost evenly, over the entire study area; (ii) if we did not recognize their influence on landslides during field surveys; (iii) if they can be linked to other factors already taken into account. In particular we excluded any anthropogenic influences (e.g. proximity to transportation networks or buildings) since instabilities are widespread even on natural slopes, and they eventually interact with infrastructures or other anthropogenic features only during their development downslope. Factors such as drainage and lineament densities were ignored, because they are already incorporated in other indicators.

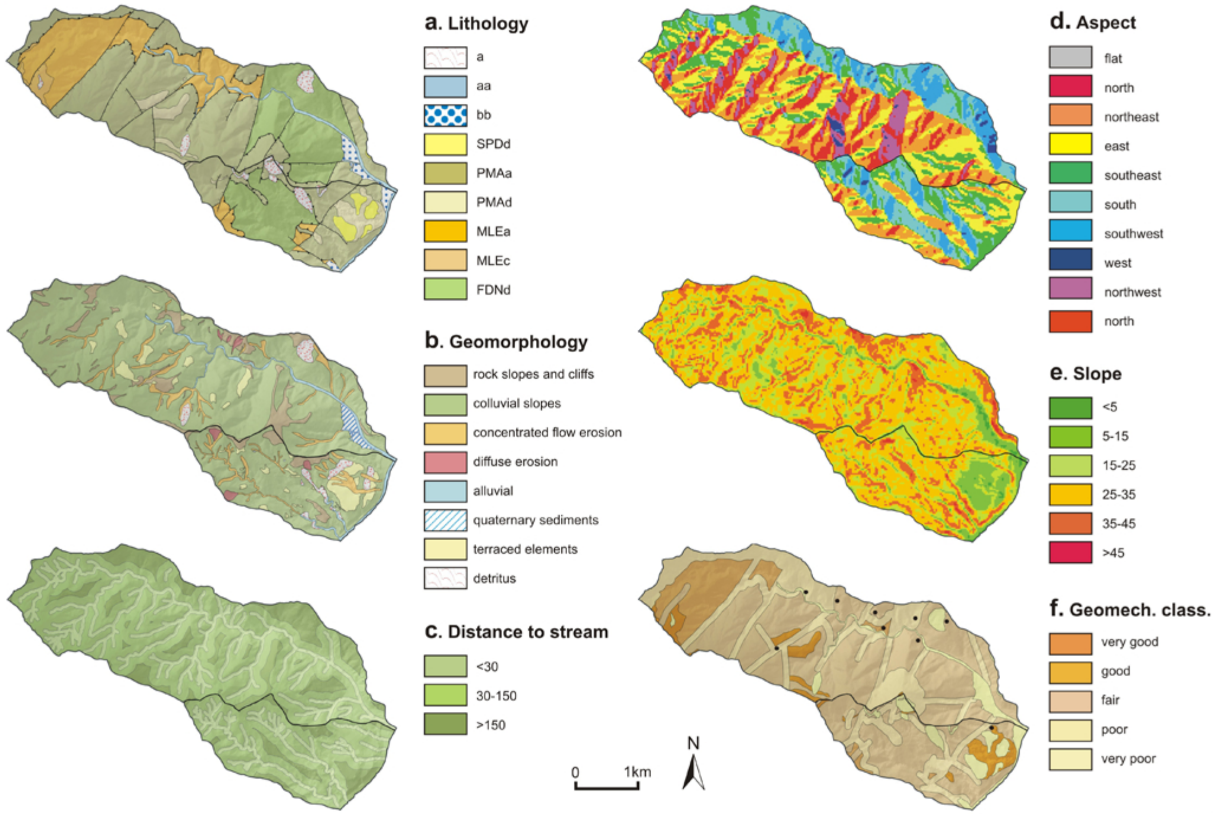

Fig. 4. Spatial distribution of the six causative factors: **(a)** bedrock lithology and lineaments (abbreviations from Messina-Reggio C. Geological Map, Foglio 601 Messina-Reggio C. della Carta Geologica d'Italia, scala 1:50 000. APAT, Servizio Geologico d'Italia, Dipartimento Difesa del Suolo, Roma, 2008); **(a)** slope deposits; aa: present-day alluvial deposits; bb: recent alluvial deposits; SPDd: calcarenites; PMAa paragneiss of the Aspromonte unit; PMAd marble of the Aspromonte unit; MLEa: mica schists of the Mela unit; MLEc: marble of the Mela unit; FDNd: phyllite of the Mandanici unit); **(b)**: geomorphological units; **(c)**: distance to stream; **(d)**: aspect of the slopes; **(e)**: slope angle (degree); **(f)**: geomechanical classification of rock types according to the RMR proposed by Bieniawski (1979); black dots indicate the measurement stations.

We mapped the spatial distribution of the causative factors (Fig. 4) on a 1:10 000 scale and acquired them as spatial layers in a G.I.S. environment with 10 m × 10 m pixel resolution. This definition is accurate enough considering the map scale and the minimum dimension of the observed objects (Hengl, 2006).

The bedrock geology of the study area consists of three different types of metamorphic rock, including low-grade phyllites that are covered tectonically by higher-grade mica schist and paragneiss. These rocks represent the late Palaeozoic basement of the European plate that was thrust over the Apennine–Maghrebian chain (Giunta and Nigro, 1999; De Gregorio et al., 2003; Festa et al., 2004; Heymes et al., 2010), then deformed during the Tertiary (Monaco et al., 1996; Bonardi et al., 2002; Somma et al., 2005; Grande et al., 2009) and Quaternary (Tortorici et al., 1995; De Guidi et al., 2003; Catalano et al., 2008). Because of their geological history, the rocks are deeply fractured and weathered. We performed a geomechanical characterization of the rock masses according to the rock mass rating (RMR) proposed by Bieniawski (1979) in