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INFRARED THERMOGRAPHIC SURVEYS FOR LANDSLIDE MAPPING AND CHARACTERIZATION: THE ROTOLON DSGSD (NORTHERN ITALY) CASE STUDY

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EXTENDED ABSTRACT

Nuovi metodi di mappatura, basati principalmente su tecniche avanzate di telerilevamento, sia da piattaforma satellitare, aerea che terrestre, possono facilitare notevolmente la produzione e l'aggiornamento delle carte geomorfologiche dei fenomeni franosi. In letteratura è stato dimostrato come la combinazione di tali metodologie rappresenti la soluzione ottimale per la mappatura di fenomeni franosi caratterizzati da diverse tipologie di copertura e da una notevole estensione, ottimizzando i tempi del rilievo e garantendo la sicurezza degli operatori (Guzzetti *et alii*, 2012).

La termografia ad infrarosso (InfraRed Thermography: IRT) è una tecnica di telerilevamento capace di mappare la temperatura superficiale, consentendo di localizzare e analizzare anomalie termiche all'interno dello scenario investigato (Spampinato *et alii*, 2011). Nel campo dello studio dei fenomeni franosi le anomalie termiche possono essere legate a potenziali criticità quali: i) discontinuità strutturali (a causa sia degli effetti di raffreddamento/riscaldamento da parte dell'aria circolante, nel caso di fratture aperte, sia a causa della differente capacità e conducibilità termica dei materiali di riempimento rispetto alla roccia intatta, nel caso di fratture chiuse); ii) zone di umidità e di filtrazione (grazie all'effetto di raffreddamento delle superfici causato dall'evaporazione dell'acqua). Ciononostante, a parte pochi studi di carattere sperimentale (Squarzoni *et alii*, 2008; Teza *et alii*, 2012; Baroň *et alii*, 2014; Gigli *et alii*, 2014a, b) nello studio delle frane la IRT ad oggi non trova un ampio utilizzo.

Questo lavoro riguarda lo studio geomorfologico della grande e complessa frana (*sensu* Cruden & Varnes, 1996) del Monte Rotolon, localizzata nell'alta Val d'Agno (Regione Veneto, Provincia di Vicenza), la cui attività ha causato crolli e inondazioni documentate fin dal XVI secolo. Il 4 Novembre 2010, successivamente ad un periodo di intense piogge, è avvenuto il distacco di una massa detritica di circa 225000 m3 dalla porzione più bassa del corpo franoso; tale massa si è incanalata nell'alveo del Torrente Rotolon evolvendosi in un debris flow molto mobile, che si è propagato a valle per circa 3 km mettendo a rischio alcune frazioni abitate (Maltaure, Turcati e Parlati) poste lungo le sponde del torrente. In seguito a tale evento il Dipartimento di Scienze della Terra dell'Università degli Studi di Firenze (DST-UNIFI) su incarico del Dipartimento di Protezione Civile Nazionale (DPCN) ha condotto una campagna di monitoraggio utilizzando un interferometro radar da terra (Ground-based Interferometric Synthetic Aperture Radar: GB-InSAR), allo scopo di analizzare la cinematica del complesso fenomeno franoso (Fidolini *et alii*, 2015). In questo quadro sono stati svolti anche rilievi geomorfologici di campagna e analisi termografiche, allo scopo di ottenere una carta geomorfologica di dettaglio (Frodella *et alii*, 2014a), per poter sia analizzare le caratteristiche fisiografiche della frana che migliorare l'interpretazione dei dati radar.

Le mappe di temperatura superficiale ottenute tramite il rilievo termografico sono state confrontate con una modellazione delle linee di deflusso svolta in ambiente GIS (Morelli *et alii*, 2014), eseguita su DTM dell'area ad alta risoluzione. L'andamento del reticolo di drenaggio dell'area di frana così ottenuto ha mostrato, nei settori analizzati, un buon accordo con il pattern delle anomalie termiche individuate. La presenza di queste ultime, come mostrato dall'analisi dei dati pluviometrici, risulta essere connessa alle precipitazioni piovose, perciò tali anomalie termiche sono state interpretate e segnalate nella carta geomorfologica come "canali effimeri". Queste depressioni lineari create nelle pareti rocciose ad opera dell'erosione concentrata dell'acqua costituiscono potenzialmente aree sorgenti per le colate di materiale tipo "debris flow", e perciò rappresentano settori critici del corpo di frana. Le analisi geomorfologiche hanno suggerito come il debris flow del 4 Novembre 2010 costituisca un fenomeno a rischio elevato, che ha coinvolto materiale detritico di copertura di una frana ampia e complessa. Quest'ultima per: i) estensione (0,63 km^2); ii) caratteristiche morfo-strutturali (presenza di trincee in roccia, scarpate in contropendenza, fratture sub-orizzontali al piede del versante); iii) presenza di fenomeni franosi accessori; iv) cinematica (lento dislocamento di intere porzioni di ammasso roccioso compatto) (Agliardi *et alii*, 2009), presenta le caratteristiche di una DGPV di tipo "Sackung" (*sensu* Zischinsky, 1969).

