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SCIENCE

Rockfall runout, Mount Cimone area, Emilia-Romagna Region, Italy

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Numerous mass movements of different typology characterize both mountainous and piedmont sectors of the Emilia-Romagna Region (Apennine chain, North Italy). Although a less spatially frequent landslide typology within the region, rock falls represent severe threats to buildings, roads and persons due to their high propagation velocity. This paper presents an extract of the Emilia-Romagna regional map of the rock fall runout areas at a scale of 1:25,000. The analysis of rock fall runout areas was based upon a three-dimensional morphological method (TDM). The zone presented in the Main Map encompasses the area surrounding Mount Cimone, in the Emilia-Romagna Region. The proposed regional map of rockfall runout is noteworthy for planning actions and strategies aimed at the prevention and reduction of landslide risk at a regional scale.

Keywords: rock falls; landslides; 3D-morphological method; northern Apennines; Italy

1. Introduction

The Emilia-Romagna Region, within the northern Apennine chain (Italy), is characterized by abundant and recurrent mass movements, among which rock falls are the most hazardous typology, even though less spatially recurrent (APAT, 2007). Rock falls represent a serious threat to urbanized areas, transport links and people due to their high velocity, independent of the volumes involved. Consequently, as part of territorial planning these phenomena must be taken into account in order to evaluate possible threats. In this context, an assessment of rockfall runout areas was performed at a regional scale (SSGS – Regione Emilia-Romagna, 2014). This work presents a map at a scale of 1:25,000 of the Mount Cimone area, within the Emilia-Romagna Region. A three-dimensional morphological method (TDM), developed within a geographyc information system (GIS), was used for rockfall assessment (Piacentini, 2006). TDM was selected since local deterministic analyses, generally based on kinematic models (Dorren, 2012; Guzzetti, Crosta, Detti, & Agliardi, 2002; Stevens, 1998), are not suitable for assessing rock fall over large territories due to the significant amount of data required and their quality and resolution that needs to be homogeneous over the entire territory. In turn, *TDM* is practical and cost-effective to initially identify areas most prone to rock falls at a regional scale. In fact, TDM does not require a significant amount of input data and can lead to effective and reliable results (Piacentini & Soldati,

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2008). The necessary data can be derived from available digital terrain models (DTM) (e.g. slope angles), remote sensing analysis (e.g. land use), and existing regional geological maps (e.g. geological units and their geo-mechanical characteristics). Our opinion is that the resulting map is helpful for recognizing areas most prone to rock fall. In addition, the map is a useful tool for preliminary assessment at a regional scale for rockfall detachment points and their runout areas aimed at completing a landslide inventory map of the whole regional territory (SSGS – Regione Emilia-Romagna, 2013a).

2. The mount Cimone area

The map presented in this paper was extracted from the Emilia-Romagna regional map of rockfall runout areas. The map encompasses the Mount Cimone area that covers a ca. 180 km^2-wide territory mostly characterized by mountainous landscape (heights ranging from ca. 580 up to 2165 m a.s.l.) (Inset A in the Main Map). This territory comprises several Apennine peaks including Mount Cimone (2165 m a.s.l.), Mount Cervarola (1623 m a.s.l), and Mount Libro Aperto (1937 m a.s.l.). The area lies within the Panaro River headwaters, one of the right tributary of the Po River. A prevalently planar or sub-planar morphology generally characterizes the main valley floors, as well as the areas at the main drainage divides. In contrast, the steepest slopes, reaching angles up to about 70°, characterize the mountainous sectors of the area and/or the valley sides where the bedrock consists of the hardest lithologies (Inset B in the Main Map).

The study area is part of the northern Apennine chain representing the sub-aerial appearance of a collisional orogenic wedge that has developed since the Oligocene as the result of the collision between Africa and Eurasia (Wilson, Pazzaglia, & Anastasio, 2009 and reference therein). The northern Apennine chain consists of a N-NE verging arcuate thrust-and-fold belt that has become definitively emerged within the last 1–2 million years. The whole area is tectonically active. Several historic and instrumental high frequency and low-intensity (Ms < 6.0) earthquakes have occurred in this sector of the Apennine chain.

