DOI: 10.4408/IJEGE.2021-01.S-02

PRELIMINARY DATA ON SLOW-MOVING LANDSLIDES-AFFECTED URBAN AREAS THROUGH GEOLOGICAL, GEOMORPHOLOGICAL AND INSAR ANALYSIS

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EXTENDED ABSTRACT

In Italia, negli ultimi decenni, i danni causati da frane e inondazioni sono in crescita esponenziale soprattutto a causa dell'espansione urbanistica avvenuta anche in aree a rischio idrogeologico più o meno elevato. Diretta conseguenza è stato, quindi, il forte incremento di danni a edifici, infrastrutture e blocco di attività commerciali procurando ingenti perdite economiche e talvolta elevati rischi per l'incolumità pubblica. Con lo scopo di prevenire i rischi idrogeologici e/o valutarne le condizioni di rischio, diviene sempre più alto l'interesse allo studio di nuovi sistemi di controllo e previsione dei fenomeni franosi da parte della comunità scientifica mondiale. A tal fine, nell'analisi dei fenomeni franosi è sempre più diffuso, sia nel mondo scientifico che professionale, l'applicazione di tecniche di interferometria satellitare che affiancano le usuali metodologie diagnostiche di campo.

Il presente lavoro si prefigge di studiare i diffusi fenomeni franosi presenti in un'area localizzata sul versante orientale della Catena Costiera Calabrese e confinante con il Bacino del Crati (Calabria centrale). L'area di studio comprende i centri abitati di Cavallerizzo, San Martino di Finita e Rota Greca che ricadono nella provincia di Cosenza e sono tutti coinvolti da eventi franosi responsabili di diffusi danni di varia entità. La presente ricerca si basa, quindi, su un attento rilevamento geologico e geomorfologico, su diversi sondaggi geognostici eseguiti nelle aree urbane, su una indagine geoelettrica che ha raggiunto la profondità di 120 m nell'abitato di San Martino di Finita, su ripetute letture di movimenti profondi ottenuti dall'impiego di un inclinometro nell'abitato di Rota Greca e, infine, su dati di interferometria satellitare derivanti da un'analisi temporale di immagini comprese tra il 1992 e il 2010.

Da un punto di vista geologico, l'area di studio è attraversata dalla faglia San Fili-San Marco Argentano che, con cinematismo di tipo normale, pone a contatto il complesso cristallino metamorfico, costituente la struttura della Catena Costiera, con i depositi sedimentari di riempimento del Bacino del Crati. L'ammasso roccioso lungo la zona di taglio si presenta fortemente cataclasizzato favorendo l'accumulo di acque sotterranee. Infatti, elevati risultano gli accumuli idrici lungo la zona di contatto tra le due litologie a diversa permeabilità, come testimoniato dalla presenza di innumerevoli sorgenti, anche con portate consistenti, dislocate lungo l'allineamento tettonico. Un deposito colluviale, con spessori che variano da un minimo di 10 m fino a 64 m e costituito da clasti di origine cristallino metamorfica immersi in una matrice sabbiosa, ricopre parzialmente il substrato metamorfico della Catena Costiera e estesamente i depositi sedimentari del Bacino del Crati. Pertanto, elevate acclività dei versanti, forte fratturazione dei complessi rocciosi, scarsa qualità meccanica delle rocce e elevati accumuli idrici, sono tutti fattori che rendono l'area di studio particolarmente predisposta a fenomeni franosi.

L'indagine geomorfologica ha consentito il riconoscimento di 225 fenomeni d'instabilità nell'area di studio con una densità di frana pari a 10.2 frane/km^2. Di questi fenomeni gravitativi, 144 sono stati classificati attivi e il rimanente in stato quiescente. Riguardo i cinematismi di frana, 183 sono di tipo scivolamento, 36 di tipo complesso e solo 6 di tipo colata. I fenomeni complessi risultano solitamente caratterizzati da cinematismi di tipo scivolamento nella parte alta e colata nella restante porzione valliva. La profondità delle superfici di scivolamento varia da pochi metri (solitamente <2 m) a oltre 20 m. La maggior parte dei dissesti superficiali censiti, si innescano nei depositi colluviali con superfici di scivolamento che si manifestano verosimilmente all'interno del deposito o al suo passaggio con i depositi argillosi di base. Tuttavia diversi dissesti sono stati riconosciuti anche nel complesso cristallino metamorfico della Catena Costiera e nei depositi sedimentari Plio-Pleistocenici.

L'analisi d'interferometria è stata condotta utilizzando dati ERS da orbita discendente dal 1992 al 2000 e dati Envisat acquisiti lungo l'orbita ascendente nel periodo 2003-2010. Tali dati hanno consentito il riconoscimento dei fenomeni d'instabilità attivi attivi al momento d'indagine e la stima dei relativi valori di movimento, risultati molto variabili e compresi tra 0.7 e 7.5 mm/anno. Tra questi valori le maggiori velocità sono state registrate all'interno delle aree urbanizzate dei paesi di San Martino di Finita e Rota Greca con valori di movimento fino a -6.5 e 7.5 mm/anno rispettivamente per i dati Envisat e ERS.

ABSTRACT

The research focuses on the instability phenomena occurring on the eastern edge of the Calabria Coastal Range using geological and geomorphological investigations, geognostic surveys and InSAR remote sensing technique. The study area is located in Cosenza province (Calabria, south Italy) and includes Cavallerizzo, Cerzeto, San Martino di Finita and Rota Greca villages. The geological setting is dominated by a variety of metamorphic-crystalline rocks constituting the Coastal Range structure. A normal fault, N-S oriented and located on the eastern side of the Costal Range, is responsible of the tectonic contact between the metamorphic rocks and the sedimentary deposits of the Crati Basin; while, a colluvial deposit overlies both the crystalline and the Neogene terrains. Continuous boreholes showed that the thickness of this deposit ranges from 10 to 65 m. The latter is involved in widespread landslides causing severe harmful to buildings and infrastructures. Envisat ascending dataset, processed by SBAS multi-temporal InSAR technique, was employed to measure the displacement time series referred to the interval 2003-2010. The data acquired along Envisat ascending orbit, which better cover the east-facing study area, showed a ground movement rate up to -6.5 mm/yr for the landslides in the urbanized areas; whereas, ERS descending orbit (ascending data are not available) showed movement rate of 7.5 mm/yr.

