Dear Editor,

We would like to thank you for your encouraging comments. We are sure that the manuscript will greatly benefit from your suggestions. All the reviewers' suggestions and comments have been taken into consideration, and modified version of the manuscript were already uploaded. Hereafter the list of Your comments is reported, followed by our response. We will also provide a version of the manuscript with the tracked revisions of Your comments, while the referees' ones are embedded in the text.

Editor: In section 4, the adopted monitoring system, the time line rationale of the Rotolon monitoring system and emergency management procedures is depicted in figure 6, but without any description in the text. To improve this section could be useful to move the text of lines 281-286 in section 4.

Moreover, a better description of the functioning of the early warning system and how the GB-InSAR is employed in it, is needed.

Authors: *The shift of suggested lines has been made and more information are now in the manuscript. Moreover, the Figure 6 has been improved.*

Editor: Then, the name of section 4 could be changed into The GB-InSAR monitoring strategy in the Rotolon early warning system.

Authors: *The title of section 4 has been changed following the suggestion.*

Editor: A description about how the thresholds for the 3 levels of warning (line 284) have been defined and which type of actions to undertake in each level of warning will be considerably improve the paper.

Authors: *We add a sentence to explain how the thresholds were defined and the action to undertake in each level of warning.*

Editor: The Discussion should be improved describing the role of the GB-InSAR in the decisional process of the Rotolon monitoring system and emergency management procedures. In particular, how the GB-InSAR monitoring influences the decision of issuing an alert? Reading lines 288-291 seems the 4 monitoring alerts issued were false alerts, because "Inspections carried out by the optical monitoring device and by means of field surveys from safe viewing points, assessed that detected accelerations did not generate significant slope failures". Following these considerations it seems the GB-InSAR needed to be used coupled with other monitoring strategies in order to avoid false alerts. Please discuss.

Authors: *The role of the GB-InSAR was better specified in section 4 (The GB-InSAR monitoring strategy in the Rotolon early warning system) and 6 (Discussion). With these explanations, we have also clarified the problem of "alerts" and the necessity of coupling with other instruments.*

Specific comments

Editor: Line 126. Please specify the full name for LOS. The first time you use an acronym the full name is needed.

Line 137. Please change "parallel to the line of sight (L.O.S.)", with "parallel to LOS". The full name of the acronym LOS has been specified in line 126.

Authors: *The necessary adjustments have been made.*

Editor: Line 282. Is Figure 5 or 6?

Authors: In this line, we are referring to figures 5 and 7. Therefore, the text is right.

Editor: Lines 288-289 outline the issuing of 4 monitoring alerts. What the authors mean for monitoring alert? Does it means the threshold exceedance of 5mm/h, i.e. alarm level? Please, explain.

Authors: *The sentence has been better specified, indicating also the alert class according to the thresholds considered*

GB-InSAR monitoring of slope deformations in a mountainous area affected by debris flow events

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Abstract

Diffuse and severe slope instabilities affected the whole Veneto region (Northeast Italy) between October 31st and November 2nd 2010, following a period of heavy and persistent rainfall. In this context on November 4th 2010 a large detrital mass detached from the cover of the Mt. Rotolon deep seated gravitational slope deformation (DSGSD), located in the upper Agno River Valley, channelizing within the Rotolon Creek riverbed and evolving into a highly mobile debris flow. The latter phenomena damaged many hydraulic works, also threatening bridges, local roads, together with the residents of the Maltaure, Turcati and Parlati villages located along the creek banks and the Recoaro Terme town. From the beginning of the emergency phase, the Civil Protection system was activated, involving the National Civil Protection Department, Veneto Region and local administrations' personnel and technicians, as well as scientific institutions. On December 8th 2010 a local scale monitoring system, based on a ground based interferometric synthetic aperture radar (GB-InSAR), was implemented in order to evaluate the slope deformation pattern evolution in correspondence of the debris flow detachment sector, with the final aim of assessing the landslide residual risk and manage the emergency phase. This paper describes the results of a two years GB-InSAR monitoring campaign (December 2010 - December 2012), its application for monitoring, mapping, and emergency management activities, in order to provide a rapid and easy communication of the results to the involved technicians and civil protection personnel, for a better understanding of the landslide phenomena and the decision-making process in a critical landslide scenario.