The bedrock of the Mount Cimone area consists of Eocene-Miocene turbiditic terrigenous formations (prevalently from medium- to thick-layered arenites and pelites) pertaining to the Tuscan Unit overlain by Createaceous-Miocene arenites, calcarenites, marls, and clays belonging to the Sub-Ligurian and Ligurian nappes (SSGS – Regione Emilia-Romagna, 2013b) (Figure 1 and Inset C in the Main Map).

The lithological and structural characteristics of the outcropping bedrock strongly influence the morphology of the area. The active morphogenetic processes are mainly due to running water, gravitational slope instability and human activities. In the study area different rock types (i.e. arenites and calcarenites) outcrop that can potentially be affected by rockfall, compounded by intense rock-mass fracturing, strata attitude and steep-slopes (Figure 1 and Inset D in the Main Map). Small-to-medium blocks, rarely exceeding pluri-metric dimensions, generally characterize rock falls in the area. Rock falls have damaged several buildings and infrastructure (e.g. roads and bridges) (Figure 2) and, at present, represent a serious threat to urbanized areas.

Vegetation covers more than 90% of the Mount Cimone area. Trees and, to a lesser extent, meadows and bush characterize the prevalent land use (Inset E in the Main Map). The remaining territory is characterized by outcropping bedrock and urbanized areas. The latter are the small towns of Fiumalbo, Pievepelago, Riolunato and Sestola.

3. Materials and methods

The map of rockfall runout areas was obtained through of application of a morphological approach (Heinimann, Holtenstein, Kienholz, Krummenhacher, & Mani, 1998; Jaboyedoff &

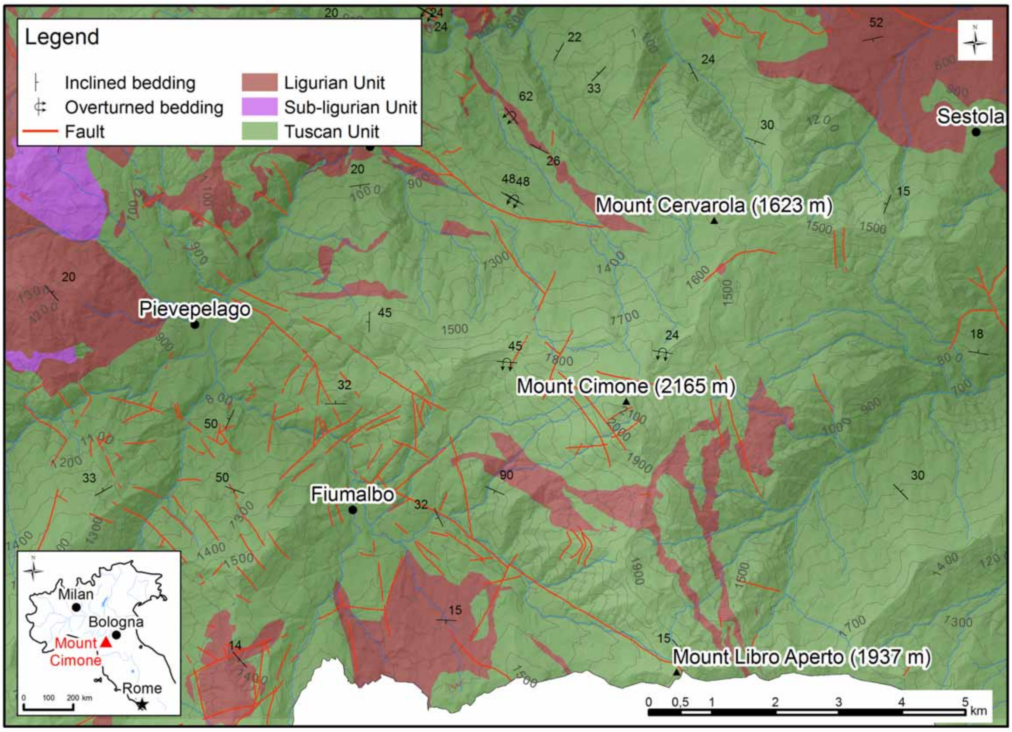

Figure 1. Geological sketch of the Mount Cimone area. Main geological units described in the text and the general structural setting are shown.