Keywords: *InSAR, geognostic surveys, landslides, Calabria, Italy*

INTRODUCTION

In the last decades, building damage caused by landslides in urban areas are increased mainly because of the urban expansion occurred on landslide-prone slopes (e.g., Ferlisi *et alii*, 2015; Guerriero *et alii*, 2019). Destructive landslides are usually triggered by downpour and/or prolonged rainfall events, earthquakes and human landscape modifications, causing fatalities, severe damage to human activities and significant economic loss (e.g., Ietto *et alii*, 2014; Bartelletti *et alii*, 2017; Diodato *et alii*, 2017). Weathering processes represent another significative predisposing factor to the instability phenomena, because these processes combined with morphological, lithological, tectonic and climatic factors, generate a significant decay of the physical-mechanical properties of the original rocks (Calcaterra & Parise, 2010; Ietto *et alii*, 2015a, 2016; Perri *et alii*, 2016; Borrelli *et alii*, 2016).

Numerous researches have led to a deepening of knowledge about the instability processes and their prediction (e.g. Costanzo *et alii*, 2016; Elmoulat *et alii*, 2020). Thus, several innovative instruments are available to monitor the activity of slopes that interact with human settlements. Among these, particular interest from scientific community has been devoted to remote sensing technique used to obtain the displacement data of the boundaries and the state of activity of slow-moving landslides (e.g., Cigna *et alii*, 2016; Cianflone *et alii*, 2018; Zao & Lu, 2018). Among remote sensing techniques for landslide monitoring the interferometric synthetic aperture radar technique (InSAR) is the most employed to analyze different types of ground movements, such as subsidence, landslides, deformation associated with fault and volcanic activity (Cianflone *et alii*, 2015; Da Lio & Tosi, 2018; Cigna *et alii*, 2020).

In Calabria (southern Italy) instability processes are widespread phenomena, involving areas characterized by high local reliefs dominated by fault trending, where weathered and deeply tectonized rocks occur (Sorriso-Valvo *et alii*, 1996; Tansi *et alii*, 2016; Borrelli & Gullà, 2017; Conforti & Ietto 2019, 2020). The aim of this research is to investigate on the landslides occurring on the eastern edge of the Calabria Coastal Chain. The research was based on geological and geomorphological surveys coupled with geognostic investigations and InSAR remote sensing technique. Envisat datasets, processed by SBAS multi-temporal InSAR technique, was employed to measure the displacement time series referred to the interval 2003-2010. The InSAR technique, compared to other procedures, shows the advantage to supply a high density of measurement points in large areas, providing time series of movement with high precision. The investigated area falls within Cosenza province, including Cavallerizzo, San Martino di Finita and Rota Greca villages involved by historic slow-moving landslides.

GEOGRAPHICAL, GEOLOGICAL AND GEOMORPHOLOGICAL SETTING

The study area is located in the northern sector of the Calabria region (South Italy). In particular, it falls on the left flank of the

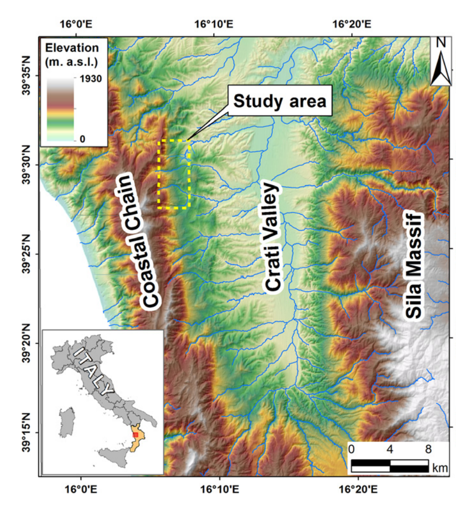

Fig. 1 - Location map of the study area

Crati valley along the foothill zone of the eastern edge of the Calabria Coastal Chain (Fig. 1). Elevation ranges between 982 and 193 m a.s.l. with an average value of 479 m a.s.l. Slope gradients range from 0 to 63 degrees, with an average of 18 degrees (Fig. 2). The studied area covers a surface of 22.1 km2 including Cavallerizzo, Cerzeto, San Martino di Finita and Rota Greca villages belonging to the Cosenza province. The climate is sub-humid, with average annual precipitation of 1300 mm and average temperature of about 15°C. Rainfall peaks occur in the period October–March, during which landslides and severe water erosion processes may trigger (Capparelli *et alii*, 2012; Ietto & Perri, 2015; Conforti & Buttafuoco, 2017; Borrelli *et alii*, 2019).

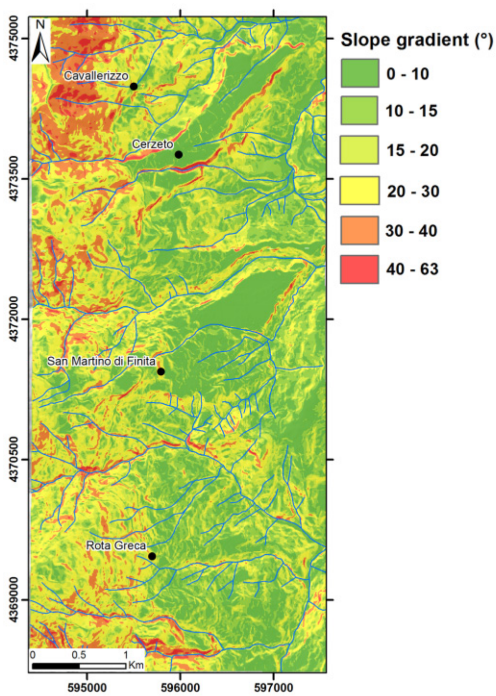

Fig. 2 - Slope gradient map of the study area

The Calabria Coastal Chain is mainly constituted by metamorphic-crystalline rocks belonging to the northern sector of the Calabria–Peloritani Arc (CPA in Amodio-Morelli *et alii*, 1976; Bonardi *et alii*, 1976). The CPA is an orogenic Mediterranean belt originated by crustal terranes in the accretionary wedge during the final stage of the Africa-Europa collision (Ben Avraham *et alii*, 1990; Vai, 1992).

