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MORPHOMETRIC ANALYSIS, MULTITEMPORAL GEOMORPHOLOGICAL INVESTIGATION AND NUMERICAL MODELLING OF THE MONTEBELLO SUL SANGRO LARGE LANDSLIDE (ABRUZZO - CENTRAL ITALY)

Nicola SCIARRA(*), Monia CALISTA(*), Enrico MICCADEI(*), Antonio PASCULLI(*), Tommaso PIACENTINI(*) & Marco SCIARRA(*)

(*) University of Chieti-Pescara - Department of Engineering and Geology - Via dei Vestini, 31 - 66100 Chieti, Italy
Corresponding author: nicola.sciarra@unich.it

EXTENDED ABSTRACT

Questo lavoro presenta i risultati di una analisi geomorfologica integrata, relativa ad un grandioso movimento franoso complesso sito in Montebello sul Sangro (Abruzzo centrale - Italia). L'area in frana è situata sul corso del Torrente San Leo, un affluente del fiume Sangro, uno dei principali fiumi del versante adriatico del Centro Italia. Il bacino di San Leo è inclinato da SW a NE, con una altimetria variabile tra 900 m a 200 m s.l.m., ed è condizionato da un contesto geologico e geomorfologico complesso tra il fronte della catena e la zona pedemontana, caratterizzata principalmente da dorsali da *thrust* e rilievi isolati. Il *bedrock* è costituito da formazioni oligoceniche e mioceniche appartenenti alle unità del Molise. Da ovest a est sono presenti: argille (Argille Varicolori *Auctt.*), alternanze di formazioni marnoso-calcaree, calcarenitiche e calciruditiche (formazione Tufillo, *Auctt.*), successioni pelitiche e arenaceo-pelitiche (Flysch di Agnone, *Auctt.*).

Lo studio è stato basato su una nuova analisi di tipo morfometrico delle reti di drenaggio superficiale, su una indagine geomorfologica multi-temporale e su alcune modellazioni numeriche di verifica finale.

L'analisi multi-temporale, basata sull'interpretazione di foto aeree, dati Lidar e rilievi geomorfologici di campo, ci ha permesso di ricostruire la recente storia geomorfologica dei luoghi con le successive fasi di riattivazione dei fenomeni franosi presenti. Questa è stata condotta mediante interpretazione di foto aeree fornite dalla Regione Abruzzo per gli anni 1954, 1975, 2009, di un volo LiDAR eseguito nel gennaio 2014 e sul rilevamento geomorfologico di campagna effettuato nella primavera del 2014.

Una analisi preliminare delle precipitazioni ha evidenziato come le più importanti riattivazioni dei fenomeni di frana verificatisi storicamente non coincidano con periodi di grande piovosità ma la riattivazione avviene dopo circa due anni di basse precipitazioni cui seguono periodi di precipitazioni medie elevate.

Le tipologie di frana presenti sono state anche esaminate attraverso analisi numeriche con differenti codici di calcolo, ben noti in letteratura: FLAC e UDEC. Il primo utilizza un codice numerico alle differenze finite mentre il secondo un codice agli elementi distinti. La differenziazione nell'utilizzazione dei due codici si è resa necessaria per esaminare con più dettaglio il comportamento di due tipologie di movimento fortemente differenti per la natura dei terreni e per le caratteristiche fisico-meccaniche. In particolare è stato indagato lo scorrimento di una colata di sedimenti limoso-argillosi ed il cinematismo evolutivo di un ammasso roccioso fortemente alterato e fratturato. Il primo fenomeno, di estensione notevole, sta arretrando verso l'abitato di Montebello sul Sangro mentre il secondo, anche per coinvolgimenti di natura sismica, ha già reso disabitato il vecchio villaggio di Buonanotte.

Una particolarità della ricerca è stata quella di focalizzare lo studio sulla rete di drenaggio superficiale che è il risultato di molteplici fattori fisici che interagiscono con i movimenti franosi. Per studiare fenomenologie veloci come le colate, in letteratura, sono state proposte diverse tecniche numeriche, tra le quali la *Computational Fluid Dynamics* (CFD) che consiste in un set di equazioni differenziali, basate sul principio di conservazione di importanti grandezze fisiche, implementate con leggi al contorno che definiscono l'erosione, la deposizione, ecc. In tale contesto, le soluzioni numeriche sono basate sulla discretizzazione del dominio fisico reale mediante *mesh*. Un approccio alternativo semplificato è l'utilizzo della tecnica del *Smoothed Particle Hydrodynamics* (SPH), senza *mesh*, particolarmente efficace nella simulazione di colate, debris flows, earth flows. D'altronde, la topografia di un bacino è modellata non soltanto processi erosivi e deposizionali fluviali, ma anche da movimenti di massa (frane) a differenti scale. Tuttavia, in qualsiasi tipo di analisi o modellazione del territorio, la conoscenza della topografia iniziale è obbligatoria. Di conseguenza, l'analisi morfometrica può essere utilizzata come strumento per identificare le caratteristiche morfologiche volte a tipizzare superfici topografiche.

Tutte le suddette analisi, integrate tra loro, ci hanno permesso di descrivere in modo completo le caratteristiche del complesso e grandioso fenomeno franoso di Montebello sul Sangro, definirne la recente evoluzione geomorfologica e delineandone i possibili scenari futuri.

ABSTRACT

In this work the results of an integrated geomorphological analysis of a complex landslide in Montebello sul Sangro (Abruzzo, Central Italy) are reported. The study is based on a new morphometric analysis of the drainage network, a multi-temporal geomorphological investigation and a numerical landslide modelling.

The multi-temporal geomorphological analysis based on the interpretation of aerial photos, LiDAR data and field geomorphological mapping, allowed outlining the recent geomorphological history and multiple activation phases of the landslides. A preliminary analysis of rainfall data showed that the most important landslide reactivations occurred after at least two years with rainfall above average.

Some numerical analyses were performed to reconstruct the behaviour on the two main typologies of phenomena affecting the area. Firstly a 2D Finite Difference Method (FLAC, 7.0) was applied to analyse the large landslide affecting the village of Montebello sul Sangro with the aim to study the evolution of the active current landslide and specifically the possible retreat of the main scarp. Then we used the Universal Distinct Element Code (UDEC, 6.0), a two-dimensional numerical software that simulates the quasi-static or dynamic response to loading of media containing multiple and intersecting joint structures, to study the behaviour of the rock mass on which the old village of Buonanotte stands.

In order to reconstruct the topography of the Montebello area before the landslide and, accordingly, to explore by computer codes the possible triggering causes of the instability phenomena, autocorrelation of local slope was introduced as a morphometric index of each area of the drainage network. The comparison between the index emerging from the selected landslide area and the other network drainage areas was then exploited.

Keywords: *large landslides, multi-temporal analysis, numerical modelling, morphometric analysis*

INTRODUCTION

An integrated geomorphological analysis of a large landslide in Montebello sul Sangro (Abruzzo, Central Italy) is currently in progress (Calista *et alii*, 2015a; 2016). The study incorporates a new morphometric analysis of the drainage network, a >60 years multi-temporal geomorphological analysis and a numerical landslide modelling.

Multi-temporal geomorphological analysis is a common tool for the analysis of landslides and in this case provided a strong support for the field geomorphological survey and for the interpretation of LiDAR data. The investigation is based on the interpretation of 1954, 1975, 2009 aerial photos provided by the Abruzzo Region, on the analysis of satellite images of Digital Globe data acquired in September 2013 and in October 2014, on the analysis of LiDAR data acquired in January 2014 specifically for this project and on field geomorphological survey carried out right after the LiDAR acquisition in spring 2014. The analysis also compared with historical documents allowed outlining the multiple activation phases of the landslides (Almagià, 1910; D'Alessandro *et alii*, 1979). In addition, analysis of historical series of pluviometric data has been carried out in order to detect the relationship between landslide activity and rainfall.

The drainage network is the result of many physical phenomena and shows a complex interaction with landslides that could be explored through a commonly used numerical technique, called Computational Fluid dynamics (CFD). The CFD tool consists of a set of differential equations based on the principle of conservation (among many others: Pasculli, 2008), supplemented by closure laws that define the erosion (for instance Pasculli & Sciarra, 2006), the depositions, etc. In this framework, the numerical solutions are based on the discretization of the actual physical domain by mesh tessellation or mesh-less approach such as, among others, the Smoothed Particle Hydrodynamics (SPH) (Monaghan, 2005) particularly effective to simulate floods, wet debris flow, earthflow (Minatti & Pasculli, 2010; Minatti & Pasculli, 2011; Pasculli *et alii*, 2013; Pasculli *et alii*, 2014). Beside the above approaches, which usually require a long computational time, the Cellular Automata technique is a promising, simplified, but effective tool to study fluvial dynamics at both reach and catchment scales (Pasculli & Audisio, 2015; Audisio *et alii*, 2015). On the other hand, the topography of a basin is determined not only by fluvial erosion and deposition, but also by weathering and landslides at different scales. The utilization of computer codes aimed at analyzing slope stability, such as Flac (Aringoli *et alii*, 2008; Calista *et alii*, 2003; Calista *et alii*, 2015b), could be also helpful to investigate which were the possible causes of the triggering factors, including not only heavy rainfalls occurrence, but also earthquakes.