Labiouse, 2011; Onofri & Candian, 1979). In particular, a three–dimensional morphological method (TDM) (Piacentini, 2006; Piacentini & Soldati, 2008). TDM is based on historical analysis of past rock falls, assumes that block energy dissipation is directly proportional to the distance of propagation, and relates to slope conditions. Starting from a detachment point, TDM allows identification of the possible runout area as a 'cone' defined by calibrated vertical (α) and horizontal (β) angles (Figure 3).

At a regional scale, a detailed field survey of rockfall detachment points is not a useful approach. As a consequence, in agreement with previous work (Piacentini, 2006; Piacentini & Soldati, 2008), the rockfall detachment points were selected taking into account the methodology as follows:

(1) Predisposing slope angles, derived from a 5 m-gridded DTM;
(2) Bedrock formations most predisposed to rock fall due to their lithological and geomechanical characteristics, derived from the Geological Map of the Emilia-Romagna Region at the scale of 1:10.000 (SSGS – Regione Emilia-Romagna, 2013b);
(3) Land use dataset, derived from the Land Use Map of the Emilia-Romagna region at the scale of 1:25.000;
(4) Areas already affected by rock falls, derived from the historical archive of past landslides of the Emilia-Romagna Region (SSGS – Regione Emilia-Romagna, 2013a).

Starting from the areas selected with the methodology above, three different scenarios of runout zones were identified based on the three different vertical angle values ($\alpha = -33°, -35°, -37°$).