Nel quadro dello studio della DGPV del Monte Rotolon, la IRT ha dimostrato di essere una tecnica ancillare versatile e a basso costo, assai utile per la mappatura e la caratterizzazione dei fenomeni franosi se integrata ai rilievi geomorfologici tradizionali, in particolar modo in settori inaccessibili e ad alto rischio per gli operatori. La carta geomorfologica di dettaglio ottenuta ha fornito a tutti gli enti coinvolti nella gestione dell'emergenza importanti informazioni ai fini della comprensione delle caratteristiche morfologiche, della cinematica, dell'estensione e tipologia dei processi agenti all'interno del fenomeno franoso analizzato.

ABSTRACT

On November 4th 2010, after several days of intense rainfall, a huge mass (about 225000 m^3) detached from the debris cover of the Rotolon landslide, converging within the Rotolon Creek river bed, and evolving into a mobile debris flow that damaged various infrastructures, putting on high risk three villages located along the creek banks. After this event the National Department of Civil Protection (DPCN) appointed the Earth Sciences Department of the Firenze University (DST-UNIFI) to start a GB-InSAR (ground based interferometric synthetic aperture radar) monitoring activity, in order to support the local authorities for the emergency management by analyzing the landslide displacements and evaluating the residual risk. During this phase accurate geomorphological and infrared thermographic (IRT) surveys were also carried out, in order to study the landslide morphological features, with the aim of improving the radar displacement data interpretation. The obtained geomorphological map suggests that the debris production and detachment are hazardous phenomena that involve the surficial detrital cover of a bigger and more complex landslide. The latter has the characteristics of a deep seated gravitational slope deformation (DSGDS).

KEYWORDS: landslide, debris flow, DSGSD, thermographic survey,geomorphological survey

INTRODUCTION

Deep-seated gravitational slope deformations (DSGSD) are gravity-induced processes affecting large portions of slopes evolving over very long periods of time (CROSTA, 1996). DSGSDs are normally not considered hazardous phenomena because their evolution is typically very slow, nevertheless under certain conditions, ground movements can accelerate evolving into faster mass movements or favor collateral landslide processes (CROSTA & AGLIARDI, 2003). DSGSDs can be triggered by different and potentially coexisting mechanisms (AGLIARDI *et alii*, 2009); according to this, a multidisciplinary approach is fundamental in order to understand the complex nature of such phenomena, with the aim of assessing the correct mitigation procedures. New and emerging mapping methods, based chiefly on satellite, aerial and terrestrial remote sensing technologies, can greatly facilitate the production and the update of landslide maps. Review of the literature has shown that a combination of satellite, aerial and terrestrial remote sensing data represents the optimal solution for landslide detection and mapping, in different physiographic, climatic and land cover conditions (GUZZETTI *et alii*, 2012). Infrared thermography (IRT) is a remote sensing technique capable of mapping the surface temperature pattern evolution, leading to the detection of thermal anomalies within the investigated object (SPAMPINATO *et alii*, 2011). In the field of landslide studies, apart from a few interesting experimental works (SQUARZONI *et alii*, 2008; TEZA *et alii*, 2012; GIGLI *et alii*, 2014a, b; BAROŇ *et alii*, 2014), IRT is still not widely applied. Nevertheless in the field of landslide thermal anomalies can reveal the presence of potential criticalities such as: i) structural discontinuities (due to the cooling/heating effect of air circulating within open fractures; different thermal transfer capacity of the infilling material with respect to the exposed sound rock); ii) moisture or a seepage zones (due to the surface cooling caused by water evaporation) (FRODELLA *et alii*, 2014b).

This paper deals with a large complex landslide (the Rotolon DSGSD), located in the uppermost Agno River valley (Veneto region, north-eastern Italy) (Fig. 1).

The 4th of November 2010 a debris mass of about 225000 m^3 detached from the lowermost part of the landslide and channelized into the Rotolon Creek riverbed, mixing with water and evolving into a mobile debris flow, which put on high risk the population of three villages placed along the creek banks (Maltaure, Turcati, Parlati) (Fig. 1a). Following this event the DST-UNIFI, on behalf of the National DPC, started a long term GB-InSAR monitoring campaign in order to analyze the Rotolon DSGSD kinematics (FIDOLINI *et alii*, 2014). In this framework accurate geomorfological field surveys and thermographic analysis were also carried out to analyze the landslide geomorphological features and improve the interpretation of radar-derived data (FRODELLA *et alii*, 2014a).

STUDY AREA

The Rotolon DSGDS affects the southeastern flank of the Little Dolomites chain, located within the Vicentine Prealps (Fig. 1a). Damages due to failures and flooding connected with the DSGSD activity are reported since the 16th century. The landslide develops in the Upper Agno Valley and involves the uppermost portion of a sub-horizontally bedded, mainly dolomitic succession, from middle Triassic to lower Giurassic in age (DE ZANCHE & MIETTO, 1981). The debris cover is characterized by boulders with scattered blocks in a coarse sandy matrix (Fig. 1b).