order to assess their quality. For this purpose we surveyed random outcrops of bedrock, representing each lithotype, and estimated the rock quality designation index (RQD), the uniaxial compressive strength, the condition of the discontinuities (spacing, roughness, persistence, filling, alteration) and groundwater condition. In particular, the uniaxial compressive strength was estimated through the Schmidt hammer readings converted according to the empirical relationship proposed by Deere and Miller (1966). The collection of other parameters followed the scheme proposed by ISRM (1981).

We noted a sharp decrease of mechanical characteristics approaching the tectonic lineaments at a distance of less than 50 m. Therefore the localized RMR analyses were spatialized by combining rock type with distance to tectonic lineaments (Greco and Sorriso-Valvo, 2005; Borrelli et al., 2007; Pellegrino and Prestininzi, 2007).

Such subdivision provides additional information concerning differences in the rock masses and represents a causative factor in describing landslide occurrence (Federici et al., 2007; van Westen et al., 2008).

The geomorphological map distinguishes terrain units according to processes in action, the origin of the features, and the materials involved. The most relevant feature is the extensive presence of a colluvial layer covering the majority of the slopes. It is characterized by almost uniform thickness (∼ 1 m) (Fig. 3), although thicker deposits, up to 3 m, may occur on some slopes. Rock slopes, concentrated flow erosion, and areas with diffuse erosion are other representative features. More than one geomorphological process could coexist; however we considered only the most prominent process in each part of the study area.

We also generated a digital elevation model (DEM) from a 1:10 000 map with 10 m contour intervals and derived three topographic features: (i) slope; (ii) aspect; and (iii) distance from drainage.

Slope angle is one of the most relevant factors controlling landsliding. Steep slopes characterize the entire Peloritani ridge: the highest peaks can reach 1200 m a.s.l. within 5 km from the coast, and the mean slope angle in the study area is 32°.

The slope aspect can influence hydrological processes, and therefore it also has an indirect bearing on weathering, vegetation and root development. But the aspect map can also suggest which slopes are more prone to landsliding considering the spatial organization of the drainage network. In fact, in active areas it is usually controlled by tectonic processes and provides information on the state of evolution of the fluvial basin (Guarnieri and Pirrotta, 2008).