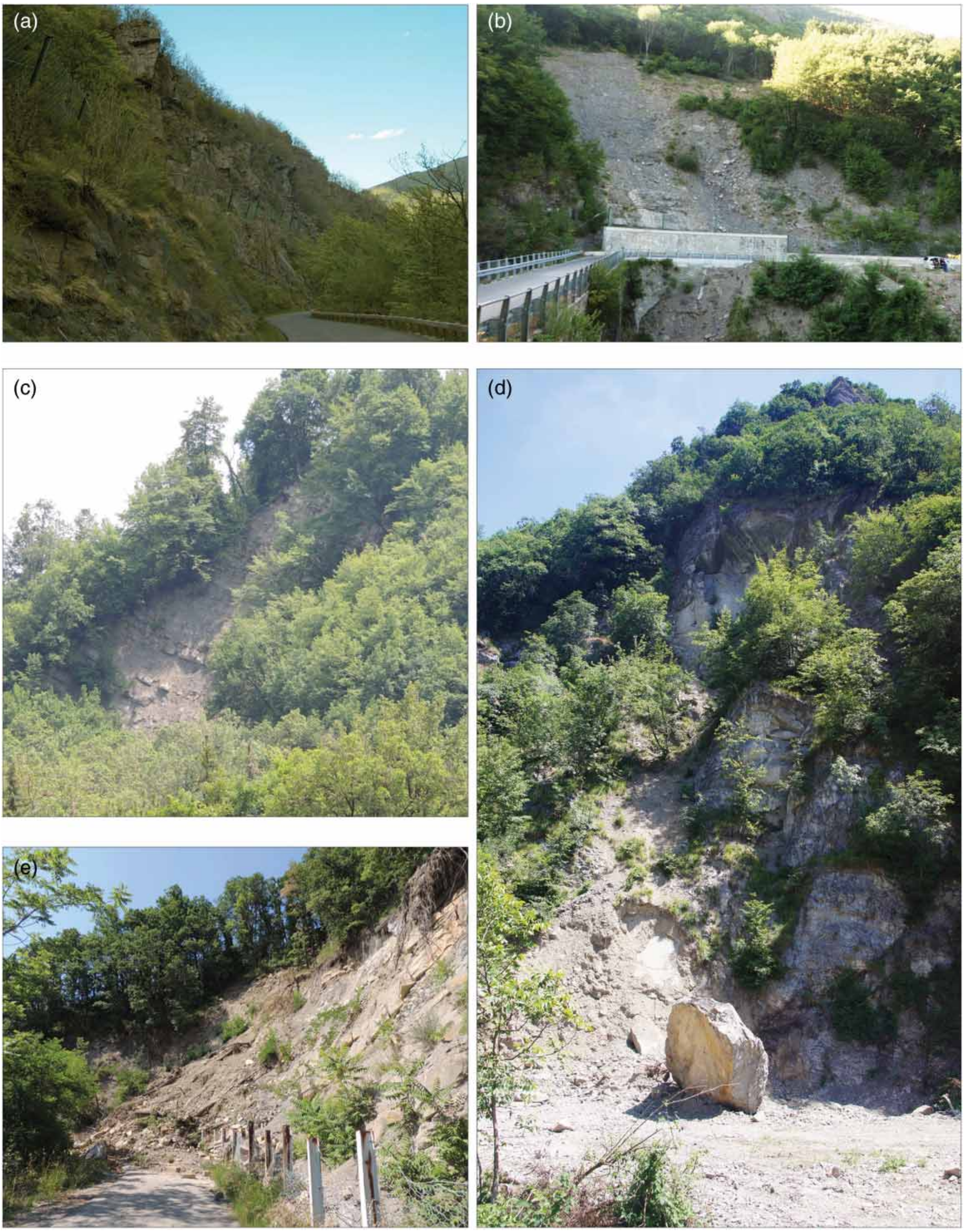

Figure 2. Examples of slopes characterized by rock fall in the Mount Cimone and surrounding area. (a) Rocky slope affected by rock falls that involved a road; (b) Rocky cliff affected by a recent rockfall on a bridge; (c) Rockfall affecting a slope characterized by alternating of hard (arenites) and weak (marls) layers; (d) Rock fall characterized by metric size blocks; and (e) Rock fall that involved and damaged a road.

In the present work, the angle values was selected in agreement with Heinimann et al. (1998) and Piacentini and Soldati (2008), as well as based on results obtained in the study area (Piacentini, 2006). The value of vertical angles considered block dimensions and slope conditions (i.e.