However, in all numerical approaches, knowledge of the topography is mandatory. Some criteria should be adopted in order to infer the landforms from currently observed morphology. Accordingly, the morphometric analysis could be exploited as a tool in order to identify specific and quantitative morphological features aimed at typifying topographic surfaces.

This integrated analysis allowed for a comprehensive description of the geomorphological features of the large earthflow – complex landslide of Montebello sul Sangro, the definition of the geomorphological recent evolution, and the outlining of possible future scenarios.

GEOLOGICAL SETTING OF THE LANDSLIDE AREA

The Montebello sul Sangro area is located in the transition zone between the central Apennines chain front (Maiella Mts) and the Adriatic coast, within the River Sangro basin in the south eastern Abruzzo area at the boundary with Molise region (Central Italy; Fig.

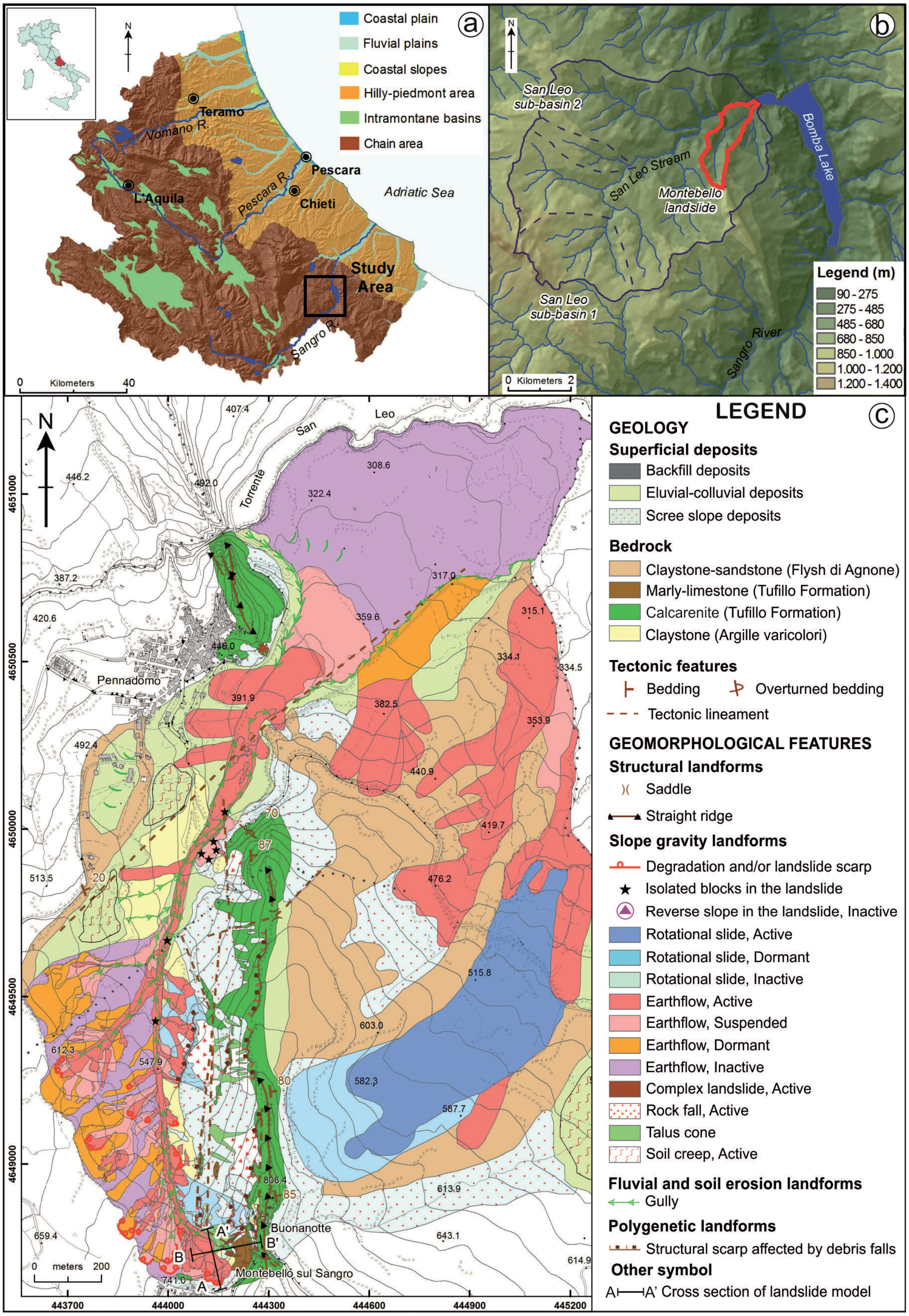

Fig. 1 - a) Physiographic map of Abruzzo Region and study area (black box); b) San Leo Stream basin and landslide area (red line); c) Geomorphological map (modified after Calista *et alii, 2016)*

1) (D'Alessandro *et alii*, 2003, 2008; Piacentini & Miccadei, 2014).

The landslide area is located in the San Leo Stream, a tributary of the middle Sangro River valley, one of the main rivers of the Adriatic side of Central Italy. The San Leo basin is sloping from SW to NE, from 900 m to 200 m a.s.l. and lies in a complex geological and geomorphological framework between the chain front and the piedmont area, characterized mostly by thrust ridges, isolated reliefs, hog-back and cuesta reliefs.The bedrock is formed by Oligocene and Miocene rocks pertaining to the Molise units. From west to east: clays ("*Argille varicolori*" *Auctt*.), alternating marly-calcareous, calcarenite, and calcirudite rocks (Tufillo formation, *Auctt.*), and pelitic and arenaceous-pelitic successions (Flysch of Agnone formation, *Auctt.*) (Miccadei *et alii*, 2013; Servizio Geologico d'Italia, 1970, 1971). The structural setting is characterized by an east overturned faulted anticline from N-S to NNW-SSE trending. It is cut by minor NNW-SSE and SW-NE trending faults. At the surface, the calcareous units are from 30°-40° E (western side of the ridge) up to 70°E (eastern side) dipping. In the northern part, calcareous units are overturned (dip 30°-40° W) and overlaps the pelitic and arenaceous-pelitic units.

The present geomorphological features outline a hog-back ridge strongly asymmetric with a gentle eastern slope and a steep western one, resulting from the erosion of the anticline flank. Northwards the ridge is deeply incised and separated by a second hog back ridge, on which the Pennadomo village is located. A wide and complex landslide involves the western side of the Montebello hog-back, passes the narrow incision between the two ridges and spreads out in the eastern side (Fig. 2). The scarp area involves the steep western calcareous slope of the ridge down to the gentle lower slope on clay units. The mass flows down along a narrow channel and then spreads out in a wide accumulation lobe, with depressions and undulations, down to the Bomba Lake. Thrust features in the accumulation area point out at least two overlapped flows, suggesting the continuous activity of the movement (Fig. 3). The regressive enlargement of the landslide scarp, affecting the Montebello village, involves the western side of the calcareous ridge with systems of tension fractures and reverse slopes areas (Fig. 3), involving Montebello village. This new village was rebuilt after landslide events (in 1864, 1898, and 1899) due to the regressive evolution of the wide landslide that involved the old Buonanotte village (Almagià, 1910).

According to the geological and geomorphological features, the mass movement is classified as a complex landslide, a combination of rotational slide movements in the upper part and earthflows in the middle and lower part (D'Alessandro *et alii*, 1979; Abruzzo-Sangro Basin Authority, 2005; IFFI Project, 2007), controlled by the geological and morphostructural setting of the carbonate hog-back and clay chaotic rocks (*Argille varicolori*). The geomorphological evolution of the western side of the relief is influenced by rock falls in the upper part of the ridge, due to fractures and jointing in the calcareous strata, while in the lower part it is influenced by the progressive involvement of the clay units in the landslide movement (Calista *et alii*, 2016).

METHODOLOGY

A detailed-scale geomorphological analysis allowed for the production of large-scale multi-temporal analysis of the Montebello sul Sangro landslide as well as morphometric analysis of drainage network and landslides software modelling.

Multi-temporal analysis is a fundamental tool for the analysis of the recent evolution of landscapes and specifically landslides. In this case, the analysis is based on air-photo and LiDAR interpretation compared to field mapping. Air-photo interpretation was performed on 1:33,000 scale aerial photos (flights IGMI, 1954 and Abruzzo Region, 1974), 1:5,000 scale aerial photo and orthophotos color images (Flight Abruzzo Region, 2009) Digital Globe satellite images and 1m resolution LiDAR data (CNR-IRPI, January 2014).

