Mechanism of the Montescaglioso Landslide (Southern Italy) Inferred by Geological Survey and Remote Sensing

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Abstract

Montescaglioso village is located in southern Italy (Matera, Basilicata region), on a hill top, at about 350 m a.s.l., along the left bank of the Bradano River. Several landslides involved this area, some of them classified as relict; the latest one occurred on December 3rd, 2013 on the south-western slope of Montescaglioso hill. A review of the geological setting of this slope is presented, aimed at defining the failure mechanism of the slope. Sub-pixel cross-correlation analysis based on SAR images was performed to infer the co-failure displacement pattern and A-DInSAR was carried out to detect the spatial-temporal deformational pattern before and after the failure. The field surveys confirmed the main role played by geological setting in structurally constraining the landslide mechanism and its complex kinematic, featured by three main distinct “kinematic blocks” with different direction of movement. The 3rd December landslide has been recognized as a partial reactivation along a slope affected by a long-lasting sequence of landslides, the last one triggered by a transient action.

Keywords

Landslide • Montescaglioso • COSMO-SkyMed • Digital image correlation • A-DInSAR

Introduction

The village of Montescaglioso (Basilicata region, Southern Italy) is located on the top of a hill at about 350 m a.s.l., along the left bank of the Bradano River. In this paper the landslide occurred on the 3rd December 2013 involving the south western slope is dealt with. The landslide caused severe damages to private houses, commercial buildings and main infrastructures. Several studies were focused so far on this event (Amanti et al. 2014; Manconi et al. 2014; Raspini et al. 2015; Pellicani et al. 2016; Amanti et al. 2016), which provided a comprehensive description of the phenomenon. According to Amanti et al. (2014), Pellicani et al. (2016) and Amanti et al. (2016), the heavy and intense rainfall, affected the area since 30th November until 2nd December, can be regarded as the trigger of the landslide.

The geological setting of the area has been reconstructed by field surveys and tens of reliable borehole

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log-stratigraphies, investigating a depth ranging from 25 m down to 66 m b.g.l. (Amanti et al. 2016). Based on these data, two litotechnical units inside the landslide slope have been distinguished: (i) a more shallow one (with a thickness increasing from 10 up to 40 m moving toward the landslide toe), mainly consisting of sands and conglomerates and (ii) a deeper one, constituted by stiff gray silty clays, ascribable to the Argille Subappennine Formation (Tropeano et al. 2002).

The landslide mechanism has been inferred by using imaging techniques such as speckle tracking from SAR images and DTM analyses, performed by Raspini et al. (2015) and Amanti et al. (2014) respectively. The displacement values exceeded 10 m in wide portions of the landslide mass; the maximum displacements (i.e. up to 20 m) were recorded at the toe of the landslide.

Satellite interferometry data are available (Manconi et al. 2014; Raspini et al. 2015), revealing a general pre-event displacement rate in the order of few mm/year, with peaks between 8 and 12 mm/year.

Methods

In this study, we present a revision of the geological setting of the Montescaglioso hill, inferred by specifically performed geological surveys, to better constrain the failure mechanism of the slope.

Furthermore, analyses based on Synthetic Aperture Radar images acquired by the COSMO-SkyMed Constellation, referred to the time period between 2011 and 2015, were carried out.

The analyses of satellite SAR images aimed at characterizing the deformational pattern of the area in the pre-failure, co-failure and post-failure phases of the 3rd December landslide. With this aim, two different techniques were used: (1) the A-DInSAR (Advanced Differential Synthetic Amplitude Radar Interferometry) and (2) the Digital Image Correlation (DIC) technique.

The A-DInSAR processing allowed us to monitor the deformational behaviour of the slope before and after the failure. The analyses were performed using the PS (Persistent Scatterers) technique (Ferretti et al. 2001) implemented in the SARPROZ software (SAR PROcessing tool by periZ, http://www.sarproz.com). This methodology enables to obtain the time series of displacement along the LOS (Line Of Sight) for those points considered as PS, characterized by high amplitude and phase stability.

Digital Image Correlation was used with the aim of monitoring the co-failure displacement. It represents an optical-numerical measuring technique which offers unique opportunities for exploring full-field displacement and deformation at the surface of objects. This is possible through the comparison and the correlation of digital images of the specimen surface, captured before and after deformation (Pan et al. 2008).

Geological and Geomorphological Setting

The Montescaglioso hill is part of the Bradanic Trough geological context, which represents the Plio-Pleistocene foredeep of southern Appennines. It is bounded by the Apennine chain to the west and by the Apulian foreland to the east (Boenzi et al. 1971; Balduzzi et al. 1982). Such a geological context is responsible for a complex geological setting of the area, as it was involved in a multistep tectonic and sedimentary evolution. Based on field surveys, a revised geological map has been obtained (Fig. 1) by distinguishing the following six geological units: (i) clays and silty clays, belonging to the Argille Subappennine Formation (Calabrian); (ii) sands, belonging to the Monte Marano Formation (Calabrian); (iii) calcarenites, belonging to the Monte Castiglione Formation (Calabrian); (iv) conglomerates, which could be associated to the Irsina Conglomerate Formation (Calabrian); (v) sands and conglomerates of marine terraces (Pleistocene); (vi) alluvial deposits related to the Bradano river.