Finally, the distance from the drainage system has been considered because relief is intensely dissected by stream segments and erosion can influence the distribution of instabilities (van Westen et al., 2008).

3.3 Susceptibility analysis and mapping

The landslide susceptibility analysis was performed using a statistical bivariate method. Bivariate techniques have been used widely in the literature for susceptibility assessment (van Westen, 1997; Cevik and Topal, 2003; van Westen et al., 2003; Süzen and Doyuran, 2004; Yalcin, 2008, Nandi and Shakoor, 2009). Each of the spatial variables (layer) discussed in the previous paragraph was considered to be an independent variable causing landslides. In the bivariate approach each independent variable is correlated with the dependent one (landslide map), and their relationships with landslide occurrences were calculated through pairwise map crossing. Furthermore, the bivariate techniques assume that the independent variables are not inter-related and that they all have the same weight in landsliding. In particular, we performed landslide susceptibility analysis using the statistical index method proposed by van Westen (1997).

In the statistical index method, the weights of the classes of each factor are calculated as the natural logarithm of the ratio between the density of landslides in the considered class and the density of landslides for the entire map; weights were calculated using the following equation:

$$w_{ij} = ln\left(f_{ij}/f\right) = ln\left[\left(\mathrm{A}^*_{ij}/\mathrm{A}_{ij}\right) * \left(\mathrm{A}/\mathrm{A}^*\right)\right] = ln\left[\left(\mathrm{A}^*_{ij}/\mathrm{A}^*\right) * \left(\mathrm{A}/\mathrm{A}_{ij}\right)\right] \quad (1)$$

where, w_{ij} is the weight of the class i of parameter j, f_{ij} is the landslide density of the class i of parameter j, f is the landslide density of the whole considered area, A^*_{ij} is the landslide area in the class i of parameter j, A_{ij} is the area of the class i of parameter j, A^* is the total landslide area, and A is the total surface of the considered area. Therefore the higher the weight of a class, the greater is its influence in the instabilities. The method was first performed in the "training area" (T in Fig. 1) that represents about 75 % of the entire study area, and its robustness and prediction skill was then tested in an adjacent "test area". The numerical rating values for each class of the six causative factors are presented in Table 1.

The calculated weights indicate that, for the geology factor, the highest value is given by Plio-Pleistocene calcarenites. They outcrop over a very small part of the basin, forming cliffs just above the initiation points of some of the landslides. For this reason, the weight is high but it is likely that there is no direct influence of this lithology on instability. Relatively high weights also occur where large bodies of detritus or loose deposits cover the slopes. The Mandanici unit (phyllite) is by far the most favourable for landsliding compared to the other metamorphic units of the Peloritani Mountains.

For the geomechanical characteristics of the rock types, a clear trend is evident. Good rocks (according to the RMR classification) have no influence on landsliding, while poor ones favour instabilities.

For the geomorphological factor, the occurrence of large bodies of mobilized material and areas with concentrated flow erosion or strong erosional evidence have the highest influence. Rocky slopes and cliffs also have influence, because they can trigger shallow landslides through the fall of boulders.

Landslides occur when the slope angle is greater than 15°. The class with the highest incidence of landslides corresponds to high slope angles (> 45°), while the frequency is lower for intermediate slope angles (25°–45°).

Three classes of aspect factors influenced landsliding; in particular, south to southwest facing slopes were the most favourable. Areas located farther from the drainage network system (more than 150 m) were the most unstable.

Calculated weights have been spatially summed together in order to map the landslide susceptibility index (LSI) for the entire study area.