The Rotolon DSGDS is characterized by a complex activity (CRUDEN & VARNES, 1996) that leads to a very irregular physiography. The whole area can be mainly subdivided in two distinct portions basing on the acting dominant slope instability processes: i) an upper "Detachment sector", followed immediately downstream by a ii) "Dismantling sector" (Fig. 1) (FRODELLA *et alii*, 2014a). The Dismantling sector has a mean slope of 34°, but includes sectors formed by sub-vertical highly weathered rock walls. This sector is characterized by a compressional stress field resulting in a toe bulging, with common against-dip fractures in its uppermost part. Nonetheless this area is apparently dominated by surficial processes, such as soil erosion, slope waste deposition and detrital cover failures, that widely cover the evidences of deeper deformations. The Dismantling sector supplies material for debris flows, which channelize downstream within the Rotolon Creek bed, therefore representing the most critical sector with respect to short-term hazardous phenomena.

INFRARED THERMOGRAPHIC SURVEYS

Theoretical background

IRT is a type of infrared imaging accomplished with calibrated infrared thermal cameras operating in the bandwidth 3 µm < λ < 14 µm, allowing the detection of thermal radiation differences on a surface object (Maldague, 2001; Laguela *et alii*, 2011). The relation between IR radiation and an object's temperature is stated by the Stefan-Bolzmann's Law:

$$W = \varepsilon \sigma T4$$

where W is the total radiant exitance from the material surface, expressed in Watt m^{-2}; ε is the object emissivity; σ is the Stephan Boltzmann constant = 5.6697×10^{-8} Wm^{-2} K^{-4}; T is the absolute temperature expressed in K of the emitting material.

This law states that the radiant power per area unit of a body depends both on its emissivity (the spectral quantity characterizing the object surface, defined as a factor that describes its efficiency in radiating energy compared to a black body; Incropera & De Witt, 1985), and on the fourth power of the absolute temperature. The Stefan-Bolzmann's Law represents the basis for radiative heat loss estimates, and constitutes the theoretical basis for infrared thermography.

The product of a thermographic survey is a pixel matrix (thermogram) collected through the thermal camera array detector, which after the correction of the sensitive parameters (object emissivity, pathlength, air temperature and humidity) represents a radiant temperature map of the investigated object. An IRT survey provides the mapping of radiant temperature, which is a function of heat flow crossing the analysed