The Argille Subappennine Formation consists of marly clays, clays and silty clays. In the study area, clays dip towards SW with an inclination of 20°. This is the main geological formation of the Bradanic Trough zone, characterised by up to 4 km thickness and a strong lateral continuity. The stratigraphic contact between the Argille Subappennine Formation and the overlapped deposits is clearly visible in the Montescaglioso hill.

The layered sands (Monte Marano Formation) outcrop in a small area and are in a stratigraphic contact with the Argille Subappennine; they pass laterally and upward to the calcarenites ascribed to the Monte Castiglione Formation. The attitude of strata is concordant with the upper deposits: dip toward SW with an inclination of 15–20°. The formation thickness observed in the study area is few meters.

The calcarenites (Monte Castiglione Formation) consist in coarse grained deposits and biocalcrudites with a great amount of fossils such as: pecten, ostrea, litotamni, lamellibranches and gastropods. They are characterised by a very clear layering of strata, about 15 cm thick and SW dipping with an inclination of 15–20°. The thickness of the calcarenites in the study area is about 30 m.

The conglomerates (Irsina Formation) are characterized by heterometric and polygenic well rounded gravels consisting of limestone, chert, sandstone and igneous elements of Apennine origin. They are generally characterised by a sandy calcareous matrix and are interlayered with sandy yellow-brown levels. In the study area, the conglomerate deposits outcrop near the cemetery (location in Fig. 2),

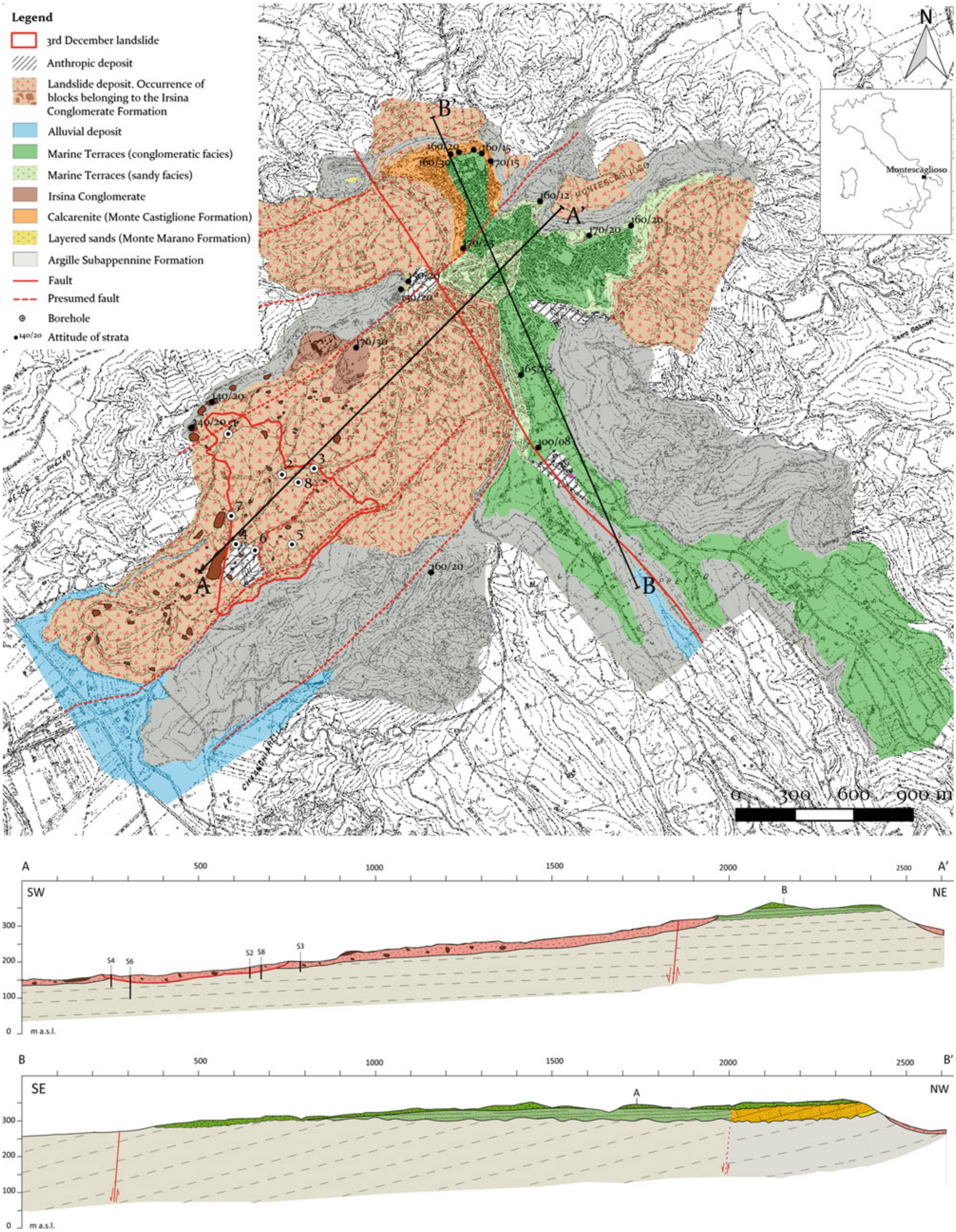


Fig. 1 Geological map of the Montescaglioso hill and related geological cross sections A-A', B-B'

where they are arranged as a south-east dipping slab. Nevertheless, many blocks of conglomerate can be surveyed all along the south-western slope of Montescaglioso hill. These blocks have an extremely variable volume, up to 10–100 m^3.