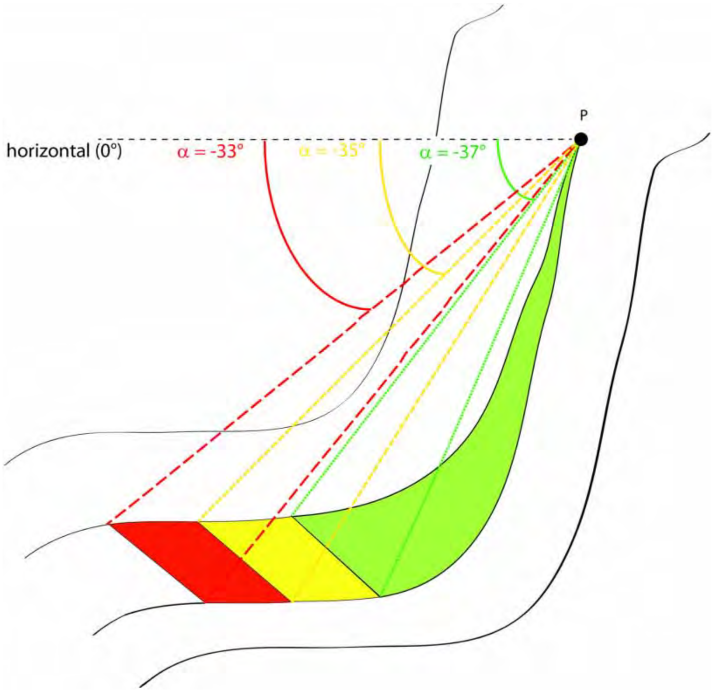

Figure 3. Outline of rock-fall runout area detection applying a three-dimensional morphological method (*TDM*). α: vertical angle defining different trajectories; β: horizontal angle defining lateral dispersion. See text for details.

vegetation and morphology) (Table 1). In particular, blocks with a diameter less than 0.5 m can stop within all three zones. In the first one, that is the closest to the detachment wall and defined by an equivalent friction angle of -37°, blocks can be stopped by trees, by very irregular topography and by scree. The second, intermediate zone, defined by an equivalent friction angle of -35°, can be reached by blocks when the conditions of vegetation, topography and land use are less

Table 1. Vertical angles adopted for the rockfall runout modelling (after Piacentini & Soldati, 2008). See text for details.

		Slope condition		
Block dimension (diameter m)	<0,5	*Vegetation*: meadow *Morphology*: regular	*Vegetation*: bush *Morphology*: slightly irregular	*Vegetation*: trees *Morphology*: very irregular
	0,5–2	*Vegetation*: bush *Morphology*: slightly irregular	*Vegetation*: trees *Morphology*: very irregular	
	>2	*Vegetation*: trees *Morphology*: very irregular		
		-33°	-35°	-37°
		Vertical angle		

favourable. Finally, in the third zone, the farthest and most conservative one, defined by angles of $-33°$, small blocks can propagate only under very unfavourable friction conditions. Blocks with diameters between 0.5 m and 2 m can reach $-35°$ and $-33°$ zones. Blocks stop in the closest zone bounded by an angle of $-35°$ when high vegetation and irregular topography occur at the foot of the rock walls. The zone bounded by an angle of $-33°$ is reached by blocks when the conditions of land use, vegetation and topography prevents stopping in the $-35°$ zone. For blocks with diameter over 2 m, only one possible stop zone can be identified, defined by an equivalent friction angle of $-33°$ (Piacentini & Soldati, 2008).

The horizontal angles (β), defining the block lateral dispersion, were assumed to be $\pm 15°$ in relation to the aspect of the slope.

Unlike the general application of *TDM*, in this work the rockfall trajectories were simulated taking into account the presence of natural boundaries close to the detaching slope, as generally represented by narrow valleys, which can reduce -or even restrict-block propagation (Figure 4). We decided to include natural boundaries (i.e. narrow valleys) in the production of rockfall runout areas in order to obtain more consistent and physically constrained scenarios. In particular, the simulation accomplished takes into account the streambed that functioned as a natural boundary for block propagation at the bottom of narrow valleys (Figure 4); this reduced the over-estimation of block propagation that in general represents a critical weakness of *TDM*.

Trajectories were simulated using a 20 m-gridded DTM and validated by field checks.