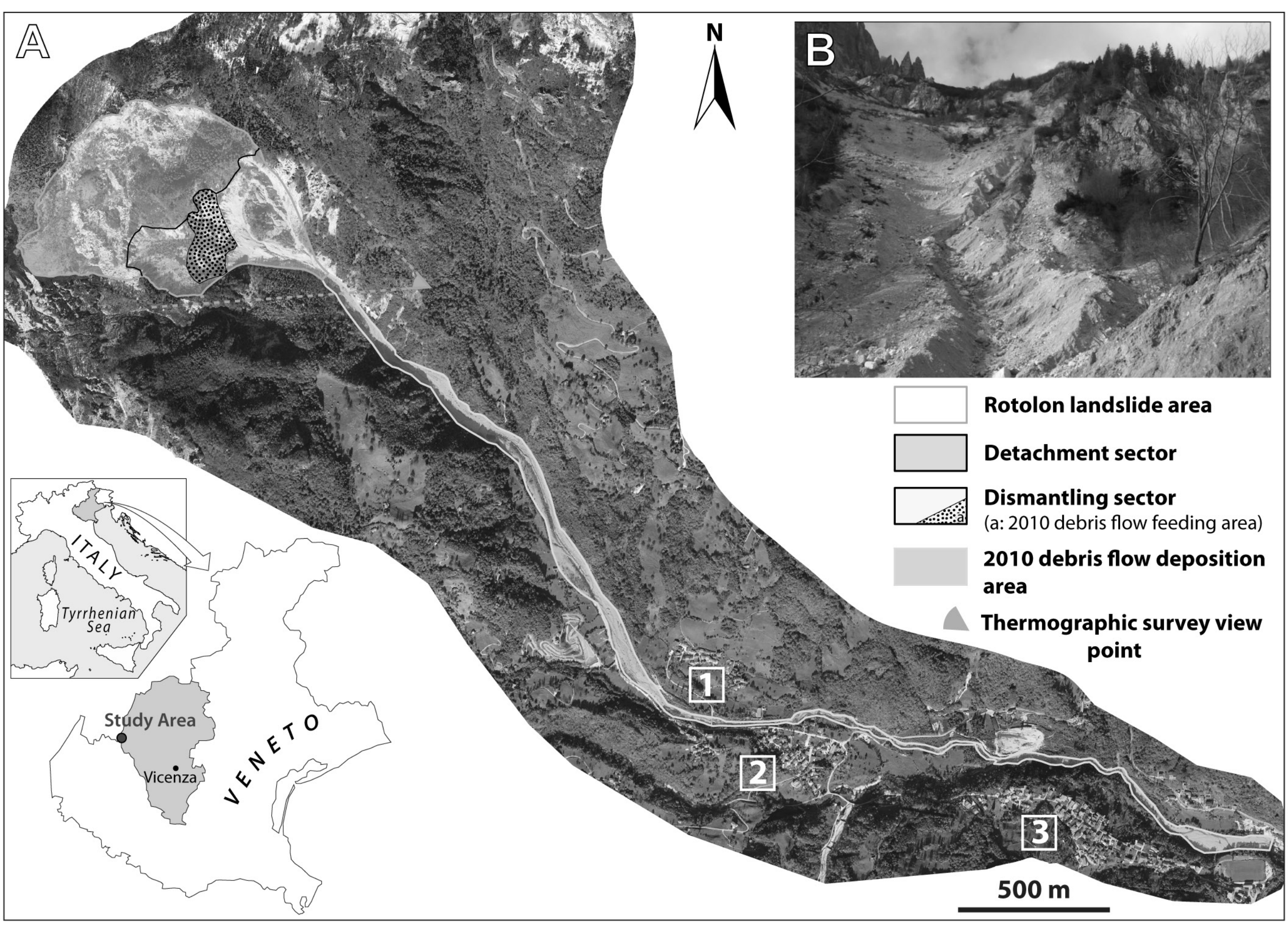

Fig. 1 - (A) location of the Rotolon DSGSD and its sectors within the Upper Agno Valley. The three villages threatened by the 2010 debris flow are also shown (1=Maltaure; 2=Turcati; 3=Parlati); (B) bottom view of the landslide "Dismantling sector"

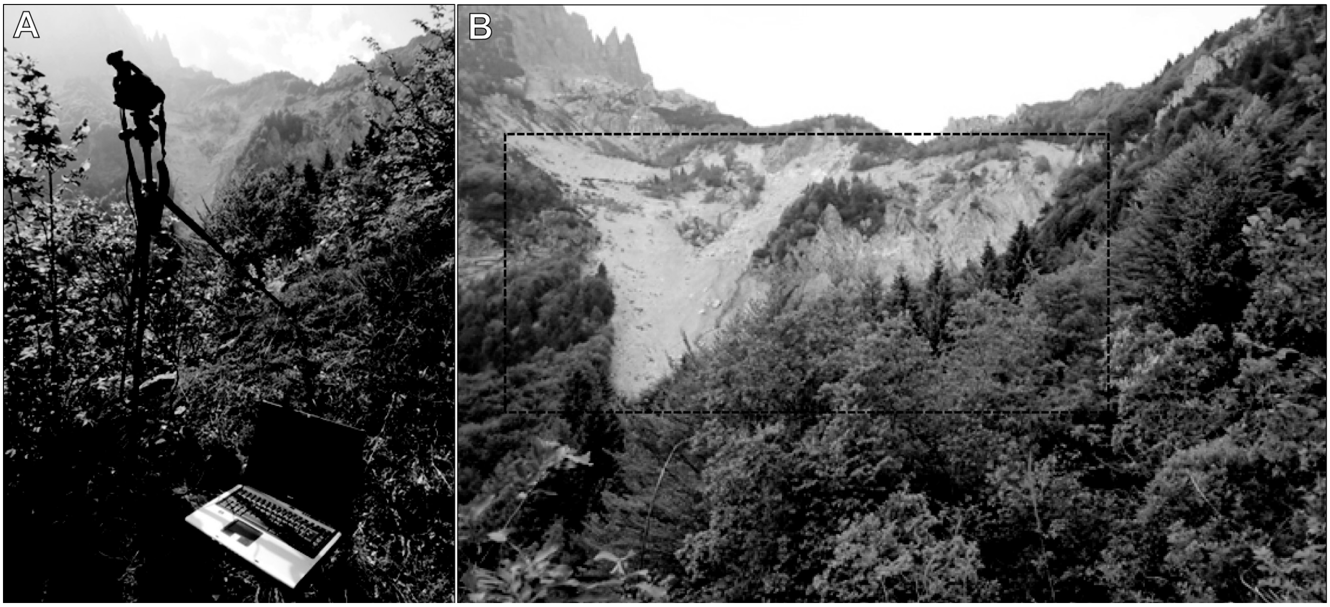

Fig. 2 - (A) FLIR SC620 tripod mounted thermal camera; (B) the Rotolon DSGSD dismantling sector (dashed square enhances the surveyed scenario)

surface and local boundary conditions. The presence of any inhomogeneity within the surface (i.e. cracks and fractures, moisture and seepage zones, subsurface voids), will influence the material thermal parameters (density, thermal capacity and conductivity), modifying its heat transfer; therefore the inhomogeneity will be displayed in the analysed scenario radiant temperature map as a "thermal anomaly" (an irregular thermal pattern with respect than the surroundings).