Marine terrace deposits outcrop in the south-eastern sector of the study area, forming a characteristic planar morphology at the hill top. They are composed of sand passing toward the top to bedded, poorly cemented conglomerates. They represent the last marine depositional event before the south-eastward migration of the shoreline, due to the strong regional uplift that involved the Bradano Trough. This is documented by up to 18 paleo-shorelines recognised so far (Caputo et al. 2010) from Montescaglioso hill to the Gulf of Taranto. The marine terrace deposits outcropping in the Montescaglioso area can be considered the oldest among the 18 terraces documented in this area (Caputo et al. 2010).

The alluvial deposits, mapped in the south-western sector of the area, are related to the Bradano river and consist of heterogeneous deposits. They are connected to the partial infilling of the previously formed deep valley, during the well-known Late Pleistocene last glacial maximum. Presumably, the thickness of the recent alluvial deposits in the area is of some tens of meters (Boenzi et al. 1971)

According to clear geomorphological evidences, as well as to the IFFI project (Inventory of Landslide Phenomena in Italy) and previous studies (Manconi et al. 2014; Raspini et al. 2015), the Montescaglioso area has been affected by several landslides before the 3rd December event. As shown in the geological map (Fig. 1), the Montescaglioso hill is characterised by many landforms ascribable to old landslides. These landforms consist of scarps and counter-slope, tilted terraces or blocks chaotically dislodged respect to the present morphology of the hill. In particular, along the south-western slope, the strong effects of landslide processes developing over time can be recognized. Indeed, this slope is characterized by colluvial deposits that mostly consist of sands and debris with rounded gravel derived from the Irsina Conglomerate. Furthermore, colluvial deposits incorporate large-sized blocks of conglomerate, highlighting the ancient landslide activity.

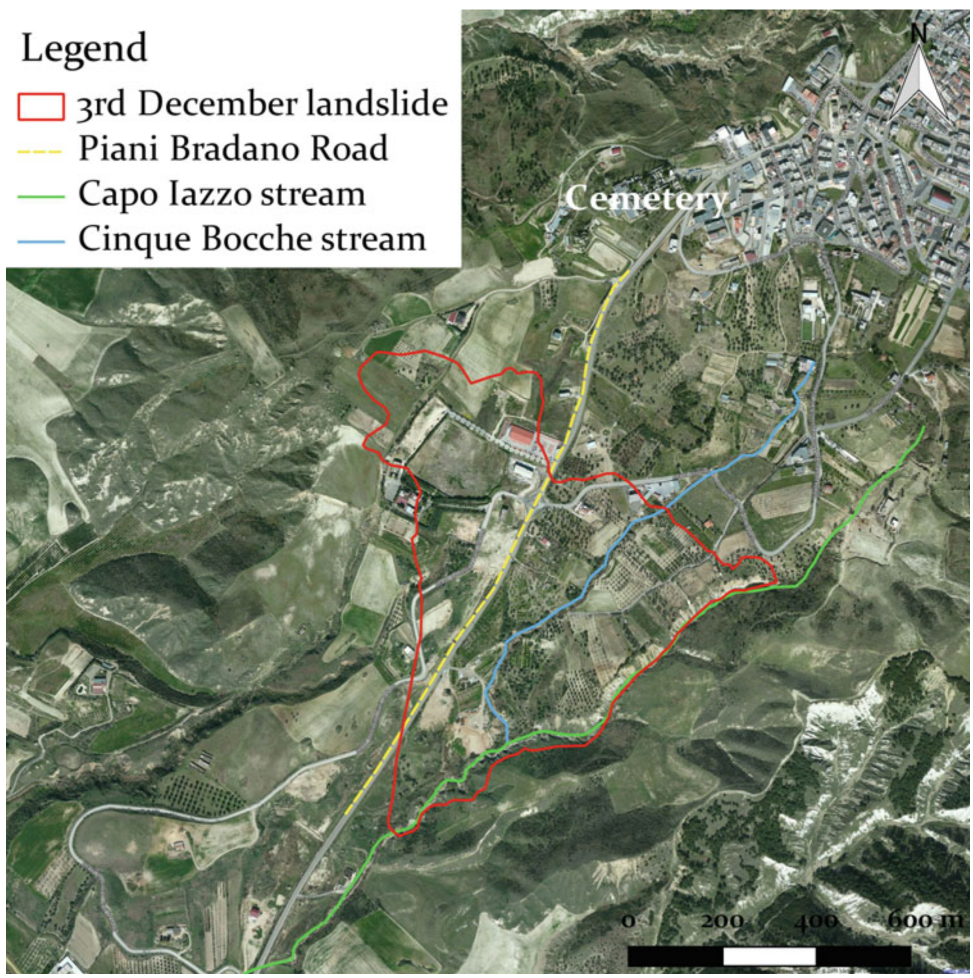


Fig. 2 Area involved in the 3rd December Montescaglioso landslide

The 3rd December Montescaglioso Landslide

On December 3rd, 2013, a landslide occurred on the south-western slope of the Montescaglioso hill, over an area about 500,000 m^2 wide. A maximum depth of 40 m for the failure surface is presumed, with an estimated volume of about 8 millions of cubic meters (Pellicani et al. 2016) (Fig. 2).