The Crati valley is a graben (Lanzafame & Tortorici, 1981) bounded by North-South striking normal fault systems active since Late Pliocene (e.g., Tortorici *et alii*, 1995; Tansi *et alii*, 2007). On the eastern side of the Coastal Chain, the master normal fault is represented by an active N–S strike fault, named San Fili – San Marco Argentano (Tortorici *et alii*, 1995), which crosses the study area. The San Fili – San Marco Argentano fault is a regional tectonic segment 30 km long. It drives the uplifting of metamorphic-crystalline rocks, forming the Coastal Chain, with respect to the sedimentary deposits that constitute the Crati graben filling. The structure of the Coastal Chain is made up of several nappes mainly constituted by ophiolitic (Amodio-Morelli *et alii*, 1976; Liberi & Piluso, 2009; Filice *et alii*, 2015). In the study area the recognized ophiolitic unit is composed by metabasalts topped by calcschists with thin levels of metapelite (Jurassic in age) (Fig. 3). This ophiolitic unit is overthrust by the continental Castagna Unit, which consists of medium to high-grade metamorphic para- and ortho- gneisses (Permian in age). The sedimentary deposits of the Crati basin (Lanzafame & Tortorici, 1981; Colella *et alii*, 1987) are mainly composed, from bottom to top, by marl and gypsum layers (Miocene in age) that locally pass upward to Pliocenic conglomerates. Sands and sandstones (Plio-Pleistocene in age) characterize the upper part, followed by clay deposits (Plio-Pleistocene in age). Continental red fan-conglomerate (Late Pleistocene in age), made up of igneous and metamorphic rock fragments in a sandy matrix, dominates some parts of the valley areas. Furthermore, colluvial deposits (Holocene in age), made up of metamorphic rocks in sand matrix, overlie both the metamorphic basement and the Neogene sedimentary terrains. East-West trending subvertical faults are also present, marking the directions of the torrential axes where alluvial deposits cropping out.

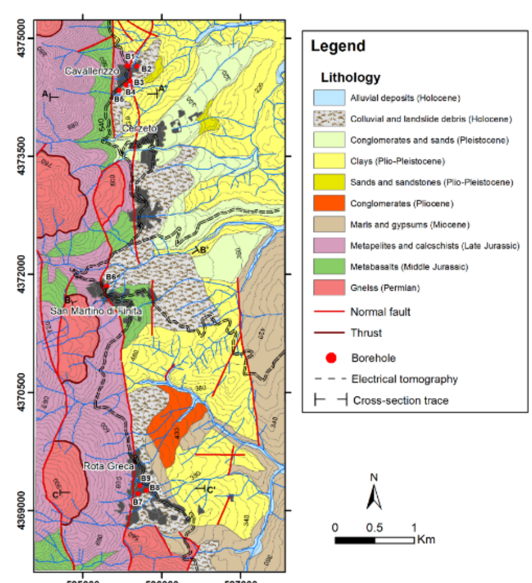

Fig. 3 - Geostructural map of the study area

The geological setting of the area, characterized by a tectonic contact between medium and low permeable rock masses, forming respectively the Coastal Chain and the infilling deposits of the Crati basin, favors the presence of abundant groundwater storage along the contact zone, where numerous springs occur. The groundwater storage is furthermore favored by the presence of a large volume of brittle fault rock produced by the master fault. Therefore, in the whole studied area, the rock masses surrounding the master fault are weak and intensely cataclasized, showing a high predisposition to the instability phenomena.

The geomorphology of the study area reflects the complex interplay between the geological and structural arrangement. Indeed, the landscape in western portion of the studied area, shaped on Palaeozoic metamorphic rocks, is dominated by a rugged topography with high dipping slopes more than 30° in average. The eastern sector, instead, is mainly characterized by rounded and gentle landform, shaped on the Neogene-Quaternary sedimentary terrains (Fig. 3). Usually, the areas dominated by competent rock show high-gradient slopes (Fig. 2). Several deep and narrow incisions, locally fault controlled (Conforti *et alii*, 2014), dissect the slopes mainly with a sub-dendritic pattern and subordinately with an angular-like pattern. Furthermore, the mountain landscape shows triangular facets on the N–S trending fault scarp and minor morphotectonic structures as straight channels, saddles and straight ridges (Tortorici *et alii*, 1995).

High relief energy, steep slopes, severe tectonic fracturing, poor quality lithologies and abundant groundwater, drive the shallow and deep-seated landslides involving both the Coastal Chain rock masses and the sedimentary deposits of the Crati basin (e.g., Casagli *et alii*, 2006; Iovine *et alii*, 2006; Gattinoni, 2009; Capparelli *et alii*, 2012; Conforti *et alii*, 2014; Cianflone *et alii*, 2018).

DATA AND METHODS

The study of the instability phenomena requires the analysis and interpretation of several geological, geomorphological and geotechnical information that interact reciprocally and are obtained through different methodologies, such as: geological and geomorphological surveys, geognostic boreholes, seismic and geoelectric survey and InSAR analysis (e.g., Ietto *et alii*, 2012, 2015a, 2018; Cigna *et alii*, 2016; Cianflone *et alii*, 2018; Faccini *et alii*, 2019). To this regard, since 1980s, several geognostic surveys were performed in the area between Cavallerizzo and Rota Greca villages (Guerricchio, 1998; Rizzo, 2005, 2008; Casagli, 2006; Tansi, 2010; Luci & Liguori, 2014) to study the landslides in the urbanized areas. Starting from these data, the research was based on a new reading of the previous geognostic data, on new geological and geomorphological field investigations and on data collected by Synthetic Aperture Radar Interferometry (InSAR) technique. The used investigation methodologies are described below.

Geological and Geomorphological data

Detailed geological and structural field investigations, integrated with air photo interpretation, were employed to map both tectonic lineaments and rock types involved in instability processes. Subsequently, a geomorphologic analysis was carried out in order to recognize the distribution, geometry, activity state and type of landslides according to Cruden & Varnes (1996). The landslides were recognized and mapped at 1:5000 scale using a combination of aerial photographs, Google Earth satellite images, landslide inventories of the Basin Authority of the Calabria region and detailed field surveys. All collected data were digitized, managed and analyzed using a geographic information system (GIS) and then employed for the construction of a database containing landslide attributes.

Geognostic data

In Cavallerizzo village, several municipal geognostic investigations were performed in the period 1982-1999 (Guerricchio, 1998; Rizzo, 2005, 2008), among these, five continuous boreholes (Fig. 3), ranging from 40 to 75 m in depth, were analyzed in this research.