Thermographic survey methodology

Terrestrial multi-temporal thermographic surveys, characterized by a series of thermal images acquired at different daily and seasonal conditions, were carried out within May an October 2012, using a FLIR SC620 tripod-mounted thermal camera (FLIR, 2009a; Fig. 2a). This instrument is characterized by a focal plane array microbolometer sensor with a 640-by-480 pixel matrix, which is able to measure electromagnetic radiation in the thermal infrared band between 7.5 and 13 µm (Long Wavelenght IR band), with a thermal accuracy of ± 2°C and a 0.65-mrad angular resolution (see Tab. 1 for further technical specifications).

Multitemporal thermographic surveys were carried in order to map and characterize geomorphological features of a critical and inaccessible sector of the Rotolon DSGSD ("Dismantling Sector") (Fig. 1b, Fig. 2b). The thermal camera acquisition point was set at a 900 m distance from the "Dismantling sector", leading to a 60 cm spatial resolution (Fig. 2). A built-in 3.2 Mpixel digital camera allowed the comparison between IR and photos taken in the visible range in order to improve the acquired thermograms interpretation.

Thermograms correction, thermal focusing and analysis were performed by means of FLIR ResearchIR software (FLIR, 2009b). In order to picture the whole analysed landslide sector, which scenario is wider than the camera field of view (FOV), adjacent thermograms (having at least a 50% of image overlapping) were mosaicked by means of FLIR systems Reporter 9 Professional (FLIR, 2012) software. The obtained radiant temperature maps are represented by means of a color scale, in which the higher surface temperatures are displayed by the lighter colors, whereas the colder temperatures by the darker ones (Fig. 3). The obtained surface temperature maps enhanced cold thermal anomalies, in correspondence of the detrital cover (affected by the 2010 debris flow detachment) and of the adjacent sub-vertical weathered rock walls, during the surveys of May (Fig. 3a) and October (Fig. 3e) 2012. These cold thermal anomalies, probably connected to moisture zones, were not detected during the survey of September 2012 (Fig. 3c), and were not visible in the correspondent scenario optical images (Fig. 3b, f).

Feature	Unit	value
Detector size	Pixel	640 x 480
Spectral range	µm	[7.5, 13]
Temperature range	C°	[-40, + 500]
Thermal accuracy	C°	± 2
Thermal sensitivity	mK	40
Field of view (F.O.V.)	Deg.	24 x 18
Spatial resolution	mrad	0.65
Minimum focus distance	m	0.3