This analysis was integrated by geomorphological surveys. The field geomorphological survey (bedrock, cover deposits, geomorphological features) and the expert knowledge-based landslides analysis (according to Italian and international literature, SGN 1994; GNGFG, 1994; ISPRA, 2007; Smith *et alii*, 2011; Guerriero *et alii*, 2013; Piacentini *et alii* 2013, 2015) allowed for the mapping and the characterization of the landslide. Landslide mapping has been performed according to WP/WLI (1993) defining the concept of activity with reference to the originating causes. Landslides are mapped, according to their activity, into four main categories: active, suspended, quiescent and inactive.

The numerical analyses were performed using two different numerical codes, for the section A-A was used the FLAC code, a two-dimensional finite difference method, for the section B-B' the UDEC code, a two-dimensional distinct element method. We chose two different codes because the investigated sections involve different rock types; in particular, the B-B section concerns rock formations with evident fracturing systems.

A morphometric analysis of the drainage network also supports geomorphological mapping, outlining topographic anomalies induced by landslide processes. Different proposed numerical indexes are discussed in the literature, ranging from parameters describing the hierarchy of river networks due to basin evolution and erosion (Horton, 1945; Strahler, 1952; Ciccacci *et alii*, 1980; Del Monte *et alii*, 2014) to, among many others, stream-length gradient (Troiani & Della Seta, 2008; Labella *et alii*, 2014; Troiani *et alii*, 2014 and references therein), and surfaces fractal dimensions (Del Monte *et alii*, 1999; Pasculli & Sciarra, 2005). Particular geological structures or landslide phenomena could introduce local anomalous values respect to the average selected morphometric indexes of the land under study. As useful tool to identify such anomalies, wavelet tools have been proposed as well (Doglioni & Simeone, 2014 and references therein).

However, in this paper, a different approach was used, based on the autocorrelation function (ACF) of the local slope values.

MULTI-TEMPORAL GEOMORPHOLOGICAL ANALYSIS

Multi-temporal analysis of the Montebello sul Sangro landslide was carried out in order to investigate complex landslide modification and activity from 1954 to 2014. This analysis, also compared to historical documents and chronicles, shows multiple activations of the main earthflow in the lower part of the slope. Main events occurred in 1864, 1898, 1899, 1971 (Almagià, 1910; D'Alessandro *et alii*, 1979) and the last one is still well documented by the 1974 aerial photos.

A description of the most important periods in the complex landslide evolution is showed below, analysing the landslide features, as illustrated in detail in the multi-temporal geomorphological map 1:10.000 (Calista *et alii*, 2016).

More in detail, the 1954 analysis outlines (Fig. 4a) the occurrence of several (59) earthflows (area from 25 m^2 to 18,000 m^2), mostly defined as reactivations of the previous landslides. With an overall surface about 166,000 m^2, the landslides partially reactivated the south-western part of the Montebello landslide area without affecting the landslide's toe (Fig. 5a).

The 1974 analysis (Fig. 4b), carried out after the large landslide event occurred in 1971, shows the presence of two different areas affected by mass movements. The first area (336,000 m^2) is within the south-western part of the Montebello landslide and is characterized by earthflows, but, differently from 1954, the landslide's toe was partially involved (about 680 m downslope from the 1954 landslide's front). In the second area (southernmost part), talus cone and complex landslides were mapped on a previous abandoned rotational landslide. The main landslide scarp has retreated, reaching the Buonanotte Village; the overall area is about 54,000 m^2.

In the 2009 analysis (based on both aerial photo analysis and field survey, Fig. 4c), earthflows were mapped (199,000

Fig. 2 - Panoramic view of the Buonanotte village hog-back ridge and of the Montebello sul Sangro landslide. a) Upper part and landslide scarp; in the background the Montebello ridge; b) lower part and landslide body; in the background the Pennadomo village

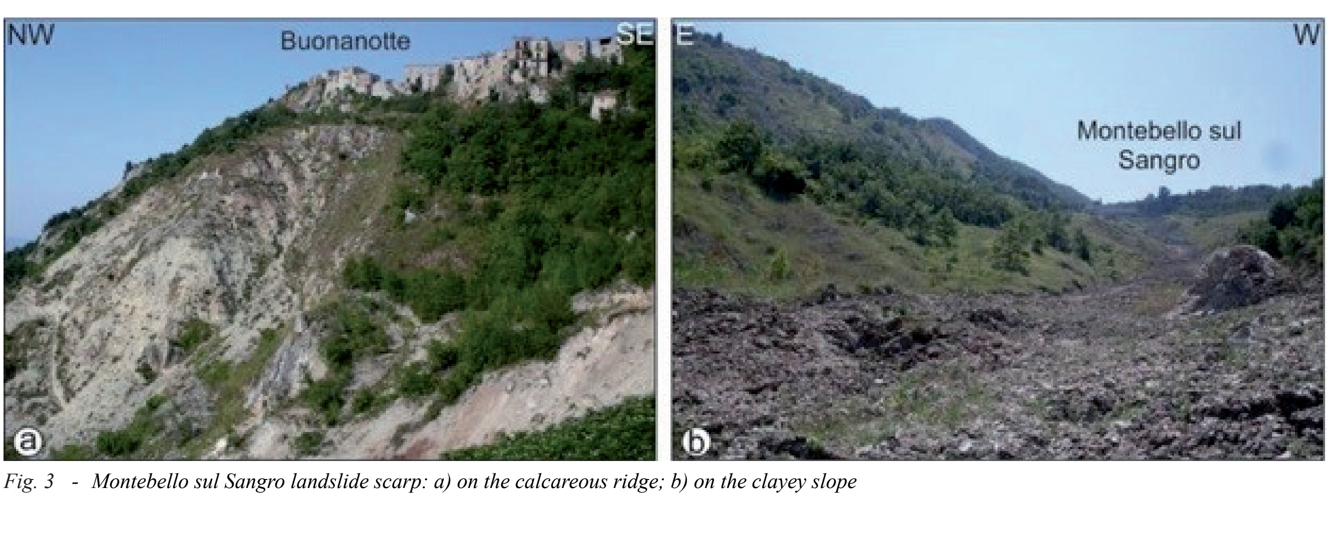

Fig. 3 - Montebello sul Sangro landslide scarp: a) on the calcareous ridge; b) on the clayey slope