The absolute value of LSI is meaningful only when it is classified into categories providing a qualitative estimate of susceptibility (Fell et al., 2008). For this reason the LSI has

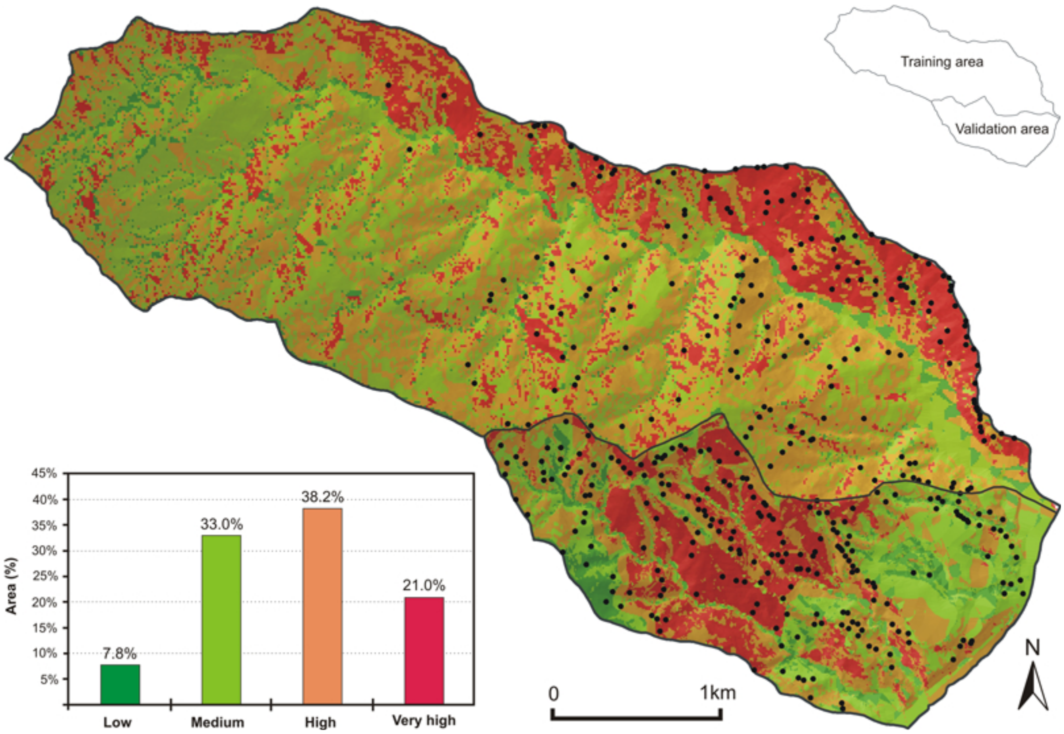

Fig. 5. Landslide susceptibility map subdivided in four landslide susceptibility classes: green, low susceptibility; light green, medium susceptibility; orange, high susceptibility; red, very high susceptibility. The bars show the percentage area within the different landslide susceptibility classes; black dots indicate the location of the landslides.

been classified into four different categories of susceptibility according to the most commonly used classification in the literature: low, medium, high and very high susceptibility.

Several subdivision procedures have been published that classify the LSI (expert-based, binary, equal interval, natural breaks, standard deviation, percentage of correspondence with landslides). In this study subdivision within the classes follows the criterion of natural breaks according to the Jenks' algorithm (Ruff and Czurda, 2008; Ruff and Rohn, 2008; Falaschi et al., 2009; Nandi and Shakoor, 2009; Piacentini et al., 2012) and was performed by analysing the frequency distribution of LSI. The natural breaks subdivision was preferred to other classification criteria, because the frequency distribution of the LSI shows obvious jumps. The final susceptibility map is shown in Fig. 5.

3.4 Validation and prediction

Validation of the susceptibility model is an essential procedure that assesses of how well it matches the distribution of landslides. Moreover, the use of independent landslide information is necessary to evaluate its sensitivity in forecasting future instabilities (Chung ad Fabbri, 2003; Guzzetti et al., 2006). There are different criteria with increasing grades of accuracy in the validation procedure. Guzzetti et al. (2006) also proposed a classification of the quality level of the susceptibility models and associated maps. Low quality models do not meet any tests of reliability, or validate the model with the same landslide information used to obtain the models themselves. High quality models estimate the error associated with the predicted susceptibility index value and, in addition, validate the model using independent landslide information that was not used to produce the model. The model presented here has been tested following this last criterion.