In San Martino di Finita one continuous borehole, drilled up to 70 m depth, and one electrical resistivity tomography, were performed between 2009 and 2010 years (Tansi, 2010) (Fig. 3). The borehole was located close to the tomography tracing allowing a useful comparison of the relative collected data. The resistivity survey was conducted along one line, about 780 m long, that crosses the urbanized area. Data were acquired by a Syscal R2 (Iris Company) georesistivimeter, equipped with a multielectrode cable with 39 channels spaced at 20 m intervals, allowing to reach an investigation depth of 120 m.

Finally, in Rota Greca village, three continuous drilling of vertical boreholes, carried out up to 20 m depth in 2014 (Luci & Liguori, 2014), were used (Fig. 3). In order to gain some insight into the kinematics of the slope, deep displacement has been periodically measured between 2014-2019 using an inclinometer placed in the borehole B7. The measurements were carried out two times for year, except for the 2016 year due to a malfunction of the instrument. The used inclinometer sensor type was biaxial servo-accelerometer MK4 type, having an accuracy of ± 5°. The collected data were elaborate through the Arts-Boviar Inclinometro 3.5 software.

InSAR data

In this work, we used ERS dataset, acquired along the descending track in the period 1992-2000 (ascending data are not available). We employed these datasets because they allowed us to monitoring the ground deformations in a longer period, which is previous to significant instability events (a.g. Cavallerizzo landslide in 2005). These data were processed by PS technique (Ferretti *et alii*, 2001) within the scope of the extraordinary plan of environmental remote sensing and realized by the Italian Ministry for the Environment Land and Sea (http://www.pcn.minambiente.it/mattm/progetto-piano-straordinario-di-telerilevamento/). Furthermore, we considered the Envisat ascending datasets used by Cianflone *et alii* (2018) to investigate the ground deformations in the whole Crati valley. We chose to use the dataset from ascending orbit because it better covers the east-facing study area respect the descending orbit. The ascending dataset includes 38 images acquired in 2003–2010 (Tab. 1). Pairs of images were selected to apply constraints on the maximum orbital separation (350 meters for the perpendicular baseline) and temporal distance (700 days for temporal baseline) between the two passages, aimed to minimize spatial and temporal decorrelation effects (Berardino *et alii*, 2002). The Envisat dataset was processed by means of SBAS multi-temporal InSAR technique (Berardino *et alii*, 2002) to obtain the displacement time series and the mean ground velocity map. In detail, the SBAS algorithm on the Geohazard Exploitation Platform (GEP) (https://geohazards-tep.eo.esa.int), developed by ESA, was used. 3D unwrapping by the algorithm is performed by this SBAS version, which not include external atmospheric model. For the topography subtraction step the 90 meters SRTM digital elevation model (DEM) was utilized, while atmospheric contribution is removed by "standard" filtering in time and space. Ascending data were processed applying a multi-looking factor equal to 4 m for the range direction and 20 m for the azimuth with a final ground resolution of 90 m (Cianflone *et alii*, 2018 and references therein).

Orbit Type	Track/Beam	N. of used images	Number of pairs	Temporal span	Ground Resolution (m)	Incidence angle (°)
Ascending	86	38	137	04/05/2003 19/09/2010	90	23

Tab. 1 - Characteristics of the satellite images employed in the studied area

Velocity maps in the Line of Sight (LoS) of satellite SAR geometry were produced by Envisat ascending data processing.

CGPS (Continuous Global Positioning System) data were used to validate InSAR LoS velocities. In detail, InSAR velocities recorded in a circular buffer with radius of 200 m around CGPS sites were compared with the velocities recorded by CGPS, obtaining maximum differences of ±1.5 mm/yr for the ascending tracks (for more details see Cianflone *et alii*, 2018).

RESULTS

Landslides features

The geomorphological analysis provided detailed data about the spatial distribution, typology and state of activity of the landslides. A total of 225 landslides (Fig 4a) were mapped, covering a surface of 8.6 km^2 that corresponds to about 38% of the surveyed area and to 10.2 landslide/km^2 density (Table 2). The size of the inventoried landslides spans several orders, from a minimum value of 276 m^2 to a maximum one of 721075 m^2, whereas the average area is 37490 m^2 (Tab. 2). According to classification scheme proposed by Cruden & Varnes (1996), the inventoried mass movements were grouped into three main landslide typologies: slide, complex and flow types. (Fig. 4a). It was found that the higher number of landslides can be classified as slides (183) and they account the 81.3% of the collected landslides. Only six flow-type landslides were mapped, constituting about 2.7% of the checked unstable phenomena; whereas, 16% (36) is the percentage reached for the complex movements (Tab. 2 and Fig. 4b). The complex landslide, consisting of multiple kinematic types, are mainly slides evolving into flow-like landslides. Multi-temporal aerial photos interpretation coupled to field investigations allowed to

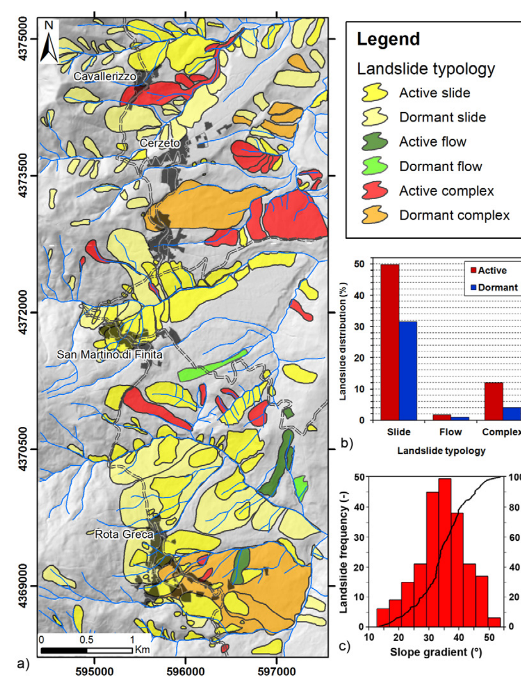

Fig. 4 - a) Landslide inventory map of the study area; b) Distibution of landslide typology; c) Frequency distribution of the landslides with respect to slope gradient

distinguish active (64%) from dormant (36%) landslides.

Failure surface depth ranges from shallow (<2 m) to very deep (>20 m). The deep-seated landslides involve the cover materials and/or the bedrock; whereas, most of the shallow landslides affect cover materials or surficial weathered bedrock. In many cases, shallow landslides are a partial reactivation of pre-existing dormant deep landslides.