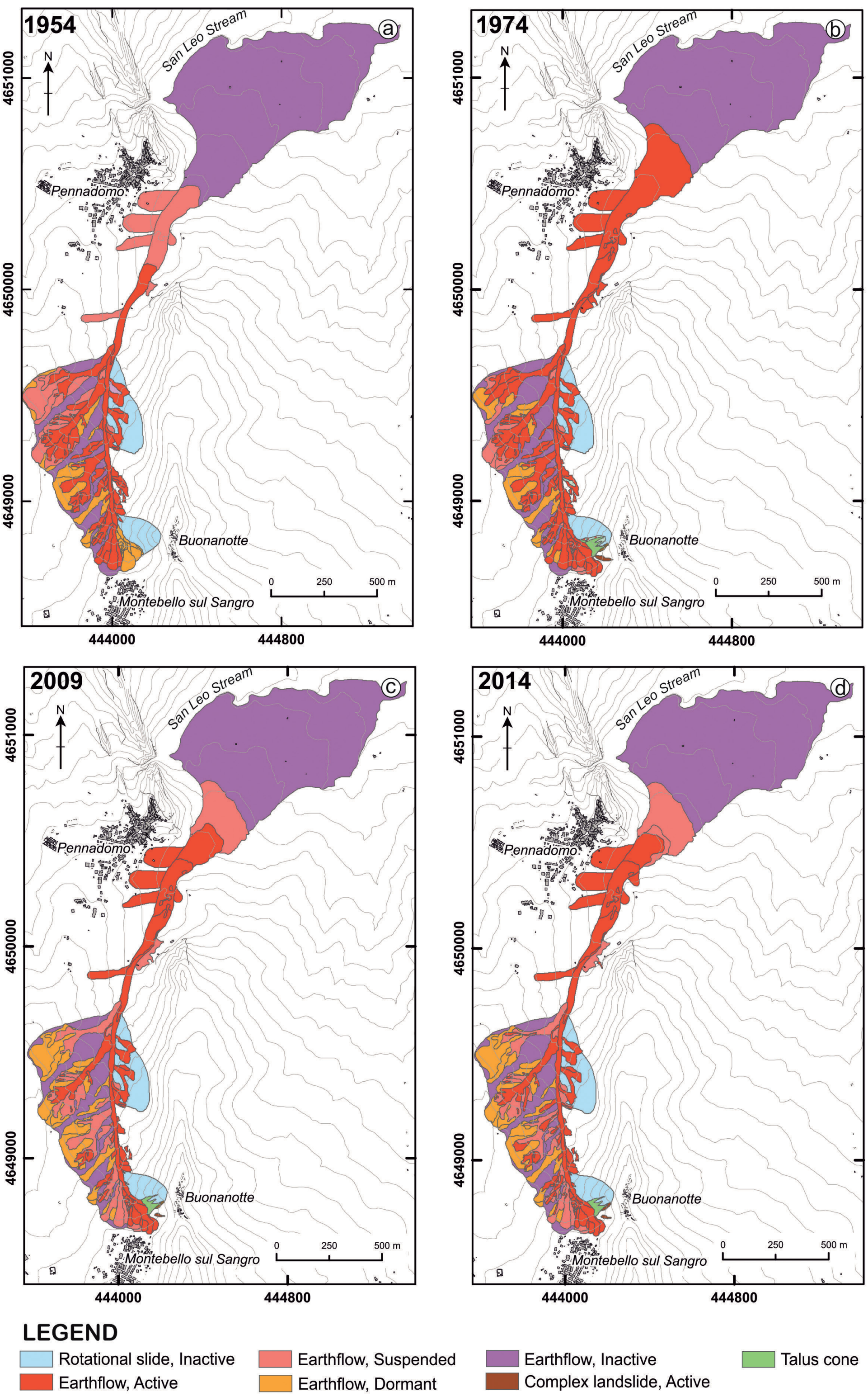

Fig. 4 - Maps of the Montebello sul Sangro landslide in 1954 (a), 1976 (b), 2009 (c) and 2014 (d)

m^2) as reactivations of the previous landslides in the south-western sector. Complex landslides were also recognized in the southernmost part. The Landslide's toe was less involved in the reactivation process compared to the previous analysis (about 235 m upslope the 1974 landslide's front).

The analysis of the landslide in 2014 (Fig. 2; Fig. 4d) results from the combination of the field survey and photo-geological analysis (LiDAR 2014). Both large landslides (mostly dormant and/or abandoned) and small landslides (generally more recent and active) were mapped. The main landslide is an earthflow with a surface area of about ~1.1 km^2 and with average slope of 18°, extending from 802 m a.s.l, below the Buonanotte Village, to the San Leo River to 317 m a.s.l. The total reactivated landslide area is 240,000 m^2.

Through the comparison of multi-temporal images, it has been also possible to evaluate the velocity of the surface portion of the landslide, by measuring the movement of some blocks embedded in the landslide body. The analysis was carried out through satellite images (images taken of the September 2013 and October 2014 by Digital Globe, Fig. 5b,d) and Lidar data (January 2014, Fig. 5c). The estimated velocity from September 2013 to January 2014 is about 0.83 m/day and from January to October 2014 is about 1,1 m/day.

Local regressive enlargement of the landslide scarp continued in 2015, as reported by field surveys (January and February 2015) and outlined by damages to infrastructures (road and homes) in Montebello sul Sangro village.

LANDSLIDE ACTIVITY AND RAINFALL

The possibility of identifying a relationship between rainfall and reactivations of the landslide was investigated. We analysed rainfall records of the "Bomba" Meteorological station compiled for the hydrological year (October-September) from 1921-22 to 2013-2014 (Fig. 6). The station is located about 5.5 km NE of the Montebello sul Sangro landslide at approximately 458 m a.s.l..

Rainfall data show how the main event of the Montebello sul Sangro landslide in 1971 (4/21/1971) do not match with heavy metereological events, but with high rainfall (648 mm) from

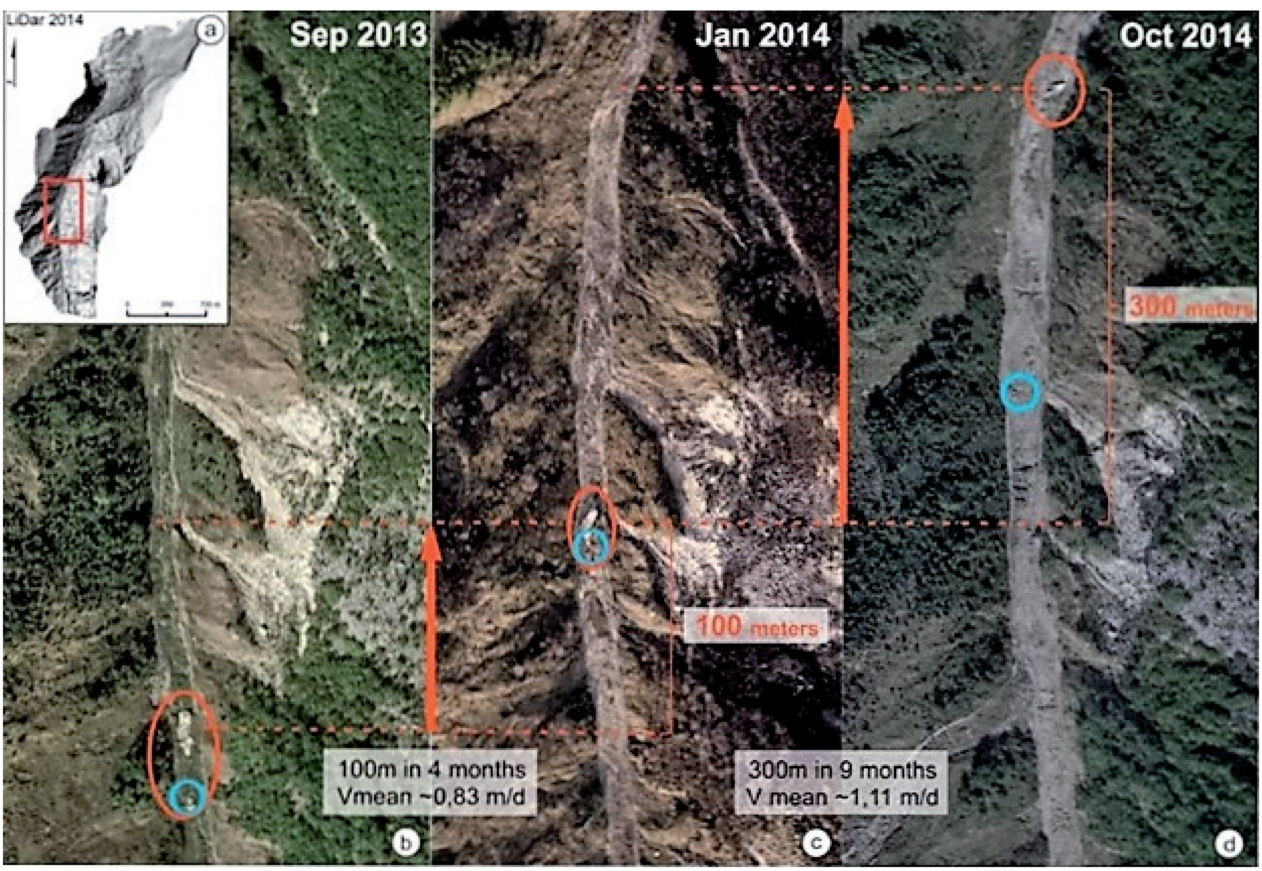

Fig. 5 - Satellite image and aerial photo of the Montebello sul Sangro landslide: a) LiDAR image of the Montebello landslide, the red box indicates satellite image and aerial photo considered; b) Satellite Image acquired in September 2013 (by Digital Globe); c) LiDAR acquired in January 2014 (by CNR-IRPI); d) Satellite Image acquired in October 2014 (by Digital Globe). In red and blue the two blocks, the dotted line indicates the projection of the displacements of the blocks

September to April (541 mm between December-April). Dry years with rainfall below average, especially if consecutive, determine conditions that could have inhibited landslide reactivation. Recently, the hydrological year 2008-09 was exceptional in terms of amount of rain (1289 mm), after two years with below average rains (2006-07 with 389 mm, 2007-08 with 783 mm) and the Montebello sul Sangro landslide was remobilized. The most evident reactivations are movements occurred in winter and spring 2013-2014 following long-lasting and above average precipitation (1074 mm) (Fig. 6). Also in this case, it followed two years with low rainfall (under 800 mm). The main events do not match with the extreme rainfall events, but always with periods and seasons of above average of precipitations.

MORPHOMETRIC ANALYSIS OF DRAINAGE NETWORK

The morphometric analysis was performed on the point matrix sampled from the drainage network on the DEM of the area. Accordingly, the drainage network was sampled in a matrix (from west to east, from north to south), with a selected resolution (25 m or 5 m), and converted into drainage points with UTM WGS84 coordinates, elevation, and slope data (hereafter Old Point Numbering: OPN). In this context, the ACF refers to the correlation of the local slope of a selected OPN with the local slope of all the other OPNs.

The analysis was performed for the whole San Leo basin (25 m resolution) and for some selected sub-basins (25 m resolution), including the Montebello landslide drainage area (5 and 25 m resolutions).