Tab. 1 - FLIR SC620 thermal camera main technical specifications

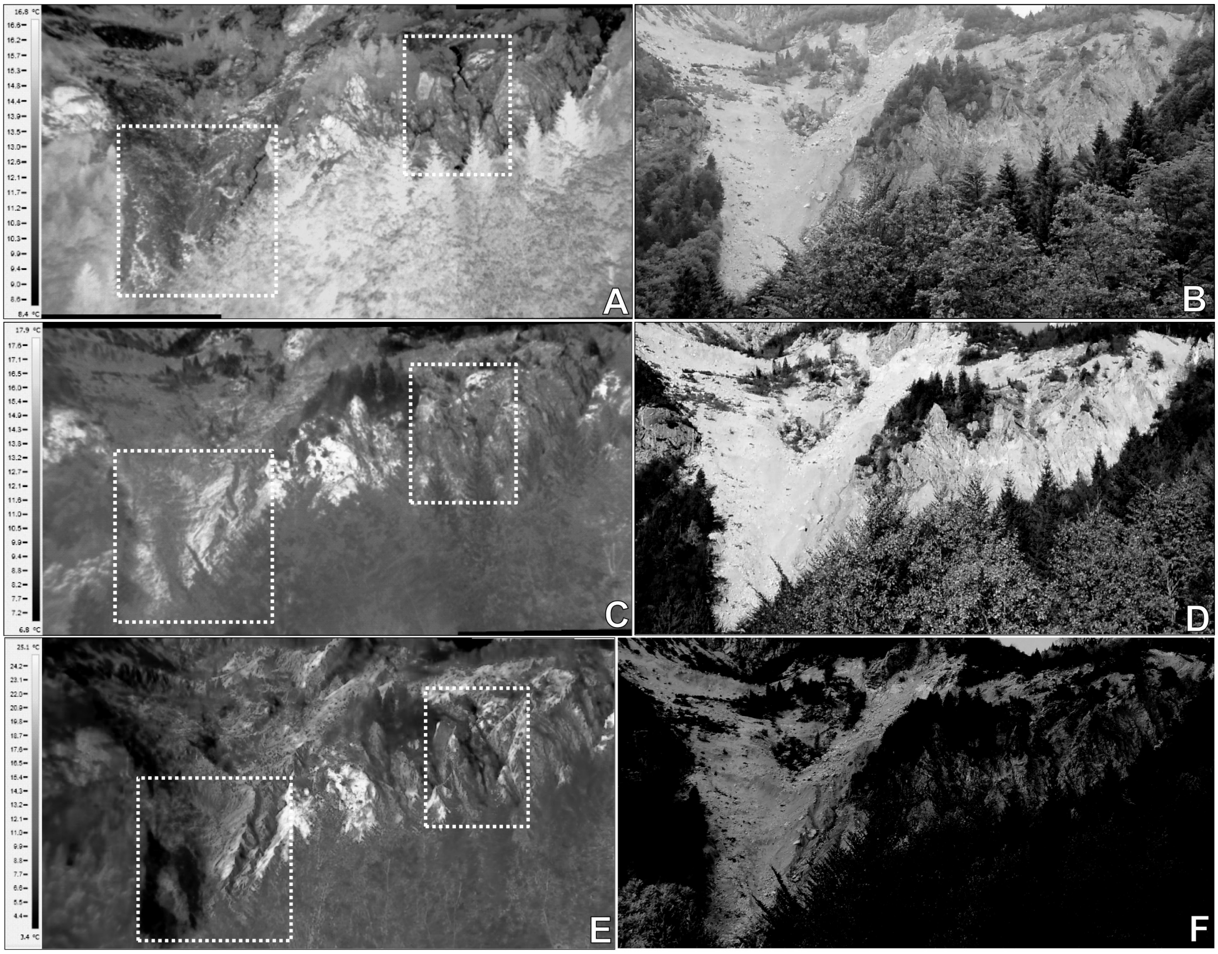

Fig. 3 - Mosaicked thermograms (A-C-E) of the Rotolon DSGDS "Dismantling sector" and correspondent optical images (B-D-F), collected during the surveys of May 31st 2012 (A-B), September 21st (C-D) and October 10th 2012 (E-F); dashed squares locate the sectors were the cold thermal anomalies were detected

DISCUSSION AND CONCLUSIONS

A flow direction modeling was performed in a GIS environment (Morelli *et alii*, 2014) on the landslide post event high resolution aerial Lidar DTM (Fig. 4). The resulting drainage network pattern shows a good accordance with the detected cold thermal anomalies in correspondence of the analysed sector.

Daily cumulative rainfall values (Fig. 5) confirmed that the presence of the cold thermal anomalies was connected to the seasonal precipitation (May 31st and October 10th 2012 surveys were performed during rainy periods, whereas the survey of September 21st 2012 followed a dry summer period), which caused water circulation and moisture zones within the debris cover and on the weathered rock wall surface; therefore the detected thermal anomalies were interpreted as ephemeral creeks. These linear depressions created by concentrated water erosion represent critical sectors of the DSGSD, being potential source areas for debris flows, and were mapped as "channels"

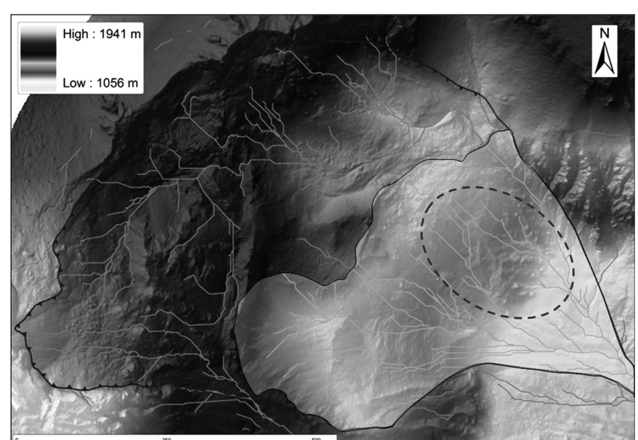

Fig. 4 - Rotolon DSGSD upper sector (light area enhances the Dismantling Sector);light lines represent the modelled drainage pattern. Dashed oval enhances the landslide drainage pattern in correspondence of the detected cold thermal anomalies