Geological surveys showed that the instability processes involve mainly the colluvial deposits, which is produced by weathering processes and by the cataclasic zone generates by the fault movements. The depth of the failure surfaces is mainly located between the bottom of colluvial deposit and the top of the sedimentary deposit of the Crati basin. Mass movements were also observed in the metamorphic-crystalline rocks, constituting the Coastal Chain, and subordinately in the Plio-Pleistocenic deposits of sand and clay.

Field observations suggested that the tectonic deformations, coupled with the intense jointing state of rock masses, control the spatial distribution of some mass movements. Indeed, several landslides were observed close to the tectonic lineaments, which are the cause of a pre-existing weakness zone in the rock mass. The poor mechanical state of the tectonized rocks encourages the groundwater drainage and the consequent deep weathering processes, both held responsible of instability phenomena. (Conforti & Ietto, 2019, 2020). Furthermore, also the slope gradient seems to play a key role on the distribution of landslide occurrences. Indeed, more than 93% of landslides occur on slopes with gradients more than 20°, which characterize only the 37% of the study area (Fig. 4c).

In Cavallerizzo village, evidences of active landslides were recognized mainly in northern and southern part of the urbanized area, where many buildings and infrastructures are damaged. Indeed, in 2005 the southern portion of the village was involved in a large complex-type landslide (e.g., Iovine *et alii*, 2006; Gattinoni, 2008) (Fig. 5a), causing the abandonment of the entire village and its relocation in a new area. Instability phenomena occur also along the village perimeter toward the

Landslide		Count	Landslide area		Landslide size (m^2)		
Typology	Activity	(-)	(km^2)	(%)	Minimum	Maximum	Mean
Slide	Dormant	70	2.8	33.3	1039	384771	40163
	Active	113	2.8	32.8	276	160039	24436
Flow	Dormant	2	0.1	1.1	29159	64621	46890
	Active	4	0.2	1.8	8843	79199	38331
Complex	Dormant	9	1.6	18.5	14515	721075	173078
	Active	27	1.1	12.5	2578	294850	39174
All landslides		225	8.6	100	276	721075	37490

Tab. 2 - Distribution of type, activity, count, area of landslides and summary of landslide size for the landslide inventory of the study area

valley (Fig. 4a). Anyway, geomorphological evidences of landslides involving the historic center were not recognized.

In San Martino di Finita village the whole urbanized area is affected by several large active instability phenomena (Fig. 4a), causing heavy damage to buildings (Figs. 5c and 5d) and infrastructures. The landslides are slide-type with deep failure surfaces and are triggered close to the San Fili-San Marco Argentano fault scarp. Toward valley areas, the instability phenomena show composite slope movements and a partial overlap of secondary landslide scarps occurs.

Rota Greca village is involved by two large dormant landslides in the northern and southern part (Fig. 4a). Instead, the central and some of the southern part of the urbanized area are involved by active instability phenomena with a slide-type kinematic, causing severe damage to buildings and infrastructures (Figs. 5e and 5f). The landslides are characterized by deep failure surfaces and are triggered close the master fault scarp that crosses the whole village. In this area, the triggering of small rapid landslides, allocated in unstable areas classified as dormant or active, is frequent.

Fig. 5 - a) Cavallerizzo landslide occurred on march 07 2005; b) Cavallerizzo landslide, photo dated 2020; c and d) Landslide damage in San Martino di Finita Village; e and f) Landslide damage in Rota Greca Village

Geognostic Surveys

In the urbanized area of Cavallerizzo village, the continuous sampling of five drilled boreholes showed the presence of two distinct horizons. The shallower horizon is composed by a colluvial deposit constituted by heterometric clasts of metabasalts and metapelites immersed in a poor sandy matrix. This rock fragments belong to the metamorphic-crystalline complex of the Coastal Chain. The colluvial deposit was found in all boreholes with variable thickness, ranging from 30 to 64.4 m (Fig. 6), depending from the slope morphology. Beneath the first horizon, a bed of Plio-Pleistocene clay, belonging to the infilling sedimentary deposits of the Crati basin, was found a variable depth in all drilled boreholes. A water table was also found within the boreholes at variable depth. The analysis of the piezometric data shows a great storage of water with a preferential drainage

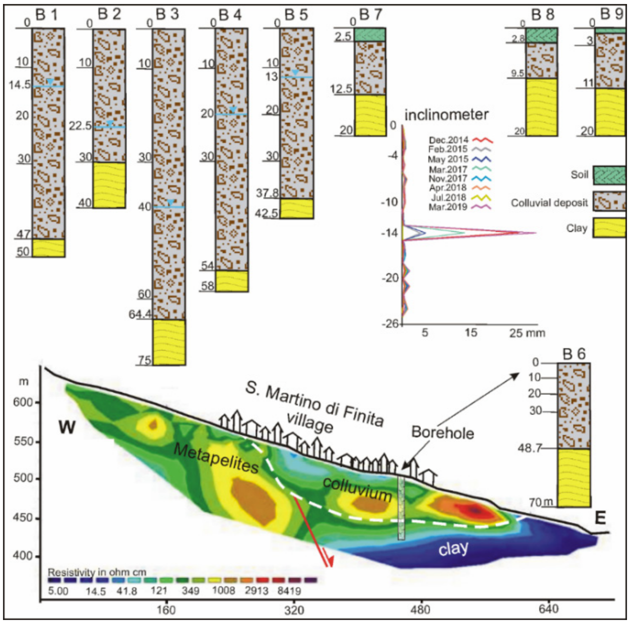

Fig. 6 - B1-B5 Boreholes drilled in Cavallerizzo village; B7-B9 and inclinometer are the geognostic surveys performed in Rota Greca village; B6 and Electrical resistivity tomography section are the geological investigations carried out in San Martino di Finita village. See Fig. 3 for locations of boreholes and tomography lineament

axis in correspondence of the borehole B3 located in the landslide area triggered in 2005. The set of borehole data, coupled to geological surveys, allowed the construction of the geological section A-A' in Fig. 7.