Heights, longitude, latitude and slope (in degree) were given. Hence, the arithmetic average value of the local slope was calculated for each selected (s) area:

$$\overline{x}_{slope}^{area,s} = \left(\sum_{i=1}^{N} x_{slope,i}\right) / N$$

where $x_{slope,i}$ was the slope of the *i-th* (in OPN) point and *N* was the total number of stream points. Then, for each point, its distance from all others was calculated introducing a new numbering of the points (NPN), according to the increasing values of their distances from the selected point. Then, for each selected area (*area,s*) with *M* representing the total number of points, the local slope correlation of each *j-th* point (in OPN or NPN) with the slope at point *k* (in OPN or NPN) was determined through the following (Cliff & Ord, 1973) formula:

$$ACF(k)_{autocorr,j}^{area,s} = \frac{\left(\sum_{j=1}^{M-k} (x_{slope,j}^{area,s} - \overline{x}_{slope}^{area,s})(x_{slope,j+k}^{area,s} - \overline{x}_{slope}^{area,s})\right)}{\sum_{j=1}^{M} (x_{slope,j}^{area,s} - \overline{x}_{slope}^{area,s})^2} \quad (1)$$

In order to identify the correlation distance for the slope in each point, Bartlett's criterion was selected (Kaggwa, 2000). Then we considered the minimum value of the k_{index}, with

$$\left| ACF(k_{index}) \right| \leq 1.96 / \sqrt{M}$$

as the index that identifies the correlation length.

An example is reported in Fig. 7a, related to Point 2 of the Montebello Sub Basin at 5 m resolution. Such a correspondence implies the assumption that the area under study is covered with equispaced points. In this paper, these requirements are only partially satisfied. However, as a first attempt, some suggestions may be acquired.

Thus the morphometric analysis was performed for the whole San Leo basin (Fig. 8) and for three sub-basins including the Montebello landslide (Fig. 9).

In detail, in Figs. 7b, c, d, the normalized distributions of frequencies of the values of k_{index} that indicate in some way the correlation distance, are reported. Inspection of the ACF distribution related to Montebello Landslide Basin (Fig. 7b) clearly shows a different morphometric distribution (peak at intermediate values) compared to the correlation distribution of Sub Basin 1 and 2 (peak at low values and then decreasing, Fig. 7c,d). The whole San Leo Basin (Fig. 7e) is characterized by a bi-modal frequency distribution of the correlation point. Finally, comparison between plots reported in Fig. 7b,f shows that not only the mode of the drainage network sampling, but also the sampling resolution may affect the frequency distribution of the correlation length.

The different distribution of the k_{index} in the case of the whole San Leo basin compared to the Montebello Landslide Basin is also evident from the maps distribution of the values, respectively Fig. 8 and Fig. 9 (Drainage network k-index). The San Leo shows low values and a scattered distribution in almost the whole basin except for some local high values in the SW part of the basin (including sub-basin 1). The Montebello landslide sub-basin shows a clear trend, with low values in the centre of the basin and very high values in the upper and lower parts of the basin, outlining strong topographic anomalies in the scarp area and in

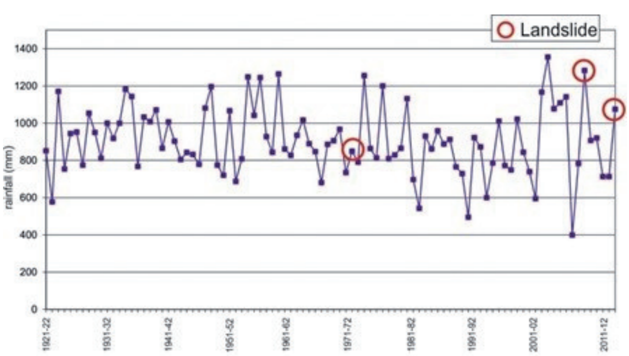

Fig. 6 - Annual rainfall historical series (Bomba, 458 m a.s.l.). The x-axis shows the hydrological years and the y-axis shows the annual rainfall in mm. Red Balls represent the main reactivation of the landslide

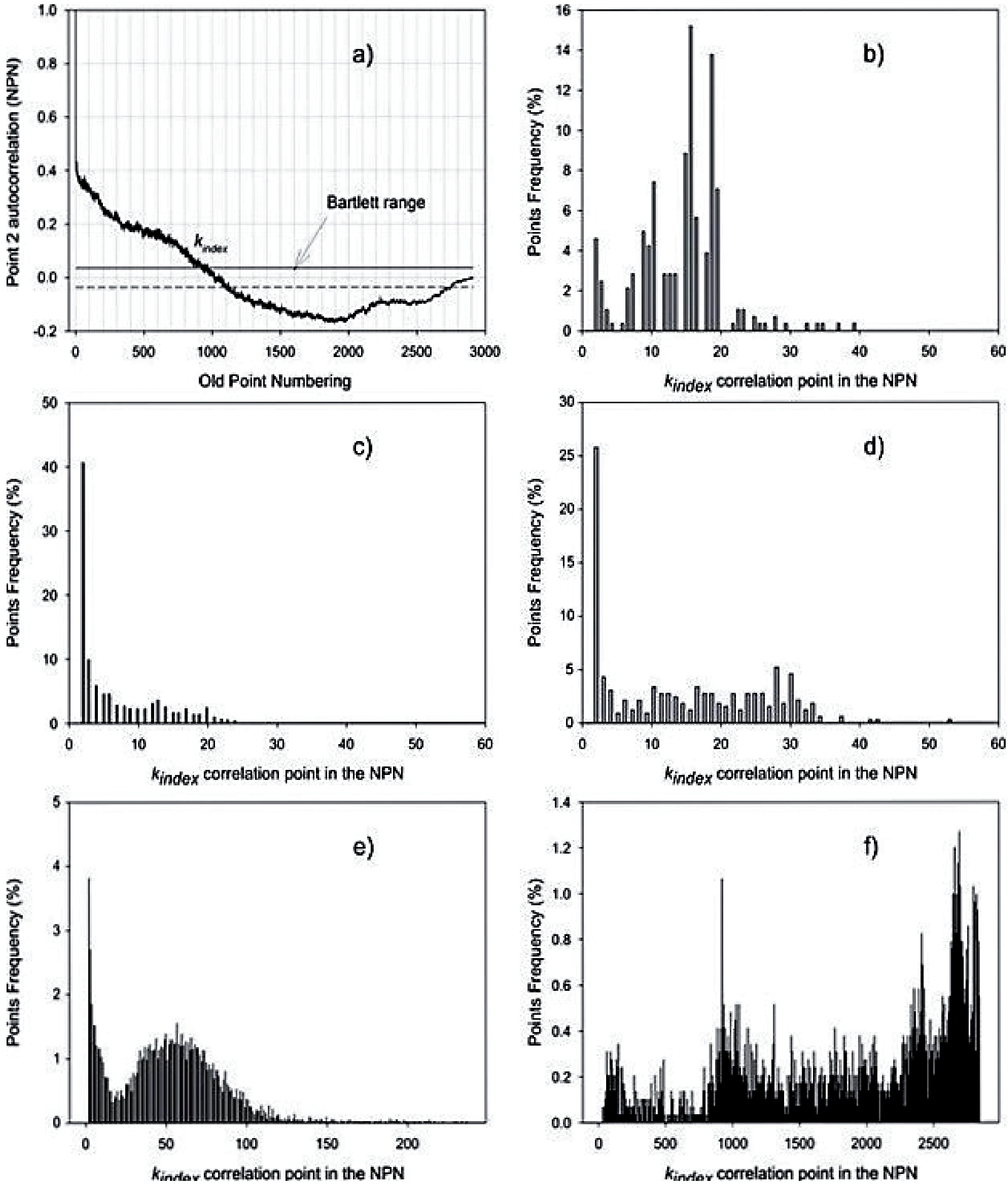

Fig. 7 - a) Montebello Landslide Autocorrelation (5 m resolution); b) Montebello Landslide (25 m resolution); c) San Leo Sub Basin 1 (25 m resolution); d) San Leo Sub Basin 2 (25 m resolution); e) San Leo Global Basin (25 m resolution); f) Montebello Landslide (5 m resolution) (after C*ALISTA et alii, 2015b)*