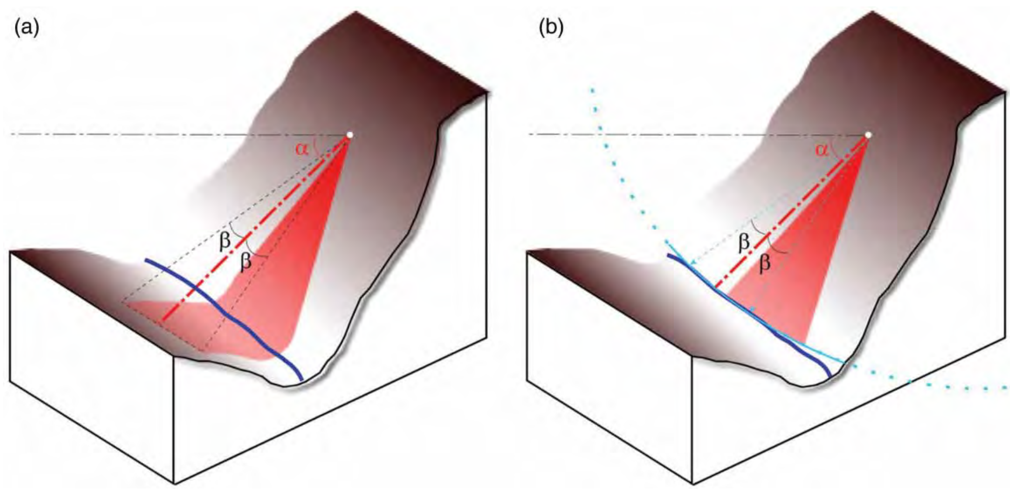

Figure 4. Outline of the adjustment applied to the *TDM* for detecting rockfall runout within the Mount Cimone area. The adjustments take into account the presence of natural boundaries. (a) runout areas resulting in a narrow virtual valley without the adjustment; and (b) runout areas resulting in the same valley after the adjustment. See text for details.

4. Rockfall runout map of the mount Cimone area

The Mount Cimone area presents a generally smooth morphology and gentle relief, showing low-to-medium energy. The sectors of the area that show the maximum relief energy, as well as the maximum relief difference between hillcrests and valley floors, coincide with outcrops of the hardest rocky types which can produce rock falls. These outcrops also have high slope angles and are generally characterized by massive arenites and calcarenites or by an alternating hard (i.e. arenites and calcarenites from medium-to-thick layered) and weak layers (marls and clays) showing the highest hard/weak ratios (i.e. $h/w > 1/3$) (*cfr.* Insets C and D in the Main Map). Field surveys demonstrated that attitude of strata and their orientation with respect to the slope often influence rockfalls. In addition, exposed fault planes and intense rock-mass fracturing due to the presence of shear zones generally predispose rock-mass mobilization. In addition, rock falls are favoured in areas with physical weathering due to seasonal temperature variations, which is more intense at the highest elevations. Physical weathering acts at rock-mass surfaces producing rock disintegration, exfoliation and augments rock crumbling due the presence of joints and fractures. Taking into account rockfall predisposing factors, the map of detachment points was created (Inset F in the Main Map). The map shows the points where rock blocks of different diameters can mobilize. A detachment point was considered the pixel centroid that satisfies these characteristics:

(1) Slope angles $>33°$, selected on the basis of previous analyses and in accordance with the values proposed in previous works (Heinimann et al., 1998; Piacentini & Soldati, 2008);
(2) Bedrock belonging to one of these rock types, considering the geo-mechanical characteristics of rocks already affected by falling: (i) alternating strata with a relationship between hard and weak layers (i.e. h/w ratio) >3, or (ii) alternating strata with a relationship between hard and weak layers ranging from 1/3 up to 3;
(3) Land use belonging to one of these three classes: (i) bush, or (ii) trees, or (iii) rock, selected because their potential to contain bedrock outcrops, and so detachment points (Figure 2c and 2d).

The map does not directly incoporate inherent rock-mass fracturing (i.e. conditions of fractures and joints) because, at the scale of the analyses, here it is not possible to obtain the necessary detail. Moreover, this map represents a preliminary study that can be augmented with *ad-hoc* field surveys aimed at obtaining information on rock fractures and joints that will be fundamental to a second phase, where deterministic slope stability analyses can be performed.

This map presents three different propagation scenarios derived from the simulation of three different vertical angles. Table 1 presents the relationships among the vertical angles adopted for the TDM simulations, blocks dimensions and slope conditions. The latter are defined by vegetation and terrain morphology. The scheme illustrating these relationships is also included as an inset on the Main Map.