The effectiveness and the prediction skill of our model have been verified through a partition of the study area (Chung and Fabbri, 2003). We elaborated our model in the training area (T), and the validation was performed in the remaining part (V). We took into account the physiographical boundaries of the catchments, thus considering the watershed as boundaries of the training and validation areas (Fig. 5); 75 % of the study area, containing 182 landslides, was used as the training set, while the remaining 25 %, containing 215 landslides, was used for model validation.

The validation area was excluded before assessment of the model; thus, the landslide susceptibility map was drawn up first and only subsequently combined with the landslide distribution data in the test area (V) that is therefore independent of the model.

A quantitative assessment of the performance of the susceptibility model is provided by the *success rate curve* (Chung and Fabbri 2003; van Westen et al., 2003; Guzzetti et al., 2006; Poli and Sterlacchini, 2007; Blahut et al., 2010;

Table 1. Calculated weights in the training areas for the classes of the six causative factors; * arbitrarily assigned.

Instability factor/Classes	% Area covered by the class	Landslide density (%)	Weight
Lithology			
Slope deposit	1.33 %	2.7 %	0.69
Present-day alluvial deposits	2.06 %	0.0 %	0.00
Recent alluvial deposits	1.24 %	0.0 %	0.00
Calcarenites	0.09 %	2.2 %	*1.00
Aspromonte unit (gneiss)	48.35 %	41.9 %	−0.14
Mela unit (mica schist)	21.82 %	10.2 %	−0.76
Mandanici unit (phyllite)	20.61 %	42.9 %	0.73
Marble	4.49 %	0.0 %	0.00
Geomechanical classification			
Very good	3.62 %	0.0 %	0.00
Good	11.57 %	0.4 %	−3.49
Fair	49.41 %	67.8 %	0.32
Poor	30.67 %	26.9 %	−0.13
Very poor	4.73 %	4.9 %	0.04
Geomorphology			
Rock slopes and cliffs	8.70 %	13.9 %	0.47
Colluvial slopes	78.17 %	78.1 %	0.00
Concentrated flow erosion	5.09 %	2.5 %	−0.72
Areas with diffuse erosion	0.33 %	0.3 %	−0.07
Alluvial	2.06 %	0.0 %	0.00
Quaternary sediments	1.24 %	0.0 %	0.00
Terraced elements	3.20 %	2.6 %	−0.22
Detritus	1.22 %	2.6 %	0.77
Slope angle (°)			
< 5	5.11 %	2.5 %	−0.72
5–15	4.07 %	0.9 %	−1.55
15–25	19.03 %	14.9 %	−0.24
25–35	38.65 %	40.2 %	0.04
35–45	25.50 %	30.5 %	0.18
> 45	7.65 %	11.0 %	0.37
Aspect			
Flat	5.03 %	2.5 %	−0.70
North	8.67 %	6.4 %	−0.30
Northeast	18.68 %	18.6 %	−0.01
East	18.28 %	12.3 %	−0.39
Southeast	13.11 %	9.7 %	−0.30
South	11.64 %	17.2 %	0.39
Southwest	5.93 %	11.4 %	0.65
West	2.16 %	4.2 %	0.66
Northwest	7.40 %	4.2 %	−0.56
North	9.09 %	13.5 %	0.39
Distance to stream			
< 30	24.01 %	5.0 %	−1.58
30–150	60.05 %	69.0 %	0.14
> 150	15.94 %	26.0 %	0.49

Piacentini et al., 2012). This is drawn by plotting on the x-axis the cumulative percentage of the study area within each class of susceptibility and on the y-axis the cumulative percentage of landslides in each susceptibility class, ranked from the most to the least susceptible. The shape of the curve gives information about the degree of success of the model – the larger the area under the curve, the better is the performance in fitting the landslide distribution. For the susceptibility model in the study area, the curve rapidly departed from the x-axis and then approximated this axis in its final part, and the area under the curve (ACU) is 0.70, indicating a good success rate (Fig. 6). In detail half of the landslides (50 %) are found in the 26.1 % most susceptible zone, and approximately a quarter (24.8 %) of the landslides fall within the most susceptible 10 % of the area. The area evaluated and mapped as very highly or highly susceptible covers 84.4 % of the total mapped landslides, and only 1.8 % of the landslides are mapped in the lower susceptibility class.