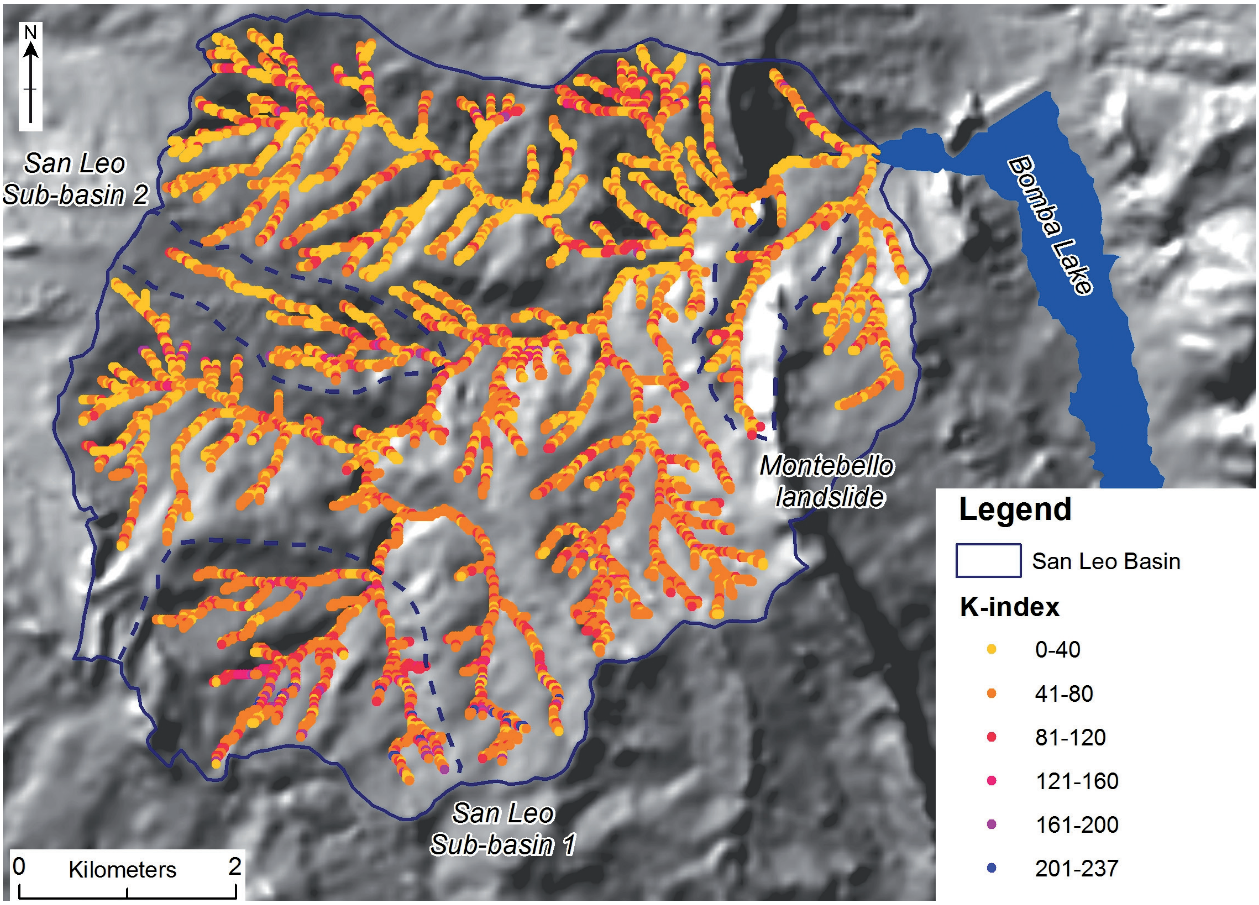

Fig. 8 - k_{index} distribution along the whole San Leo basin (after Calista *et alii, 2016)*

the accumulation area of the landslide.

The final step (in progress) is the reconstruction of the original topography of the Montebello area. A suitable tool to this purpose is the well-known Metropolis-Hastings algorithm (Arminger & Muthen, 1998) that is able to reproduce a spatial domain of points whose characteristic (for instance their slopes) are correlated to each other, following a selected spatial distribution such as that obtained by the AFC approach.

LANDSLIDE MODELLING

Section A-A'

The modelling was performed on the section A-A' (see Fig.1) located close the town of Montebello sul Sangro in order to analyse the influence of the state of evolution of the landslide for the identification of the landslide scarp retreat and the possible hazard affecting the village located upstream to the main scarp (Calista *et alii*, 2003; Calista *et alii*, 2007).

The discretization mesh (Fig.10a) is composed of four-sided elements modified so as to be close to the reference geological section; in our case, a four-sided mesh having a size of about 2 m was used. Between the clay deposits and the scree slope deposits a discontinuity has been inserted characterized by the following properties: no cohesion, friction angle of 10°, normal and shear stiffness of 67 MPa. According to Mohr-Coulomb constitutive model we assigned to each lithotype the physical and mechanical properties of Table 1 obtained by laboratory tests.

We proceeded by successive steps. Initially the section was analyzed using the parameters previously described. Subsequently, in order to verify the possible detensioning of the zones upstream of the slope, a second analysis was performed removing the movement of the landslide deposits, improving their mechanical characteristics and increasing the cohesion value of up to a maximum of c'= 10 kPa (Sciarra *et alii*, 2011). In the first analysis the section was unstable; a large movement in the most upstream of the current landslide flow is generated. At these conditions the numerical code is unable to further investigate the behavior of the model and to study the possible regression of the landslide scarp. The new analysis performed increasing parametrically the value of cohesion identified the

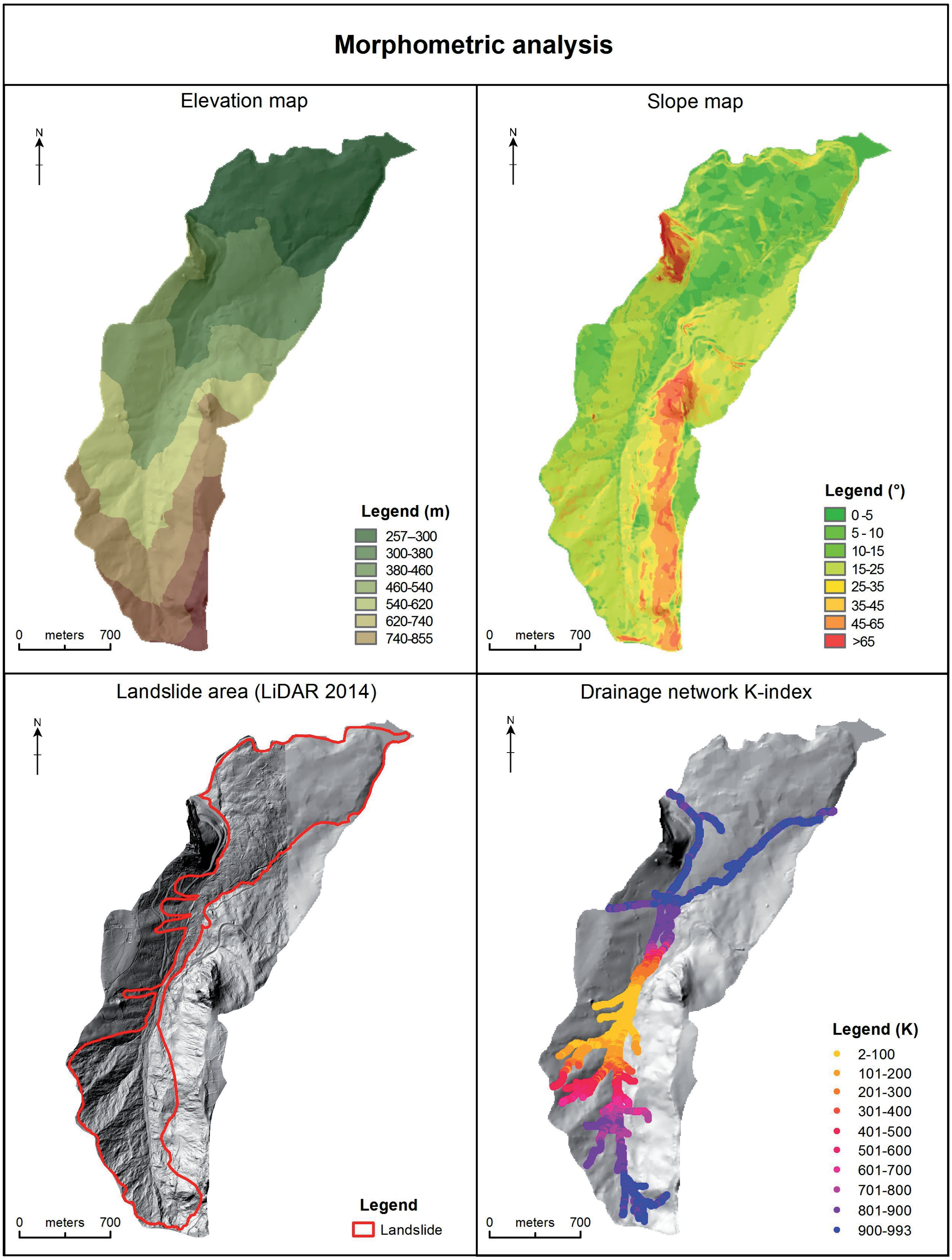

Fig. 9 - Morphometric map of Montebello Landslide Basin (after Calista *et alii, 2016)*