In the Mount Cimone area the diameters of mobilized blocks are generally sub-metric and rarely exceed the metric dimension as the regional archive of past rock falls demonstrates, also confirmed by field surveys conducted for this work (*cfr.* Figure 2 for some examples). Nevertheless, the map allows evaluation of situations in which potential detachment blocks can exceed 2 m in diameter (i.e. vertical angle $\alpha = -33°$) in order to generate a more precautionary scenario.

The Main Map reports the runout zones for the entire Mount Cimone area and seven insets as follows: (1) the physiography of the area (elevation map); (2) the areal distribution of slope angles (slope map); (3) a simplified scheme of the different lithotypes outcropping in the area grouped by their geo-mechanical characteristics; (4) a map of lithotypes generally affected by rock fall; (5) land use; (6) the map of rockfall detachment points; (7) the map of vulnerable elements affected by rock falls.

5. Conclusions

The analyses performed to recognize the rockfall detachment points and the TDM used to obtain the map of rockfall runout proved to be a suitable and cost-effective method for investigating rock fall at a regional scale. The map produced is a reliable tool for preliminary identification of areas affected by rockfall. It requires few data inputs (i.e. slope angle, land-use characteristics, geo-mechanical characteristics of bedrock), which can be easily collected from DTMs and existing geological and land-use maps. Starting from the input data, the first step consists in recognizing rockfall detachment points and, successively, by applying the TDM method the rockfall runout scenarios can be developed. The areas identified by *TDM* can be successively analysed with respect to vulnerable elements (e.g. infrastructre, urban areas). In this regard, the map also highlights possible interactions among the potential rockfall runout zones and vulnerable elements of the territory. This allows identification of those zones where the highest risk of rock fall occurs and where additional detailed analyses – and eventually mitigation actions – must be planned. From this perspective, the proposed map represents a reliable and cost-effective tool useful for planning strategies aimed at reducing rockfall risk. To this end, the map presented should be analysed and interpreted considering potential future mitigation systems.

Software

Initial data input was performed using *Feature Manipulating Engine* rel. 2008 (FME), whilst the computation of trajectories, as well as the final map, was performed using Esri ArcGIS 10.

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Rockfall runout map of the Mount Cimone area: application of 3D-morphological method in the Emilia-Romagna Region (Italy)

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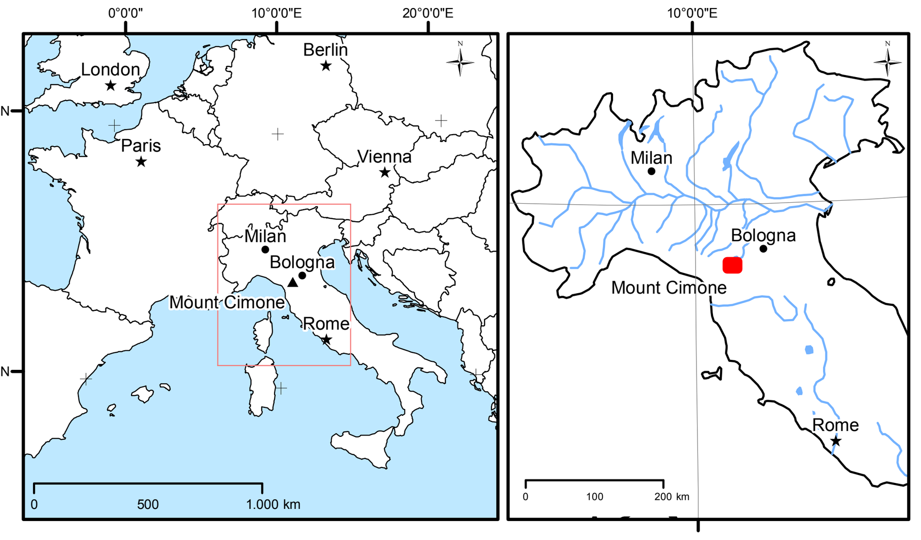