The landslide shows a triangular-shaped area, which is delimited by the main crown, at an elevation of about 200 m a.s.l., the foot, located in Capo Iazzo stream about at 100 m a.s.l., with a total length of 1200 m and a width of 800 m.

The intense rainfall, occurred between the 5th and 8th October 2013 and the 30th November and 2nd December 2013, have been regarded as the trigger for the landslide event (Manconi et al. 2014; Pellicani et al. 2016; Amanti et al. 2016). More in particular, the rain gauges located at Ginosa (8 km east of Montescaglioso), recorded 246 mm in 68 h for the event of October and 151.60 mm in 56 h, between 02.00 PM of 30th November 2013 and 10.00 PM of 2nd December. Considering the intensity of the last event (cumulated rainfall of 151.60 mm), a return period of about 20–50 years can be attributed according to Pellicani et al. (2016). Moreover, according to the same Authors, if the annual maximum daily precipitation is accounted for, the measured daily rainfall (125 mm) has a return period ranges from 20 to 100 years, depending on the stations considered.

The 3rd December landslide had a complex manifestation. The evidences of ground failures were collected at 01.00 PM of the same day, in proximity of the main road (namely Piani Bradano road), for a length of about 500 m. In the following hours, several private houses have been damaged, as proved by displacement up to 6 m of their foundations. However, some damages were documented by local witnesses in private areas the day before the event localized at the toe of the landslide (Pellicani et al. 2016). The last phase of the movement (occurred in the night between the 3rd and 4th December) was typified by a retrogressive style, causing a northward replacement of the landslide area.

Results

A-DInSAR Analysis

The complete COSMO-SkyMed dataset is composed by 60 SAR images, acquired in the ascending geometry during the time interval between May 2011 and May 2015 (Fig. 3). The satellite has a right-looking configuration, the LOS angle with respect to the North is 78 degrees and the incidence angle is about 30°. The COSMO-SkyMed descending dataset was discharged because it includes few images, both for the pre-failure and the post-failure period, with a discontinuous temporal distribution.

Two different A-DInSAR analyses were performed: (1) the pre-failure and (2) the post-failure analysis. Pre-failure analysis was carried out by processing the images acquired before the landslide event.

The pre-failure dataset consists in 37 images, from May 2011 to the December 3rd, 2013 (Fig. 3a). On the other hand, post-failure analysis was performed taking the SAR images acquired after the landslide event, namely 23 images (Fig. 3b).

Regarding the pre-failure analysis, in accordance with the results obtained by Raspini et al. (2015), the occurrence of displacements were observed also outside the area involved in the 3rd December landslide. The maximum displacements were recorded where the hypermarket and the traffic roundabout were located (yellow circle in Fig. 3a). In these locations the displacement average velocities range from 5 to 10 mm/year. As already stated also by Raspini et al. (2015), the time series of displacement inside the landslide area do not show an evident and well defined acceleration phase prior to the slope failure.

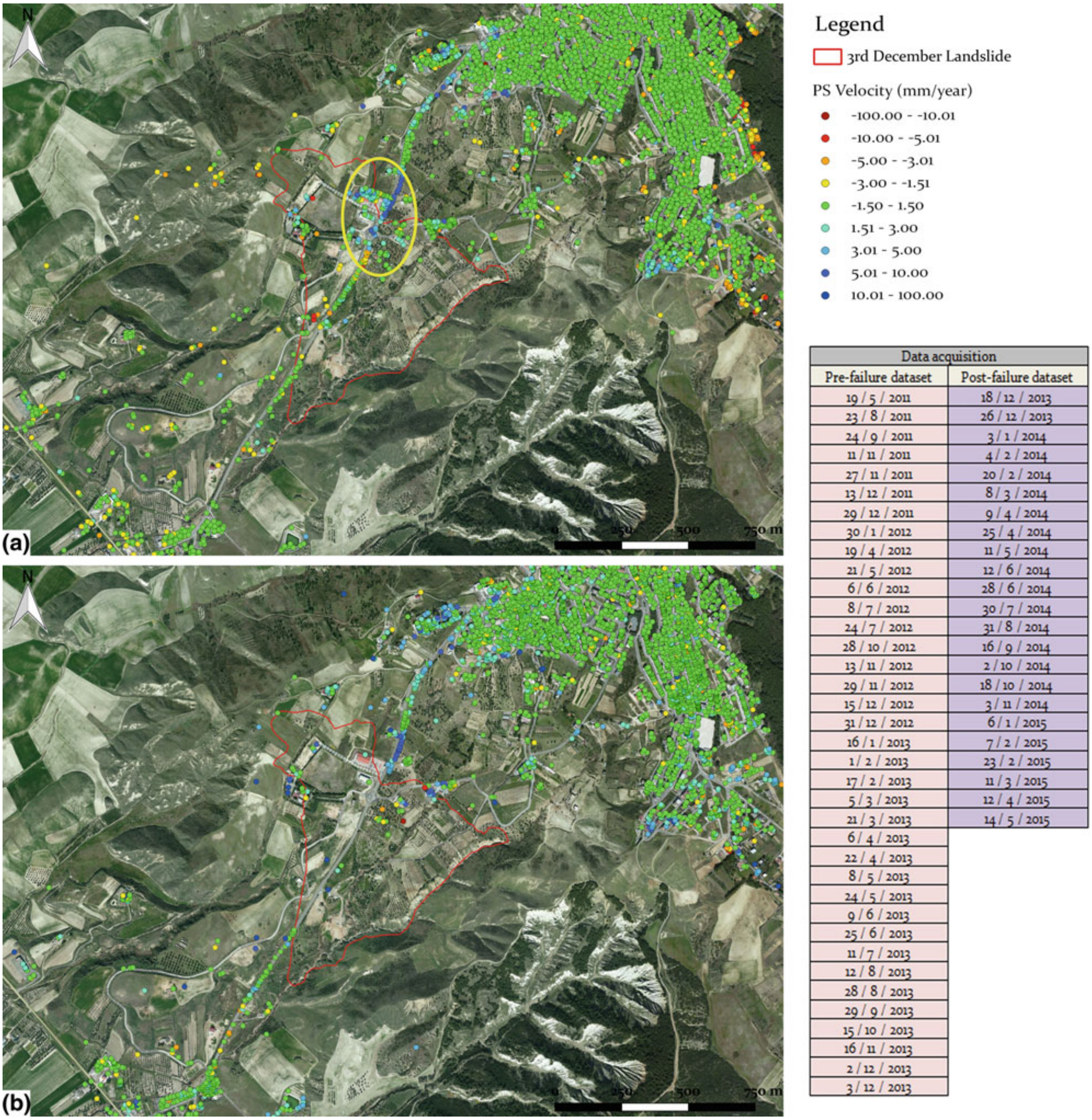
The post-failure analysis does not provide many measurement points inside the area involved in the 3rd December landslide, probably due to the remediation works that could have caused the loss of coherence in this area. However, the deformational behavior, outside the landslide body is similar to the pre-failure one, highlighting the slow and persistent deformations affecting the south-western slope of Montescaglioso hill.