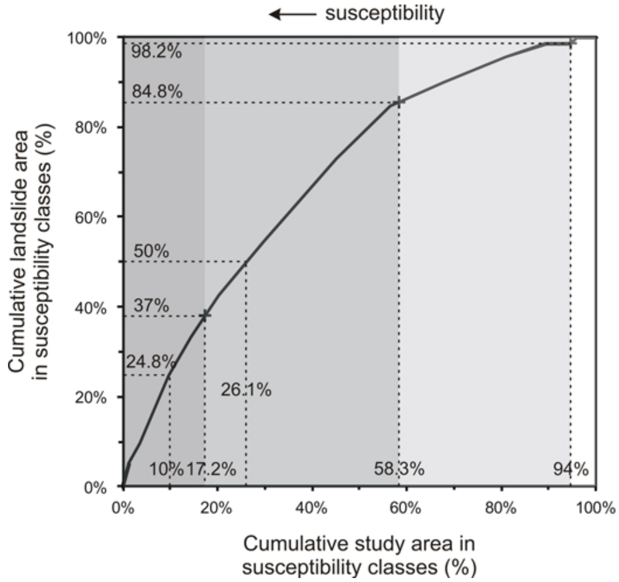

Fig. 6. Analysis of the fitting degree of landslide susceptibility model.

In the validation area we used independent landslide information in order to test the ability of the model to predict the locations of landslides. We plotted the cumulative percentage of landslides as a function of the spatial probability of occurrence (Fig. 7). Very few landslides (5.9 %) were within the lower class of susceptibility, while 70.9 % of landslides were correctly classified by the model as they occur in regions classified as being of high or very high susceptiblity.

4 Tectonic implications

The bivariate technique allowed us to perform and successively validate a susceptibility model for shallow landslides, proving the relevance of each geo-environmental factor in landsliding and the relative weight of each class. In this way we have been able to identify combinations of main factors leading to instability. These combinations generally consist of poor or very poor rock types, especially paragneiss and phyllite, steep (35°–45°) colluvial slopes or slopes covered by loose deposits, and at distance from the drainage network.

The occurrence of such combinations can be considered in framework of the geological heritage of the region of the Peloritani Mts.

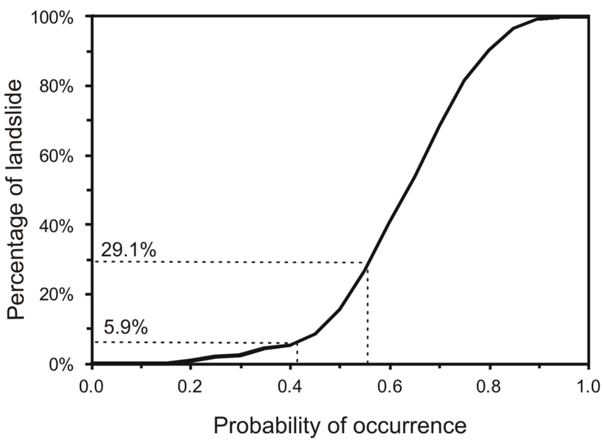

Fig. 7. Analysis of the landslide susceptibility map in the validation area (V) in relation to the distribution of the landslides.

Vertical tectonic deformation, acting intensely especially during the last 5000–6000 yr, contributed to the topographic rejuvenation of the relief by inducing erosional processes (Cyr et al., 2010) and allowing the release of lithostatic load causing a shallow and dense net of discontinuities in the rock masses. The denudation process is also favoured by geological conditions of highly deformed and weathering-prone metamorphic rocks (Morgagni et al., 1993; Le Pera and Sorriso-Valvo, 2000; Snyder et al., 2003; Calcaterra and Parise, 2005; Marques et al., 2010; Goswami et al., 2011). Lithostatic release and erosion mutually enhance their effects by favouring degradation of the rock masses (Riebe et al., 2001; Hren et al., 2007) and consequently the acceleration of slope processes where the normal evolution of the landscape involves a slower cyclical accumulation and mobilization of loose superficial material (Dietrich et al., 1982; Burbank, 2002).