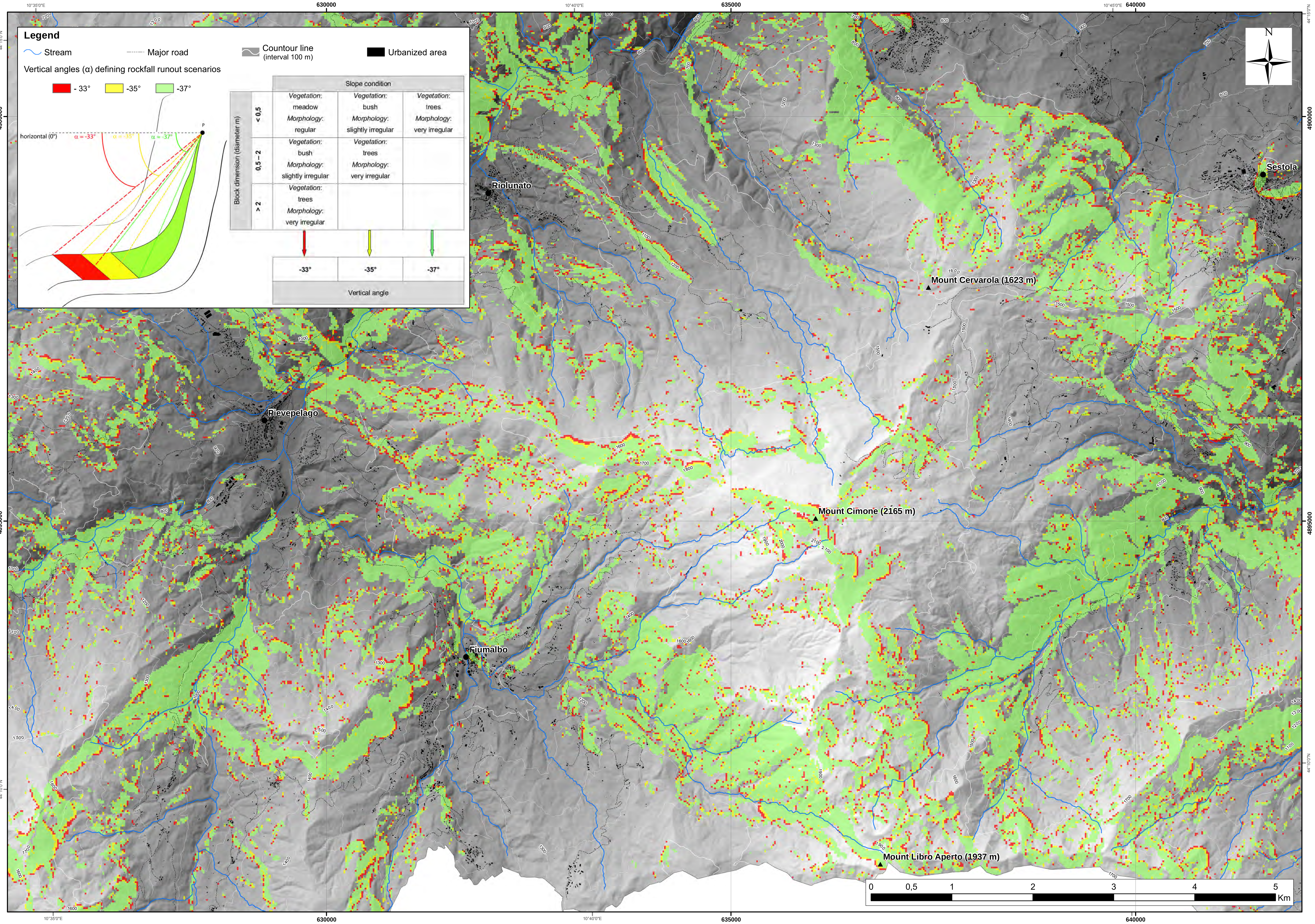

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