DIC Analysis

To retrieve the co-failure displacement pattern, in terms of both intensity and rate, 2D sub-pixel image-correlation analysis was carried out. Such an application is based on the employment of SAR amplitude images and, more in particular, of the reflectivity maps obtained by computing the average time amplitude of the COSMO-SkyMed images acquired pre- and post-landslide occurrence in the ascending geometry (Fig. 4).

The images (with an average resolution of about 3 m/pixel) have been managed in Co-Registration of Optically Sensed Images and Correlation (COSI-Corr) (Leprince et al. 2007), an open-source plug-in working in ENVI package software. The algorithm implemented in COSI-Corr is based on a robust coarse-to-fine scheme and a sub-pixel matching method with a theoretical precision of 1/50 pixel (Leprince et al. 2007).

In this study, a frequency correlator engine has been used, with a window size of 64 × 64 pixels (192 × 192 m) and a



Data acquisition	
Pre-failure dataset	Post-failure dataset
19 / 5 / 2011	18 / 12 / 2013
23 / 8 / 2011	26 / 12 / 2013
24 / 9 / 2011	3 / 1 / 2014
11 / 11 / 2011	4 / 2 / 2014
27 / 11 / 2011	20 / 2 / 2014
13 / 12 / 2011	8 / 3 / 2014
29 / 12 / 2011	9 / 4 / 2014
30 / 1 / 2012	25 / 4 / 2014
19 / 4 / 2012	11 / 5 / 2014
21 / 5 / 2012	12 / 6 / 2014
6 / 6 / 2012	28 / 6 / 2014
8 / 7 / 2012	30 / 7 / 2014
24 / 7 / 2012	31 / 8 / 2014
28 / 10 / 2012	16 / 9 / 2014
13 / 11 / 2012	2 / 10 / 2014
29 / 11 / 2012	18 / 10 / 2014
15 / 12 / 2012	3 / 11 / 2014
31 / 12 / 2012	6 / 1 / 2015
16 / 1 / 2013	7 / 2 / 2015
1 / 2 / 2013	23 / 2 / 2015
17 / 2 / 2013	11 / 3 / 2015
5 / 3 / 2013	12 / 4 / 2015
21 / 3 / 2013	14 / 5 / 2015
6 / 4 / 2013	
22 / 4 / 2013	
8 / 5 / 2013	
24 / 5 / 2013	
9 / 6 / 2013	
25 / 6 / 2013	
11 / 7 / 2013	
12 / 8 / 2013	
28 / 8 / 2013	
29 / 9 / 2013	
15 / 10 / 2013	
16 / 11 / 2013	
2 / 12 / 2013	
3 / 12 / 2013	

Fig. 3 Persistent scatterers derived from A-DInSAR analyses. **a** Pre-failure analysis. **b** Post-failure analysis. The negative values indicate movement away from the sensor (*yellow-red color*), while positive values represent movement toward the sensor (*blue color*). The table shows the datasets used for the two analyses

sliding step of 2 pixels (6 m), and the displacement fields in East/West and North/South directions with a ground sampling distance of 6 m have been obtained.

Figure 5 shows that the resulted horizontal displacements, ranging from 2 to 22 m, were reached during the 3rd December landslide, with a prevalent S-SW direction, in agreement with Raspini et al. (2015). The here performed sub-pixel image-correlation analysis for the displacement measurements from satellite images (SAR reflectivity maps, in this case), i.e. without employing neither ground control points nor external DEM, represents a further example of the technique suitability.