The geognostic surveys carried out in San Martino di Finita village consist in one borehole and one electrical resistivity tomography. The borehole core samples showed the existence of a first level of colluvial deposit constituted by heterometric clasts of metapelite and calcshists in a poor sandy to clayey matrix. The thickness of this first horizon was of 48.7 m, beneath of which a level of Plio-Pleistocene clay was found. (Fig. 6). The borehole data were compared with the information provided by the tomography tracing that cross the borehole axis. Terrains with high electrical resistivity values (color from green to yellow/brown in Fig. 6) were found in uppermost part with respect to San Martino di Finita village and San Fili-San Marco Argentano fault. These electrical values are attributable to metapelite and calcschist rocks recognized by geological survey. A surficial layer, recognizable by more conductive values (light blue color) was observed close to the village. This horizon corresponds to a more weathered level (clayey level) in the colluvial deposit. Finally, in the most eastern side of the section (Fig. 6), beneath a not homogeneous horizon characterized by a high electrical resistivity values (color from green to yellow/brown), a layer with more conductive values (dark blue color) was found. The latter is comparable to the clay layer, lying beneath the colluvial deposit observed by the borehole core samples. The collected data enabled to construct the geological section B-B' in Fig. 7.

Three boreholes were carried out in Rota Greca village (Fig. 6), showing the presence of a first thin horizon of soil with thickness up to about 3 m. The second horizon is constituted by a colluvial deposit of metapelites and gneiss heterometric clasts in a poor sandy matrix. The thickness of this layer ranges between 9.5 and 12.5 m, beneath of which a Plio-Pleistocene clay horizon was found up to the investigate depth of -24m. Only one borehole (B7 in Fig. 6) was equipped with an inclinometer, where annual measures were collected since 2014. Inclinometer displacements have clearly revealed the existence of a slide surface located between the bottom of colluvial deposit and the top of clay layer. Indeed, the sliding surface is located approximately at -14 m depth, where the displacements reached up to 30 mm. This value suggests the clear presence of a slow-moving landslide in the urban center. The collected geological data, obtained from field surveys and drilled borehole allowed the construction of the geological section C-C' in Fig. 7.

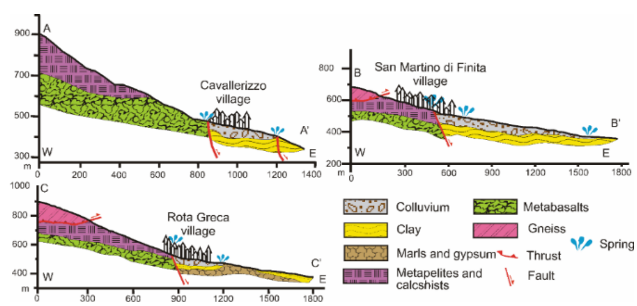

Fig. 7 - Geological cross-section passing through the urbanized areas; see Fig. 3 for location

InSAR survey

In Cavallerizzo village surrounding, the PS ERS descending (Fig. 8) shows velocities between 1.3 and 3.5 mm/yr in the middle part of the urban area. The area is also well covered by Envisat data acquired along ascending orbit (Fig. 9). Coherent pixels were recognized by Envisat ascending dataset in the landslide areas located both in upslope and in downslope zones with respect to the village. The pixels showing highest mean velocities (about -4 mm/yr), along LoS, are located upslope (Fig. 10). Instead, in downslope area the pixels show velocities between -0.7 and -3.2 mm/yr. Along the northernmost village portion, involved by an active rotational slide, coherent pixels with mean velocity between -1.9 and -5 mm/yr were observed. Other pixels with velocity of -3 mm/yr were identified in the southward portion of the village, which is involved in a dormant complex landslide. The analysis of time series of the pixels in the whole Cavallerizzo area shows a general homogeneity of the displacements temporal evolution.

In the all-time series a significative displacement (between 12.8 and 5mm) was observed in the period 27/02/2005 – 08/05/2005 coincident with the activation of the landslide on the march 7th 2005 (Fig.11).

Moving southward, in correspondence of Cerzeto village, which is not involved in landslide phenomena, the PS ERS descending (Fig. 8) showed almost null velocities (between 0.15 and 1.75 mm/yr). More pixels of the Envisat ascending dataset highlighted as well a general stability (mean velocity between -0.9 and 1 mm/yr) close to the village. A pixel with a velocity of about 6 mm/yr was observed only near municipal hall.

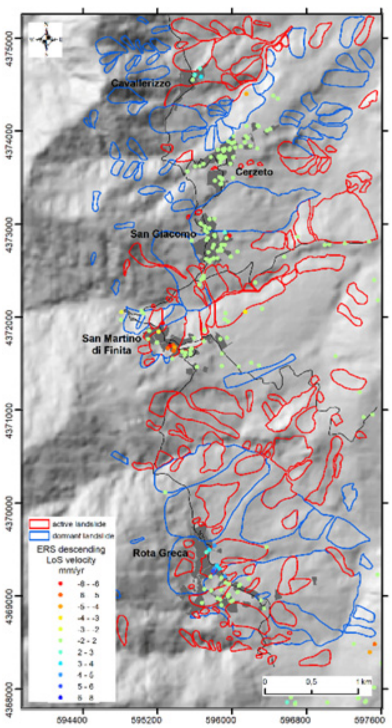

Fig. 8 - ERS descending LoS ground velocity maps for the study area

In the San Giacomo village (fraction of the Cerzeto village) the PS ERS descending were characterized by velocities ranging from -0.9 to 1.6 mm/yr (Fig.8). Several Envisat ascending pixels, with a mean velocity between -1.8 and 0.5 mm/yr, were observed in the northern portion of the San Giacomo urban area (Fig. 10), located in a dormant complex landslide. Instead, in the middle part of the village, where no landslides were mapped, several pixels were identified, showing a decrease of mean velocity from western (-3.7 mm/yr) to eastern side (-0.6 mm/yr). Furthermore, heading to south, close to the cemetery, two pixels with mean velocity next to zero were recognized. The urban area of San Martino di Finita is also characterized by high slope velocities (up to 7.5 mm/yr) recorded by the PS ERS descending, while velocities around zero were recorded only in the southernmost part of the village. In

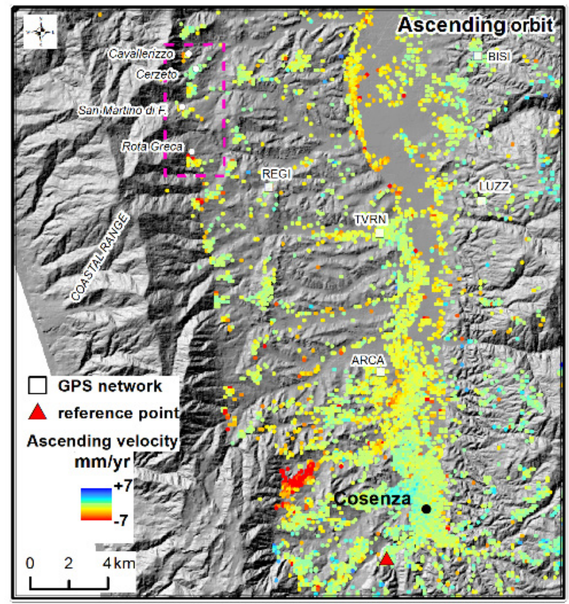

Fig. 9 - Envisat ascending LoS ground velocity maps; the dotted line shows the study area (modified from CIANFLONE et al., 2018)