In a mountain range bounded by active normal faults, relief responds very quickly to changes in the base level (Densmore et al., 1998; Goldsworthy and Jackson, 2000); even in a period of a century or less, river systems are able to adjust to the deformation (Keller and Pinter, 1996). Footwall uplift produces short, steep catchments in which the effects of tectonics are reflected both by the state of activity of the streams and the arrangement of the whole fluvial network.

In the study area the activity of the Taormina fault controls coastline shape over a whole sector of the Peloritani mountain range. The long-term activity of the fault induced the formation of a consequent drainage network represented by the main streams of the catchments. In an attempt to reach equilibrium with the tectonic activity, the main stream incisions undergo intense linear erosion and the slopes become steeper, while the erosional processes become weaker moving upwards to the secondary network (Catalano and De Guidi, 2003; Goswami et al., 2012). This allows indirect coupling of factors such as aspect or distance from the network with recent tectonic activity.

Slope aspect involved in instabilities is not only connected with hydrological or weathering processes, but also with the morphological evolution of the relief. In fact, the highest weights in landslide occurrence for S–SW and N-facing slopes (Table 1) are usually linked to the ∼WNW–ESE directed consequent drainage (Fig. 8). Similarly, because the slopes of the consequent valleys are wider (transversely) and longer (longitudinally), the number of instabilities increases with the distance from the streams. These slopes are undisturbed by the continuous erosion along stream segments, and a greater amount of sediment can accumulate. In contrast, for areas that are very close to stream segments, the formation of colluvium is retarded, and a sufficient thickness of colluvial material necessary for the occurrence of the types of instabilities considered here does not accumulate.

The relationship between recent tectonic activity and landslide distribution has also been highlighted by Goswami et al. (2011). These authors obtained the same result through frequency-area landslide statistics, showing that instabilities are mainly located where the effects, direct or indirect, of fault activity are the greatest.

5 Concluding remarks

A landslide susceptibility analysis for a representative area of the Peloritani mountain range has been carried out. The results of the validation and prediction prove the effectiveness of the model; in fact, within the performance scheme of Guzzetti et al. (1999), the model shows an acceptable percentage of correctly classified landslides. Consequently it is possible to extend the model from a relatively small area to a larger region with similar geological and geomorphological conditions.

The bivariate technique method separates each considered factor not providing their relative weights. For this reason the final map is a simple combination of factors which, although recognized as the most important ones, may not have equal incidence. For this reason, our results could be further improved by the application of more sophisticated methods for the analysis of susceptibility (i.e. multivariate techniques) that allow estimation of the relative influence of single causative factors.

Nevertheless, the experience gained during field surveys allowed us to select the most relevant factors, enhancing the reliability of the results. Fieldwork is of fundamental importance for a reliable mapping of the factors contributing to landslides, such as lithology, lithotechnical parameters and colluvium coverage. In addition, we suggest that the influence of active tectonics, and its spatial variation over the entire Peloritani region, should be taken into account as causative factors in future small-scale susceptibility assessments.