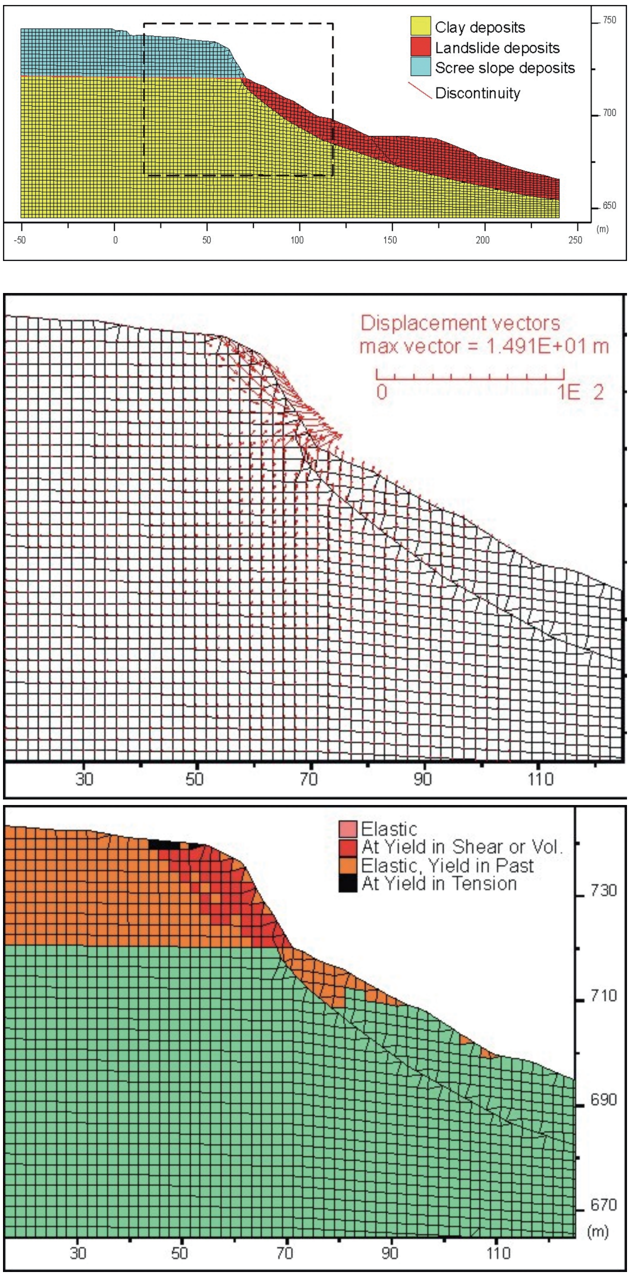

Fig. 10 - a) Schematic reconstruction of the geological section. Second analysis: b) displacements vectors graph; c) plasticity indicator graph

area potentially mobilizable in the outer plate of the slope deposits (Fig. 10 b,c). We can observe in Fig. 10c that the outer area of the deposits is fully plasticized and the most superficial meshes are at yield in tension. The numerical modeling allowed us to reconstruct, with a good precision, the actual evolutionary process of the entire slope.

Section B-B'

The section B-B', studied by the numerical code UDEC, is of particular interest because it is located in close proximity to Buonanotte village, now deserted and located right in the highest part of the section (Fig. 1). We used the UDEC code as it allows us to insert several joint systems and to study their influence on the stability of rock slope.

After defining the borders of the model and the topography, the main discontinuities were included (Fig. 11): the major faults (F1, F2, F3 in Fig. 11); two families of fractures S1 (dip 60° and spacing 3 m) and S2 (dip 20° and spacing 20 m); finally, the stratification (in green in Fig. 11), which is also considered as a discontinuity. At the right of the main fault (F1), the stratification presents a dip of 110° and a spacing of 15 m, while at the left, the dip is about 145° and the spacing 4 m.

After inserting all the discontinuities, a grid with maximum mesh size of 5 m was generated; the software adapts the mesh size considering the discontinuities and stratification borders.

To describe the actual behaviour of the different rock types, two different constitutive models were adopted: for clays and landslide deposits we used the constitutive model of Mohr-Coulomb with the same physical and mechanical properties used in the analysis of section A-A' (see Tab. 1); for the calcarenites and marls the Hoek & Brown (1998) constitutive model was used. The constitutive model of Hoek and Brown is described by the law:

$$\sigma_1 = \sigma_3 + \sigma_{ci} \cdot \left(m_b \frac{\sigma_3}{\sigma_1} + s\right)^a$$

where σ_1 = maximum principal stress at peak of deformation; σ_3= minimum principal stress; σ_{ci} = uniaxial compressive strength of intact rock; m_b, s and a = constants depending on the properties of the rock; all these parameters are summarized in Tab. 2.

Regarding the included discontinuities, based on the Coulomb constitutive model, the parameters are: joint shear stiffness (*Ks*) = 1E9 Pa/m; joint normal stiffness (*Kn*) = 1E10 Pa/m; for the stratification: friction angle 35° and cohesion of 50 kPa; for the fractures: friction angle 25° and no cohesion.

The analysis of the results shows that the main displacements are found along the fault F1. From Figs. 12 and 13 we can note that the wedge bounded by fracture F3 and the lithological limit between limestone and marl tends to move downward moving along F1. We can also observe the activation of an important movement in the lower part of the slope.

CONCLUSIONS

The integrated geomorphological analysis allowed defining the features of the large landslide of Montebello sul Sangro (Abruzzo, Central Italy). The mass movement is classified as a complex landslide, a combination of rotational slide movements and earthflows. It is controlled by the geological and

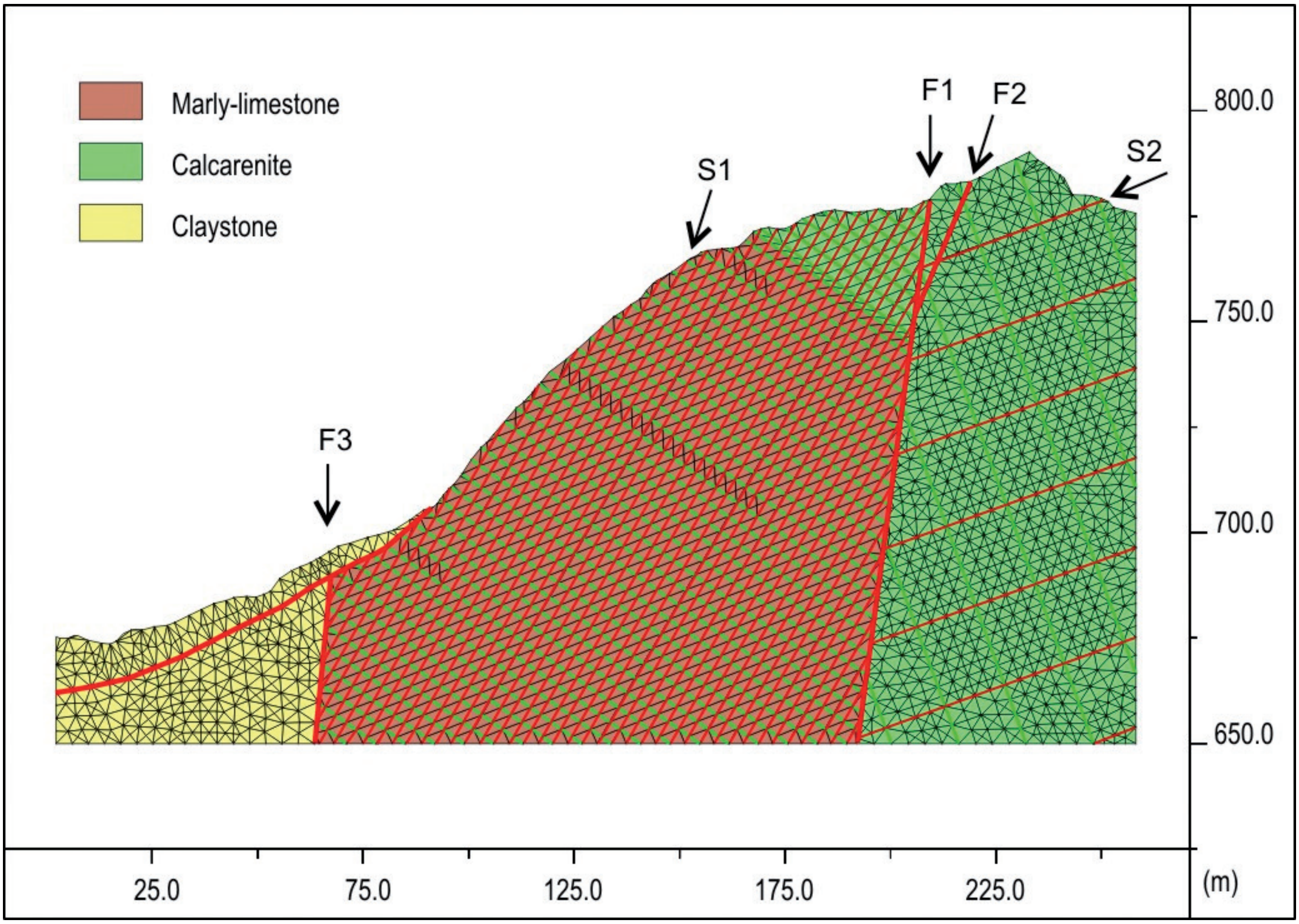

Fig. 11 - Morphometric map of Montebello Landslide Basin (after C*ALISTA et alii, 2016)*

morphostructural setting of the carbonate (*Tufillo Fm.*) and clay chaotic rocks (*Argille varicolori*) outlining an outstanding hog-back ridge. The geomorphologic evolution of the western side of the relief is influenced by rock falls in the upper part of the ridge, due to fractures and jointing in the calcareous strata, while in the lower part it is influenced by the progressive involvement of the clays. The regressive enlargement of the landslide scarp mainly involves the western side of the calcareous ridge with a systems of tension fractures and reverse slopes areas, involving the Buonanotte Village. Minor scarp retreat is also observed along southern portion of the landslide scarp (Montebello sul Sangro village). The presence of some blocks embedded in the landslide body allows to estimate the velocity rates of the near-surface portion of the landslide not less than 1,1 m/day (time interval September 2013-October 2014).