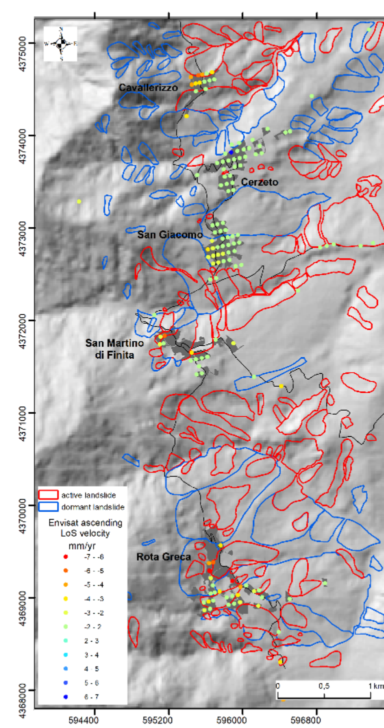

Fig. 10 - Zoom of the Envisat ascending LoS ground velocity maps for the study area

correspondence of this village, affected by two active landslides, Envisat ascending pixels with velocities between -1.8 and -5.8 mm/yr (Fig. 10) were collected. Instead, in the area between the southern

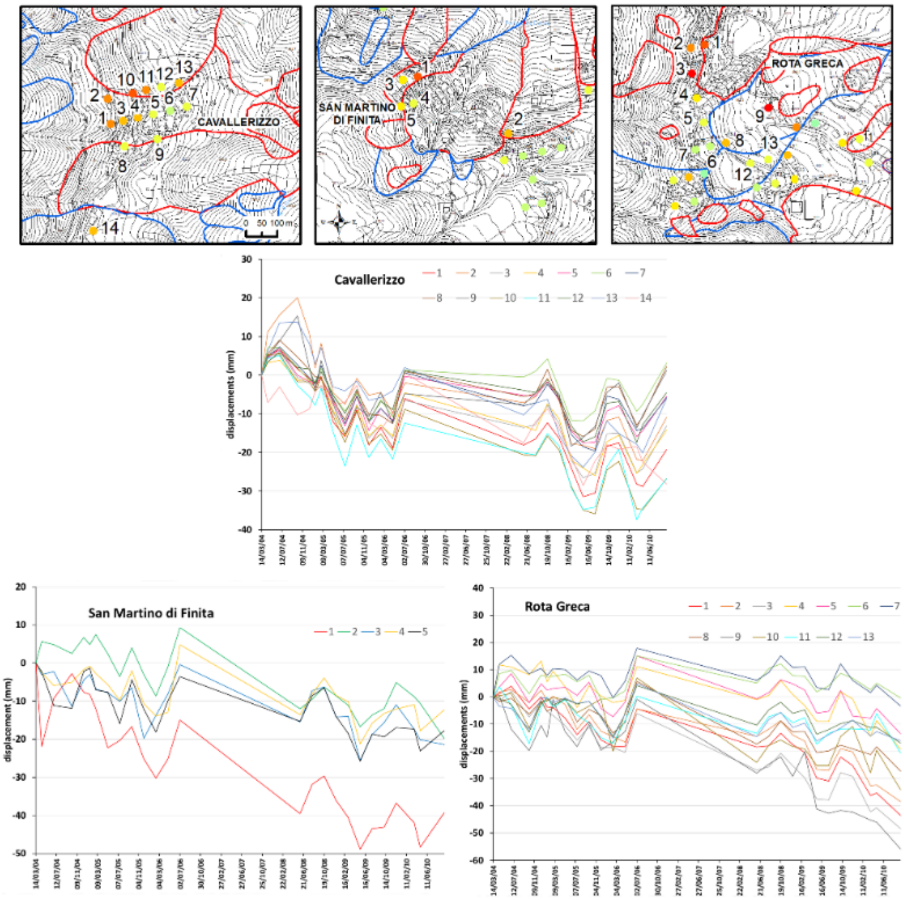

Fig. 11 - Envisat ascending time series of Cavallerizzo, San Martino di Finita and Rota Greca villages

portion of the village and the cemetery, pixels with mean velocity between -1.2 and -0.4 mm/yr were recognized. The analysis of the Envisat ascending time series (Fig. 11), for the pixels inside landslide areas, shows the maximum displacement (about 50mm) in correspondence of pixel 1.

Finally, in the Rota Greca village the PS ERS descending showed velocities ranging between -0.5 and 5 mm/yr (Fig. 8). In the same area, we recognized the Envisat ascending pixels with the highest mean velocities of the whole study region (up to -6.4 mm/yr). In detail, in the middle and southern portion of the urbanized area, involved by large dormant landslides, several pixels with velocity between -0.08 and -6.4 mm/yr were identified, indicating active instability phenomena (Fig. 10).

For the Rota Greca village, the Envisat ascending time series of pixels, located inside landslides, were also analyzed (Fig. 11). The maximum displacement is showed by the pixel 9, currently situated inside a dormant landslide, where a rate of about 55mm was recorded. The analyzed time series shows a general irregular temporal evolution among the different pixels, anyway, common periods of displacement acceleration were observed.

DISCUSSION

During the 20th century, several landslide phenomena have been recorded in the area extending from Cavallerizzo to Rota Greca villages (Nossin, 1973; Carrara & Merenda, 1976; Sorriso-Valvo *et alii*, 1996; Tansi *et alii*, 2016). The most serious and dangerous instability event occurred on the march 7th 2005, which caused severe damage to the southernmost part of the Cavallerizzo (Fig. 5a and 5b). The whole Cavallerizzo urban area, as consequence, was abandoned and relocated in a new site for directive of National Civil Protection Department. Several authors (Iovine *et alii*, 2006; Casagli *et alii*, 2006; Rizzo, 2005, 2008; Gattinoni, 2009; Ietto, 2010) argued on different aspects about the Cavallerizzo mass movement, such as: landslide modelling, trigger-causes and state of activity. Furthermore, some authors (Iovine *et alii*, 2006; Rizzo, 2008) interpreted the cover of metamorphic-crystalline fragments over the Neogenic sedimentary deposits as the result of an ancient landslide. Rota Greca and San Martino di Finita villages have also a long history of landslide damage, as reported by city archives and by professional reports (e.g. Tansi, 2010; Luci & Liguori, 2014).