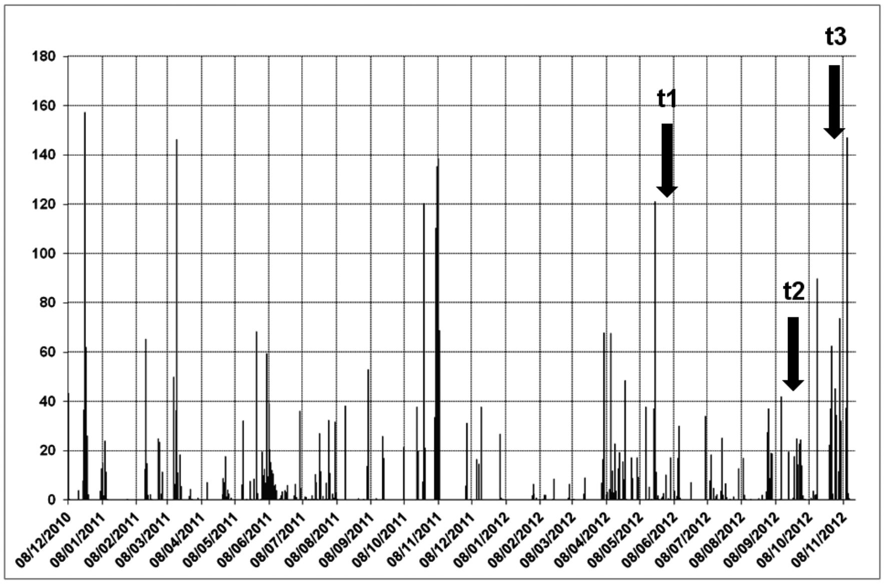

Fig. 5 - Daily cumulative rainfall histogram; arrows enhance the thermographic surveys dates (t1: May 31st; t2: September 21st; t3: October 10th, 2012).

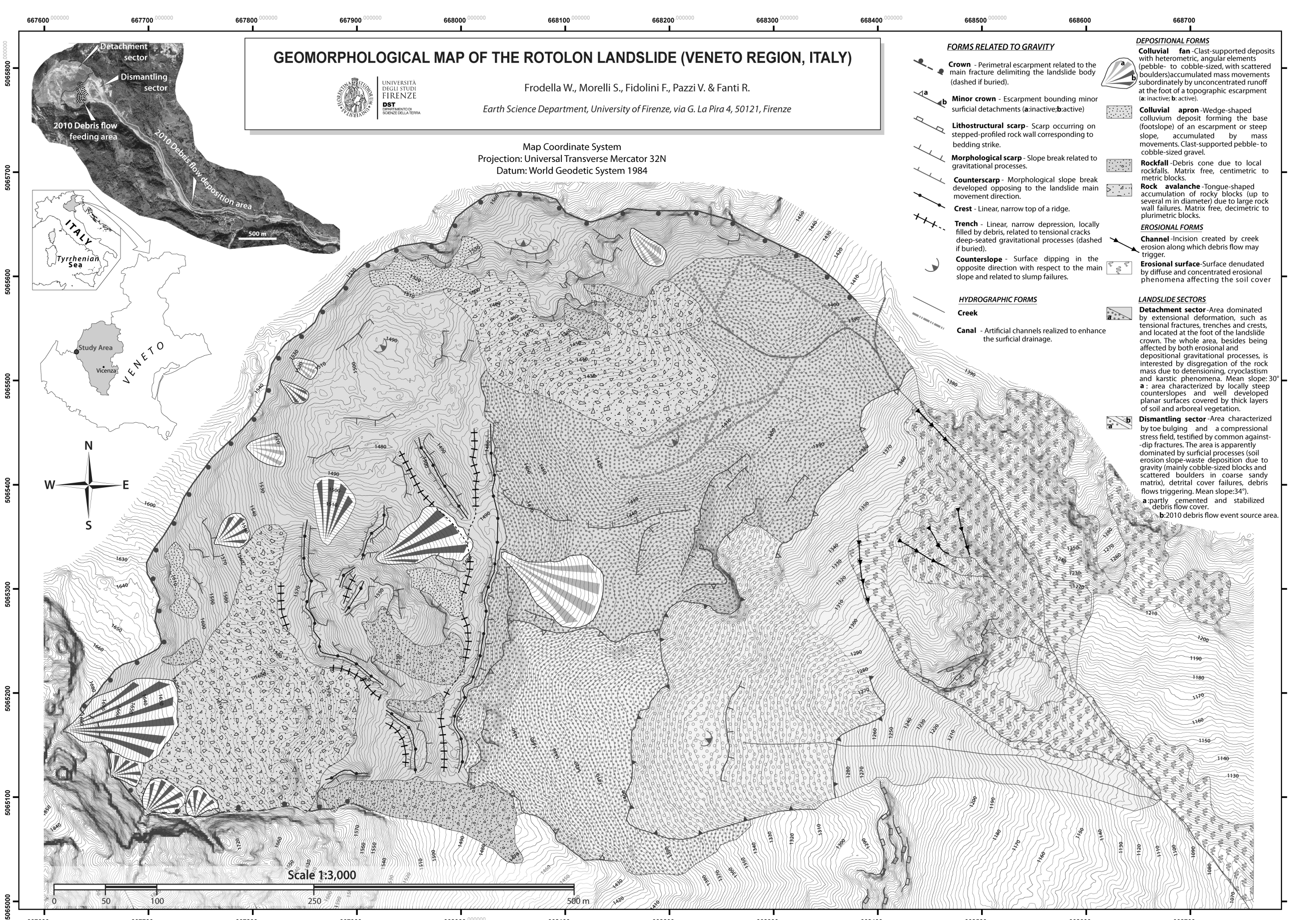

Fig. 6 - Geomorphological map of the Rotolon Landslide (modified after Frodella et alii, 2014a). Dashed square enhances the analysed "Dismantling sector"

in the resulting accurate Rotolon landslide geomorphological map (Frodella *et alii*, 2014a) (Fig. 6; Fig. 7). This product was fundamental for detecting the areal extent of the various processes acting on the landslide surface and, thus, to understand the kinematic mechanisms involving the whole rock and debris mass. It also allowed to distinguishing between dominant/secondary phenomena and long-term/short-term hazardous phenomena. In the study area secondary processes (like debris flows) appear to be the most dangerous from a short-term perspective. The geomorphological features, supported by the radar data, led to an interpretation of the complex Rotolon landslide as a DSGDS, which detrital cover can be affected by detachments and trigger debris flows.