The analysis of rainfall data indicates that important reactivation of the landslide occurred after at least two years with rainfall below average and one year above average (2009 and 2013-2014 event), except for the event of April 1971 (moderate rainfall).

A 2D numerical analysis of a section affected by an active landslide was performed by FLAC computer code. The selected section was particularly important since the related stability could also influence the stability of the nearby village of Montebello sul Sangro (Italy). The analysis was aimed at studying the evolution of the landslide and, in particular, it focused on the retreat of the landslide scarp possibly affecting the village. Indeed, blocking the movement of the current earth-flow, we can observe that the outer area of the scree slope deposits is fully plasticized and the most

	Unit weight γ (kN/m^3)	*Cohesion c' (kPa)*	*Elastic Modulus E (MPa)*	*Friction angle φ' (°)*
Scree slope deposits	17	2	100	40
Landslide deposits	18	5	0.5	20
Clay deposits	20	10	1	45

Tab. 1 - Physical and mechanical properties

	Unit weight γ (kn/m^3)	Elastic Modulus E (GPa)	*a*	*s*	m_b	σ_{ci} (MPa)
Calcarenite	24	10	0.503	0.0013	0.574	85
Marly-limestone	22	0.1	0.508	0.0003	0.39	50

Tab. 2 - Geomechanical parameter used in the analyses

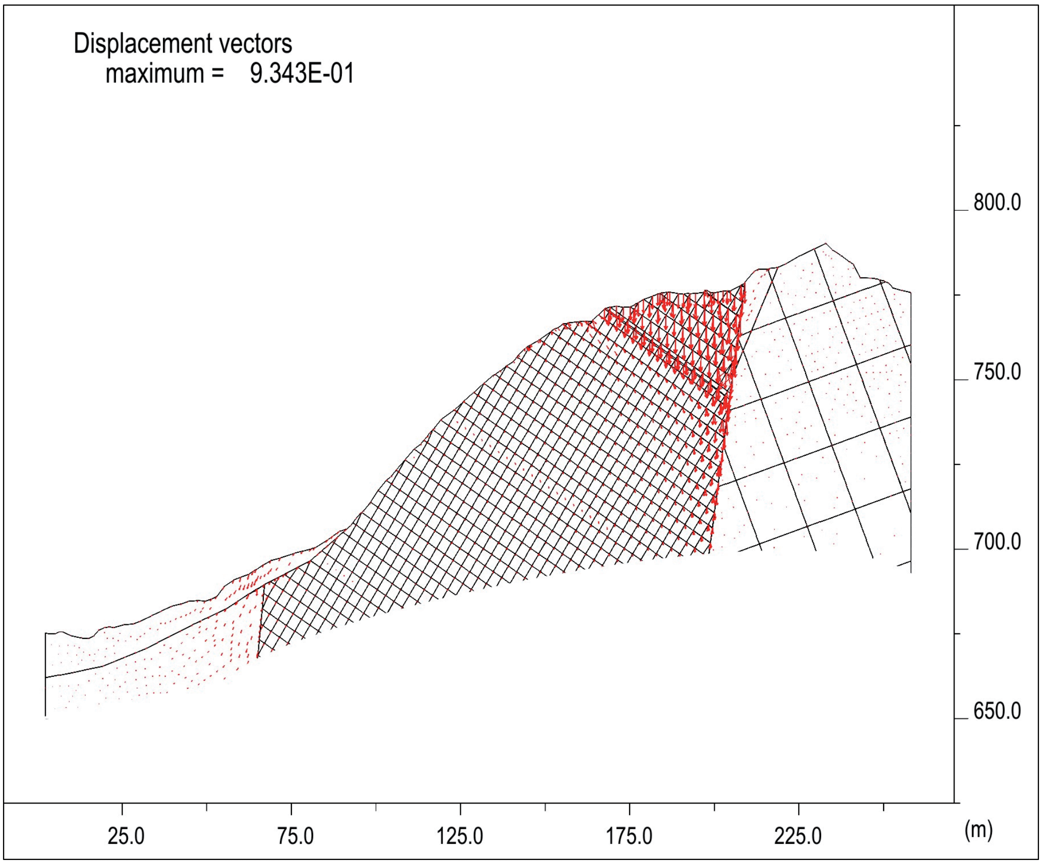

Fig. 12 - Displacements vectors

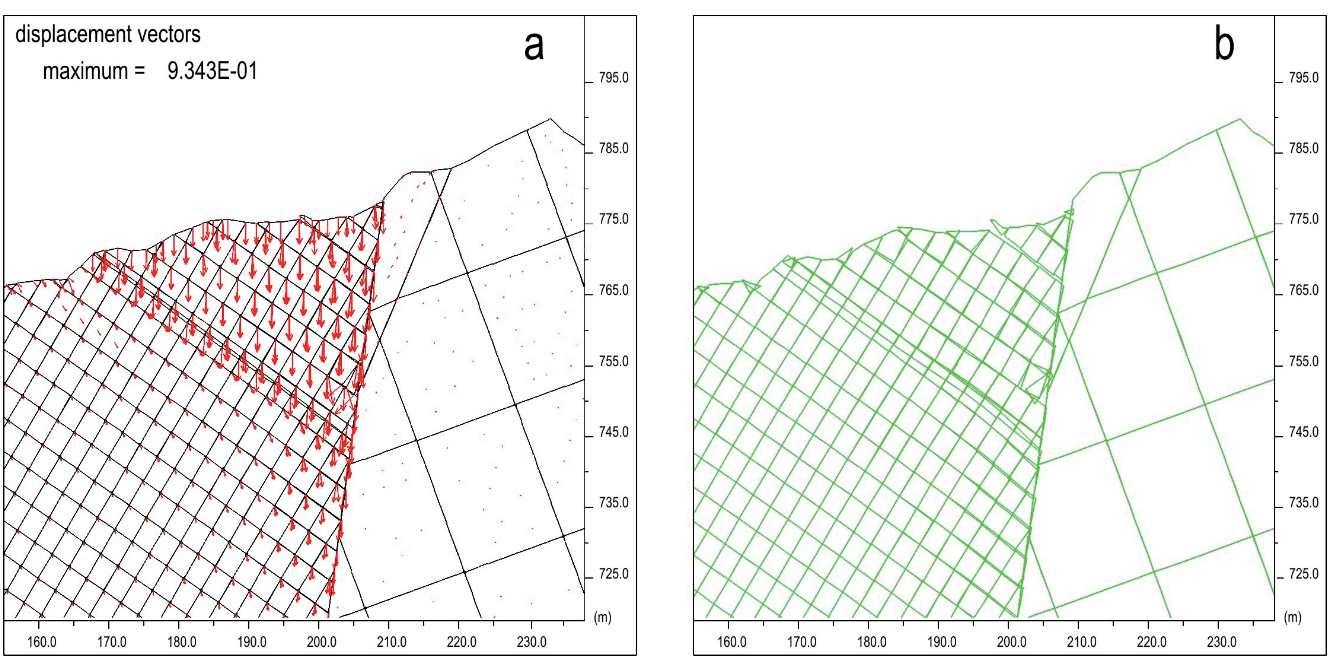

Fig. 13 - Particular of the displacements vectors (a) and the deformed grid (b)

superficial zones are at yield in tension.

The successive analysis carried out by the numerical code UDEC, along a section located in close proximity to Buonanotte village, now deserted, showed that the main displacements are found along the main fault F1 and the activation of an important movements in the lower part of the slope.

Finally, in order to reconstruct possible topographic anomalies of the drainage sub-basin affected by the landslide, the use of ACF was introduced. Even though the results in terms of kindex are sampling method-dependent, the analysis outlines a strong topographic anomaly both in the scarp area of the landslide and in the accumulation area.

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