The present research, with respect to the previous ones (Iovine *et alii*, 2006; Casagli *et alii*, 2006; Rizzo, 2008; Gattinoni, 2009; Ietto, 2010), is based on a larger investigation area in order to acquire an overview of the instability processes affecting the area between Cavallerizzo and Rota Greca villages. At this regard, new data obtained from geological and geomorphological investigations were integrated to the previous existing borehole and geoelectric data, in order to determine a reliable underground geological model.

The obtained data showed that the colluvial deposit, composed by crystalline-metamorphic fragments, characterizes the whole investigated hilly area and its thickness, ranging from minimum 10 m to maximum 64 m, is linked to the morphological variety of the slopes. Indeed, higher thickness of colluvial material occur on gentle gradient slopes or in concave areas. The collected geological data suggest that these slopes are prone to failures along definite surfaces located within the deposit or between its bottom and the top of clay layer. This assumption was also confirmed by the deep displacement data obtained through the inclinometer placed in Rota Greca village (Fig. 6). According to several authors (e.g., Hong & Wan, 2011; Sun *et alii*, 2019), the widespread instability phenomena are also favored by the great storage of groundwater, which, in the study area, is testified by an abundant presence of springs. This water storage is due to the tectonic contact between medium permeable and impermeable rock masses, corresponding to crystalline-metamorphic rocks and clay terranes respectively. Furthermore, most of landslides were recognized close to the San Fili-San Marco Argentano master fault. At this regard, several authors (Calcaterra & Parise, 2010; Borrelli & Gullà, 2017; Conforti and Ietto, 2019) asserted that the fault cores along the zones of maximum shear, where clay gouge and cataclastic rocks occur, undergo a significant loss of their mechanical properties, favouring slope instability. Therefore, terranes with poor mechanical properties and great storage of groundwater represent the main causes of the widespread mass movements in the studied area.

In the Cavallerizzo village, the PS ERS descending (1992-2000) recorded positive velocity values (target approaches the sensor) that are also compatible with eastward displacements. Furthermore, widespread landslides in urban area were recognized by Envisat ascending data collected in the period 2003-2010. All the recognized pixels recorded negative velocity values (target moves away from the sensor), which can be related with a displacement toward East, according to Casagli (2006).

In Cerzeto village, the ERS descending (1992-2000) and the Envisat ascending (2003-2010) data show not significant velocities. The same result was achieved by Casagli (2006) through Radarsat data (2003-2005) analysis.

Considering the northernmost part of the San Giacomo village, the dormant state of landslide activity is demonstrated by the almost null velocities of ERS descending data and Envisat ascending data. Instead, the western side of the middle urban area is characterized by higher Envisat ascending velocities, which can be related to an instability state according to Casagli (2006).

In San Martino di Finita village, the analysis of the Envisat ascending data confirm the urban area instability, with the exception of the southernmost sector, where ERS descending data (1992-2000) show a constant stability condition since the 1990s. Finally, the Envisat analysis showed that widespread instability conditions, characterized by different velocities, involved the whole Rota Greca village both in the 1990s (ERS descending data, velocities up to 5mm/yr) and in the 2000s (Envisat ascending data, velocities up to -6 mm/yr). Several Envisat pixels located inside landslides, classified like dormant, showed movements with significative velocities, indicating a partial reactivation of instability phenomena.

CONCLUDING REMARKS

In this work, geological and geomorphological surveys coupled to several geognostic investigations and InSAR data provided useful information to understand the instability processes affecting the area between Cavallerizzo and Rota Greca villages.

The data obtained by boreholes showed that a colluvial deposit made up of metamorphic fragments in sand matrix, overlie both the metamorphic-crystalline and the Neogene sedimentary terrains. This geological setting was also confirmed by the electrical resistivity tomography performed in San Martino di Finita village. Abundant groundwater storage, due to the presence of brittle fault rock and by the tectonic contact between medium and low permeable rock masses, occurs close to the N-S tectonic lineament, favoring the instability processes. This geological setting dominates in the whole area between Cavallerizzo and Rota Greca villages.

The mass movements were mainly observed in the colluvial deposits, where the urbanized areas are placed; anyway, several phenomena involve both the metamorphic-crystalline rocks and subordinately the Neogenic sedimentary deposits. Deep displacement data, obtained by an inclinometer placed in Rota Greca village, revealed the presence of slide surfaces located between the bottom of colluvial deposit and the top of clay layer. Therefore, steep slopes, severe tectonic fracturing, poor quality lithologies and abundant groundwater, drive the widespread instability phenomena. A total of 225 landslides were mapped in the studied area that expands on a surface of about 22 km^2, giving rise to a landslide density of 10.2 landslide/km^2. Among the checked instability phenomena, the 64% was classified in active state and the remaining represent the dormant state. The slide-type landslides are the higher number equal to 183; instead, 36 and 6 are the instability phenomena mapped as complex movements and flow-type respectively. Envisat datasets showed that the study area is well covered by data acquired along ascending orbit rather than descending one. Envisat ascending velocities revealed values up to -6.5 mm/yr for the landslides, testifying that all main urban centers are involved in active landslides.

Concerning the InSAR monitoring of ground displacements in the study area, future aim consists of the addition data from the higher resolution and/or recent acquisition systems (e.g. COSMO-SkyMed and Sentinel-1 constellations).

The obtained results suggest that the set of lithological, tectonic, geomorphological, hydrogeological and InSAR data provide valuable information for the study of cause and distribution of landslides. Thus, a reliable modelling of the landslide processes cannot be reached if one of the previous aspects is excluded. Indeed, the whole of the achieved results supply suitable information about the understanding of the landscape evolution processes, providing a useful knowledge on the assessment, prediction and reduction of the landslide hazard.

ACKNOWLEDGMENTS

This work was supported by the MIUR-ex 60% Project (Responsibility of Fabio Ietto). The authors are indebted to anonymous reviewer for the comments and useful suggestions, which were constructive for improving the quality of the manuscript.

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Received February 2021 - Accepted May 2021