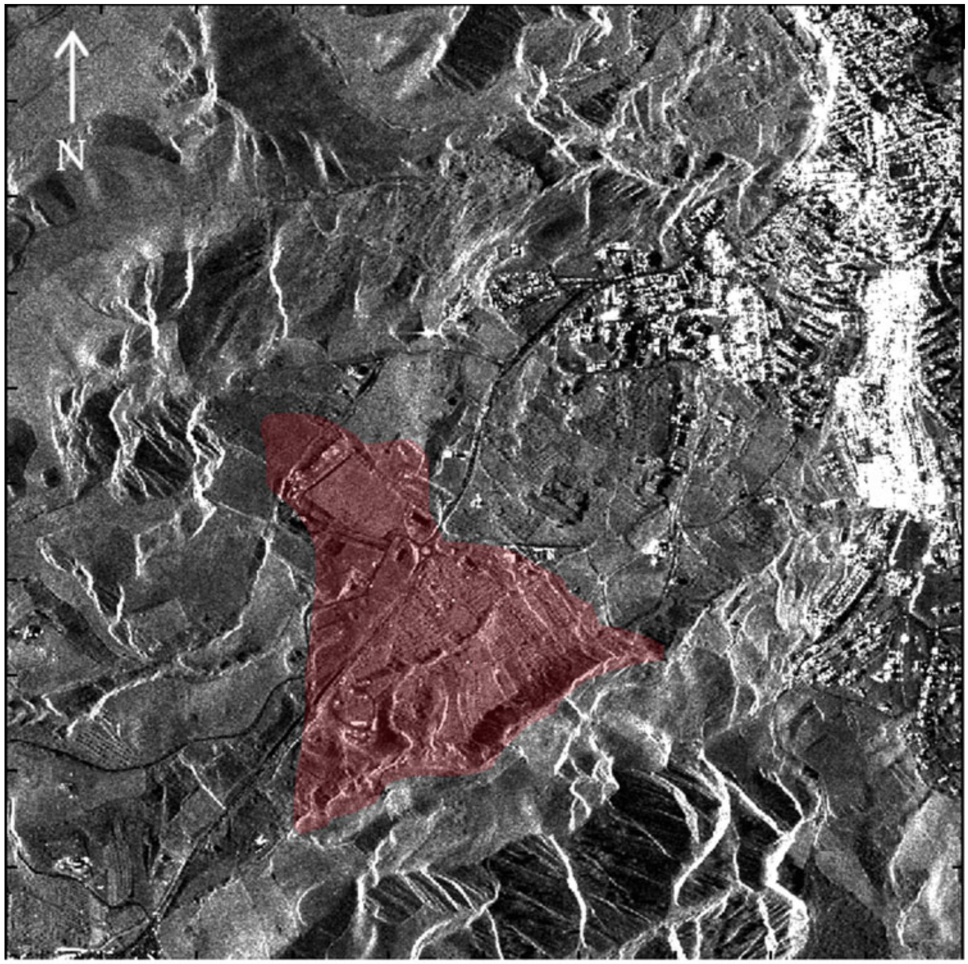


Fig. 4 SAR reflectivity map of post-landslide dataset. The landslide area is highlighted in *red*

Interpretations

The mechanism of the Montescaglioso landslide was reconstructed by using informations coming from geological survey, geomorphological observations and DIC analysis (Fig. 6). As shown in Fig. 6, the landslide is classified as a complex movement (Varnes 1978) featured by four main distinct "kinematic blocks" with different direction of movement and time succession:

- Block 1A, with a SSW main movement direction and a prevalent translational mechanism;
- Block 1B, characterized by a roto-translation mechanism toward SSW;
- Block 2, with a SW direction;
- Block 3, which represents the retrogressive evolution of the block 1 with a translational mechanism along a SSE direction.

As it regards the time stepping of the 3rd December landslide, the initial failure (step 1), which involved the main road and constitutes the main landslide body, is featured by block 1A and block 1B that moved more or less simultaneously. A significant shallow groundwater circulation was observed within the moving blocks, presumably overfeed by intense rainfall and enhanced by the local hydrographic network strongly modified by human interventions. The slight difference in the direction of movement of blocks 1A and 1B has been related to structural constraint due to the geological setting of a large block of conglomerate (Irsina Formation), that bounds the right flank of the block 1A and to the presence of two creeks: Cinque Bocche and Capo Iazzo (Fig. 2). The following vertical adjustment of the landslide mass occurred after the main failure (step 2), involved the Block 2 and originated a horst-and-graben type landform (Fig. 6). Finally, the movement of Block 3 (step 3) represents the retrogressive evolution of the landslide, occurred during the night 3rd–4th December 2013.

The field survey confirms the main role played by geological setting in constraining the landslide mechanism and its complex kinematic. The landslide appears to be structurally constrained by the dip direction of lithologies