In conclusion, according to geomorphological and radar data, the Rotolon landslide appears to be characterized by long-term deep seated processes, above which a wide spectrum of short-term secondary phenomena (minor slope failures, rock falls, rock avalanches, debris accumulation and debris flow triggering) were recognized. Presently debris flows represent the most hazardous phenomena for the inhabited areas located along the Rotolon Creek valley. In this framework IRT proved to be a very useful novel method for integrating traditional field surveys in mapping geomorphological features, especially in hazardous and inaccessible landslide sectors. Accurate mapping provides important information for local administrations and decision makers, allowing them to prepare landslide susceptibility and hazard models.

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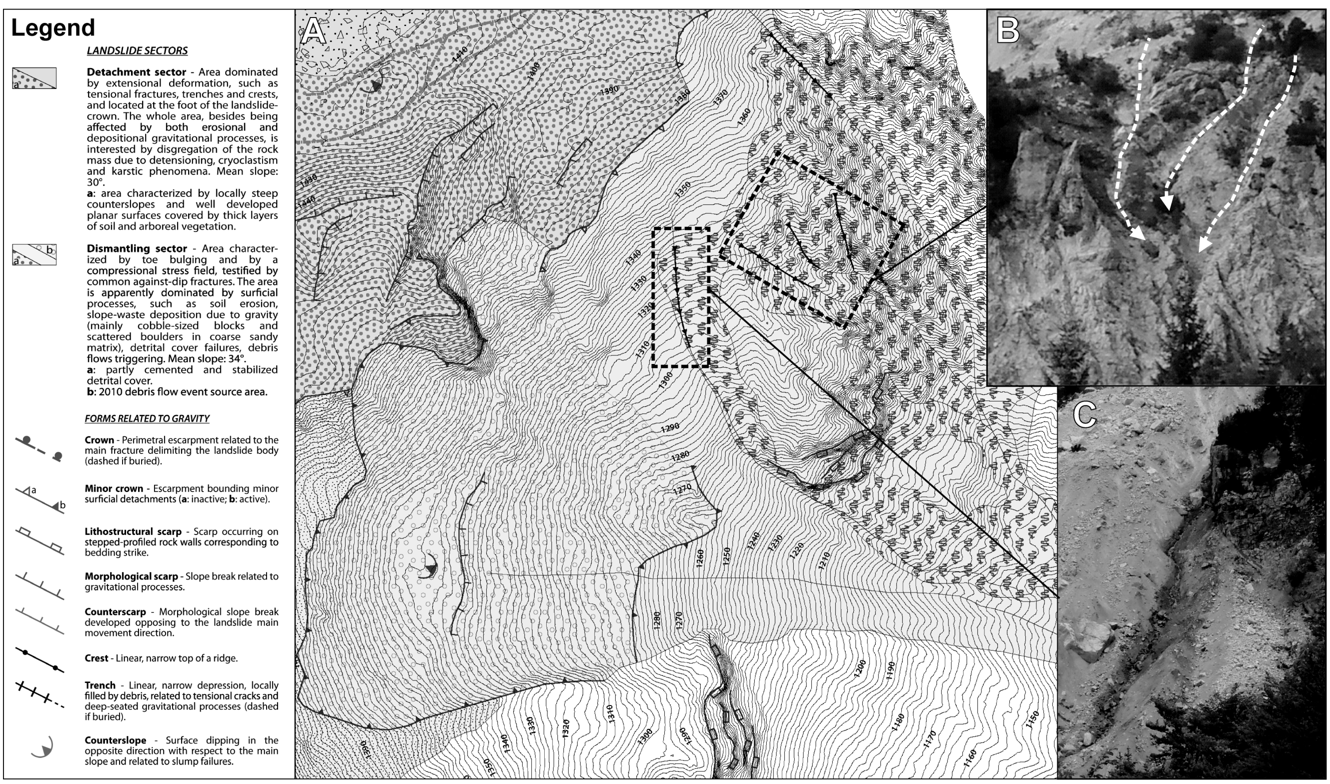

Fig. 7 - (A) Detail of the "Dismantling sector" from the Geomorphological map of the Rotolon Landslide (modified after Frodella *et alii, 2014a); (B, C) pictures of the "channels", representing potential debris flow source areas*

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