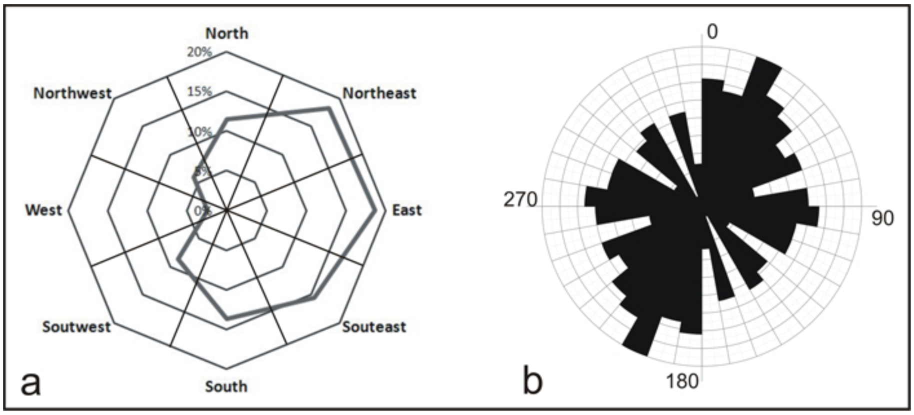

Fig. 8. (a) frequency distribution of the slope aspect within the whole study area: the highest value is for east-dipping slope; relative maxima are also for northeast- and south-facing slopes. **(b)** frequency distribution of the direction of the stream segments for the four considered catchments; note the peaks at SSW–NNE and at WNW–ESE directions.

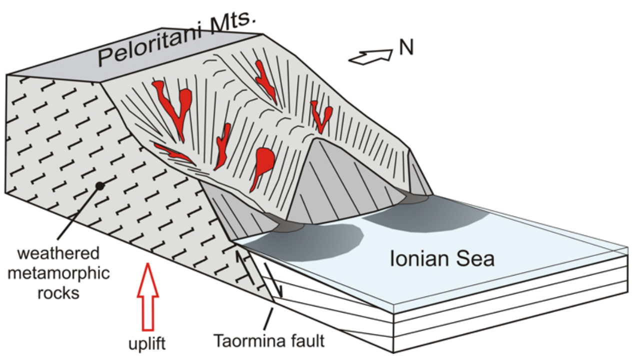

Fig. 9. Sketch summarizing the morphological, geological and tectonic features of the Peloritani Mts. Modified from Goldsworthy and Jackson (2000).

The assessment of landslide susceptibility allowed us to speculate about the effect of geological dynamics on the geomorphological evolution of relief. Our investigations focused on four representative basins, and we were able to infer some direct relationships between the general setting, derived from the active endogenic dynamics, and the superficial phenomena of relief evolution for this sector.

Erosion is favoured by geological conditions: metamorphic rocks in particular are very prone to chemical weathering. Tectonic uplift coupled with strong erosion allows the release of the lithostatic load originating as a shallow and dense net of discontinuities in the rock mass. These processes act together by favouring the weathering and consequently the formation of loose and heterogeneous material that covers most of the slopes and becomes cyclically unstable under critical conditions (e.g. extreme rainfall, earthquakes) (Fig. 9).

It was not possible to calculate the recurrence interval for the triggering rainfall events as this is much longer than the available historical records (Vecchio, 2011). Therefore, in a temporal perspective, these events are very rare and their influence on relief processes is not decisive.

The role played by fluvial bedrock incision, tectonic uplift and landslides in the evolution of relief is not universal, but rather changes from one mountain range to the other as well as with time (Korup et al., 2010). In different sectors of the Calabrian arc, several studies (Goswami et al., 2011, 2012; Santangelo et al., 2011) have recognized the direct influence of Quaternary tectonics (uplift and faulting) on mass movements and its greater relevance with respect the lithostructural and morphoclimatic factors.

In conclusion, considering the almost homogeneous geological and environmental conditions in the eastern sector of the Peloritani Mts., the landslide susceptibility model developed here could be extended without any particular integration, to the entire ridge area. Of course our model contains some limitations for this extension (limited catalogue extent, single landslide type analysed), and also other landslide susceptibility assessment methods could be tested. The spatial distribution of landslide susceptibilities highlights how large portions of the study area (about 20 %), and likely of the whole Peloritani Mts. area, are characterized by very high susceptibility. Therefore triggering events similar to that of October 1st 2009 will certainly occur again in the future. Consequently the susceptibility analysis is important not only for an understanding of the geological dynamics, but also because it represents a fundamental step in landslide hazard mitigation in the Peloritani Mts.

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APAT, Servizio Geologico d'Italia, Dipartimento Difesa del Suolo: Note illustrative della Carta Geologica d'Italia alla scala 1:50.000, Foglio 613 Taormina, S.EL.CA, Firenze, 2010.

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