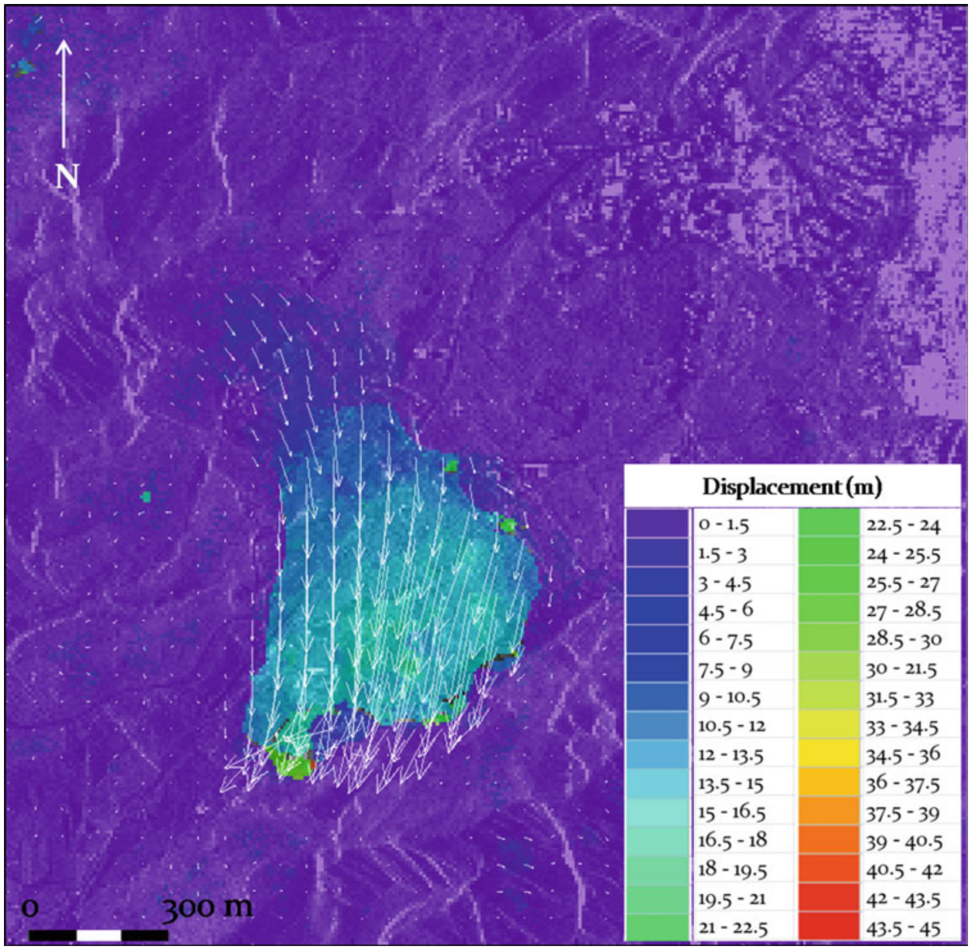


Fig. 5 2D displacement map. The *white arrows* represent the direction of the vector field

outcropping in the area and by the conglomerate blocks arrangement, particularly the one outcropping along the right flank of the landslide.

Geological evidence indicate that the landslide mass is mainly constituted of debris originated by previous landslides, which involved the Argille Subappenine and the Irsina Formations. The widespread presence of large-sized conglomerate blocks, chaotically distributed in the south-western portion of the landslide mass, demonstrates that the original bank of this formation was largely dismantled and dislodged by a sequence of landslides. Consequently, the 2013 landslide movement can be regarded as a partial reactivation of a wider, already existing landslide mass, that was triggered by the intense rainfalls causing a significant water pressure increase (Amanti et al. 2016). The lack of evident pre-failure acceleration supports this hypothesis.

The 3rd December landslide appears as the last episode of a longer landslides series which affected this slope. We finally try to depict this long-lasting history in three main stages of evolution (Fig. 7) conceptually following geomorphological studies performed in the Bradanic Trough (Boenzi et al. 2008; D'Ecclesis and Lorenzo 2006; referred to the landslide of Madonna della Nuova, located in Fig. 1 immediately north of the slope involved in the 3rd December landslide): (i) the first one related to the paleo-Bradano river and characterized by the occurrence of a huge earth slide with SW oriented movement, probably related to the strong deepening of the Bradano valley during the last glacial maximum. The successive deposition of the recent alluvial deposits of the Bradano river partially covered the foot area of this large earth slide closing this phase of evolution; (ii) the second one, with a prevalent SW direction of movement, inducing the retrogression of the more ancient landslide towards the top of the hill and responsible of the half-moon shapes of the border of the hill, presumably during the Holocene; (iii) the third one, which includes the 3rd December 2013 landslide, consists in the reactivation of the previously formed landslide masses with a diminishing spatial style of activity. These last events are kinematically related to the Bradano river tributaries network, i.e. almost NW-SE oriented continuously evolving.

Based on such a multi-stage evolution, the Montescaglioso hill slopes can be presently considered as very

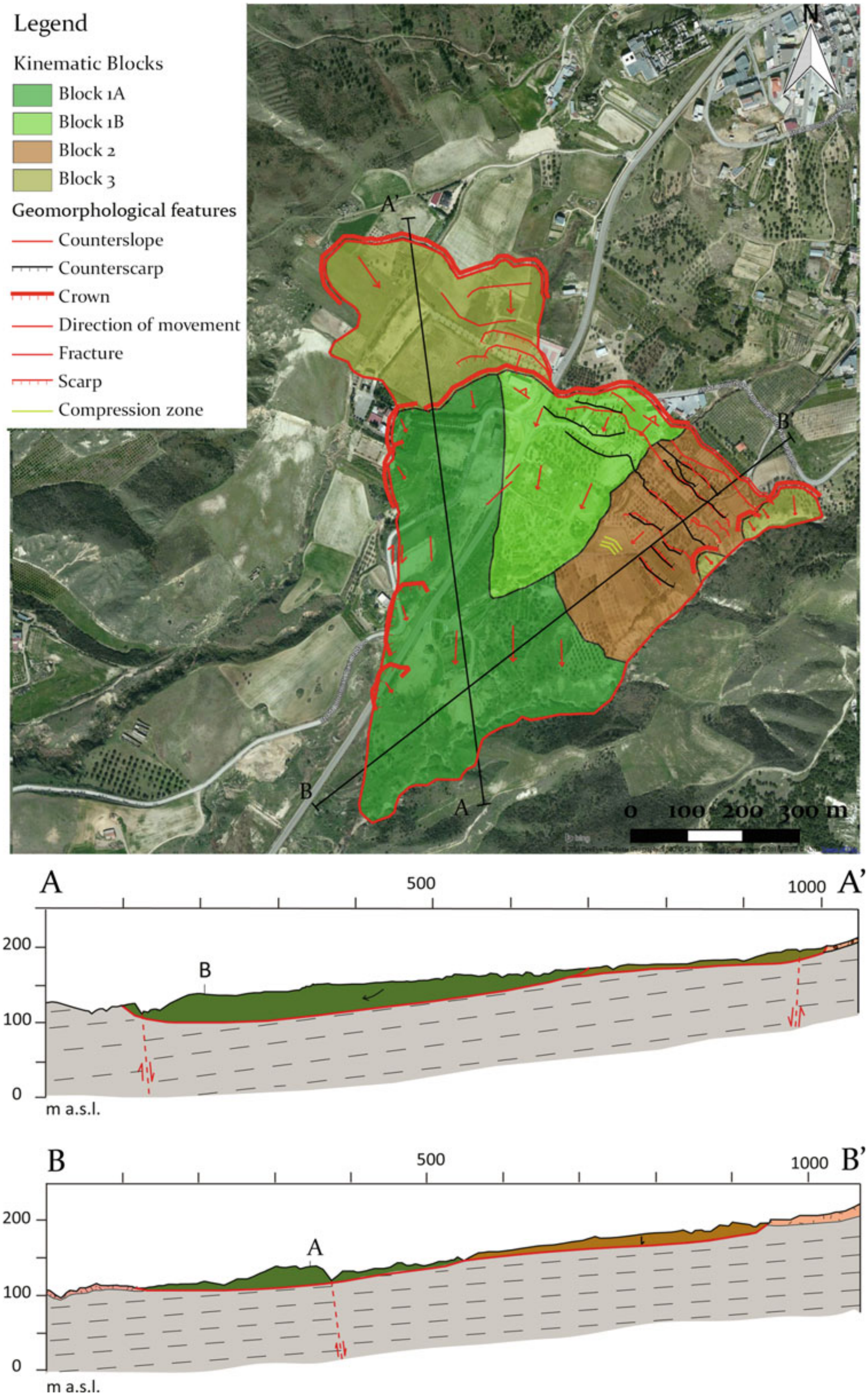


Fig. 6 Kinematic map of the Montescaglioso landslide and related cross-sections A-A' B-B'

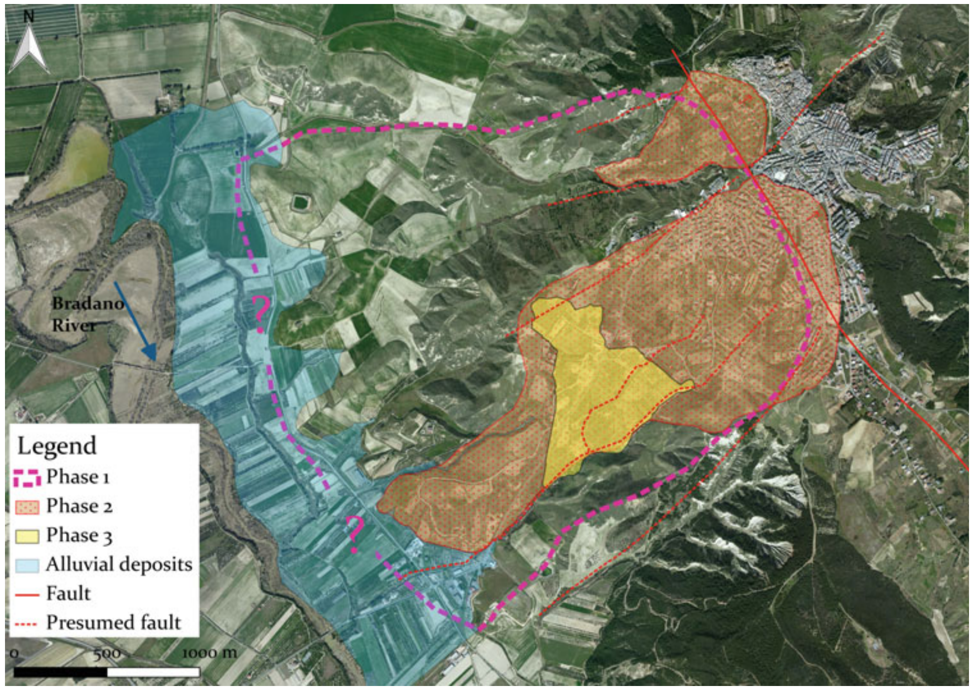


Fig. 7 Schematic evolution of the western slope of Montescaglioso hill

prone to landslide processes, reactivating portions of more ancient and complex landslide masses.

In our opinion, human interventions along these slopes should take into account and/or guarantee the water drainage of the pre-existing landslide masses.

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