1 Introduction

Deep seated gravitational slope deformations (DSGSD) are normally not considered hazardous phenomena, due to their typically very slow evolution; nevertheless, under certain conditions ground movements can accelerate evolving into faster mass movements, which may favour collateral landslide processes (Crosta, 1996; Crosta and Agliardi, 2003). Therefore, a multidisciplinary approach is fundamental in order to understand the complex nature of such phenomena, so as to assess the correct mitigation measures. In this framework advanced mapping methods, based on spaceborne, aerial and terrestrial remote sensing platforms, represent the optimal solution for landslide detection, monitoring and mapping in various physiographic and land cover conditions, particularly with large phenomena and hazardous non accessible sectors (Casagli, 2017b; Guzzetti et al., 2012). In recent decades, many advanced remote sensing technologies have gained widespread recognition as efficient remote surveying techniques for the characterization and monitoring of landslide-affected areas, in terms of resolution, accuracy, data visualization, management, and reproducibility. Among these are: digital photogrammetry (Chandler, 1999; Zhang et al., 2004), laser scanning (Abellan et al., 2006; Gigli et al., 2012, 2014c; Jaboyedoff et al., 2012; Tapete et al., 2012), Infrared Thermography (Teza et al., 2012; Gigli et al. 2014a, b; Frodella et al., 2015) and radar interferometry, both terrestrial and satellite (Luzi et al., 2004;

Casu et al., 2006; Bardi et al., 2014; Tofani et al., 2014; Ciampalini et al., 2016; Gullà et al., 2017; Nicodemo et al., 2016; Peduto et al., 2017a,b).

Ground based interferometric synthetic aperture radar (GB-InSAR) systems in particular, for their ability to measure displacements with high geometric accuracy, temporal sampling frequency, and adaptability to specific applications (Monserrat et al., 2014), represent powerful devices successfully employed in: a) engineering and geological applications for detecting structural deformation, and surface ground displacements (Tarchi et al., 1997; 2003; Antonello et al., 2004; Casagli et al., 2010; 2017a, b) for the monitoring of volcanic activity (Nolesini et al., 2013; Di Traglia et al., 2014a, b, c) for analysing the stability of historical towns built on isolated hilltops (Luzi et al., 2004; Frodella et al., 2016; Nolesini et al., 2016). Furthermore, in recent years GB-InSAR technique has developed to an extent where it can significantly contribute to the management of major technical and environmental disasters (Del Ventisette et al., 2011; Broussolle et al., 2014; Lombardi et al., 2017; Bardi et al., 2017a, b). Between October 31st 2010 and November 2nd 2010 the whole Veneto region territory (north-eastern Italy; Fig. 1) was hit by heavy and persistent rainfall, that triggered widespread flooding and abundant slope failures, causing extensive damage to people (3 fatalities and about 3500 evacuated people) and structures., not to mention heavy economic losses in agricultural, livestock, and industrial activities.

In this context on November 4th 2010, part of detrital cover of the Rotolon DSGSD suffered the detachment of a mass approximately 320000 m^3 in volume, which channelized in the Rotolon Creek bed causing a large debris flow. This phenomenon was characterized by more than three kilometres of run-out, damaging various hydraulic works (creek dams, weirs, bank protections), and threatening various structures (bridges, local roads, houses) together with those residing in the villages of Maltaure, Turcati, Parlati and the town of Recoaro Terme; Fig. 1).

On December 8th 2010 a GB-InSAR monitoring system was implemented in order to assess the landslide residual displacements and support the local authorities in the emergency management (Fidolini et al., 2015), calling into play both the national (DPC) and regional (DPCR) civil protection departments, in cooperation with scientific institutions (namely “competence centres”, CdCs), local administration personnel and technicians (Bertolaso et al., 2009; Pagliara et al., 2014; Ciampalini et al., 2015). Accurate geomorphological field surveys were also carried out in this phase, in order to analyse the landslide morphological features and improve the radar data interpretation (Frodella et al., 2014; 2015; 2017). In addition, a 3D landslide runout numerical model was performed to identify the source and impact areas of potential debris flow events, flow velocity and deposit distribution within the Rotolon creek valley (Salvatici et al., 2017).

This work is focused on the results of a long-term continuous GB-InSAR monitoring campaign (December 2010 - December 2012) carried out during the post-event recovery phase, in which monitoring, mapping, and emergency management activities were implemented to assess the landslide residual risk and analyse its kinematics. In this context field activities were carried out by local Civil Protection operators and technicians for a validation of the remotely sensed data (landslide area inspections). In particular, the analysed radar data were shared with the technicians and civil protection personnel involved in order to provide a rapid and easy communication of the results, and enhance the synergy of all the subjects involved in the recovery phase.

2. Study area

The Rotolon DSGSD is located in the Vicentine Prealps, on the south-eastern flank of the Little Dolomites chain, in the uppermost Agno river valley (Fig. 1). The instability processes of the area, such as slope failures and debris flows induced as secondary phenomena of the DSGSD, have threatened the upper Agno valley for centuries (Frodella et al., 2014). From a geological point of view, the landslide develops in the uppermost portion of a mainly dolomitic-limestone stratigraphic succession, sub-horizontally bedded from middle Triassic to lower Jurassic in age, belonging to the South Alpine Domain (De Zanche and Mietto, 1981).

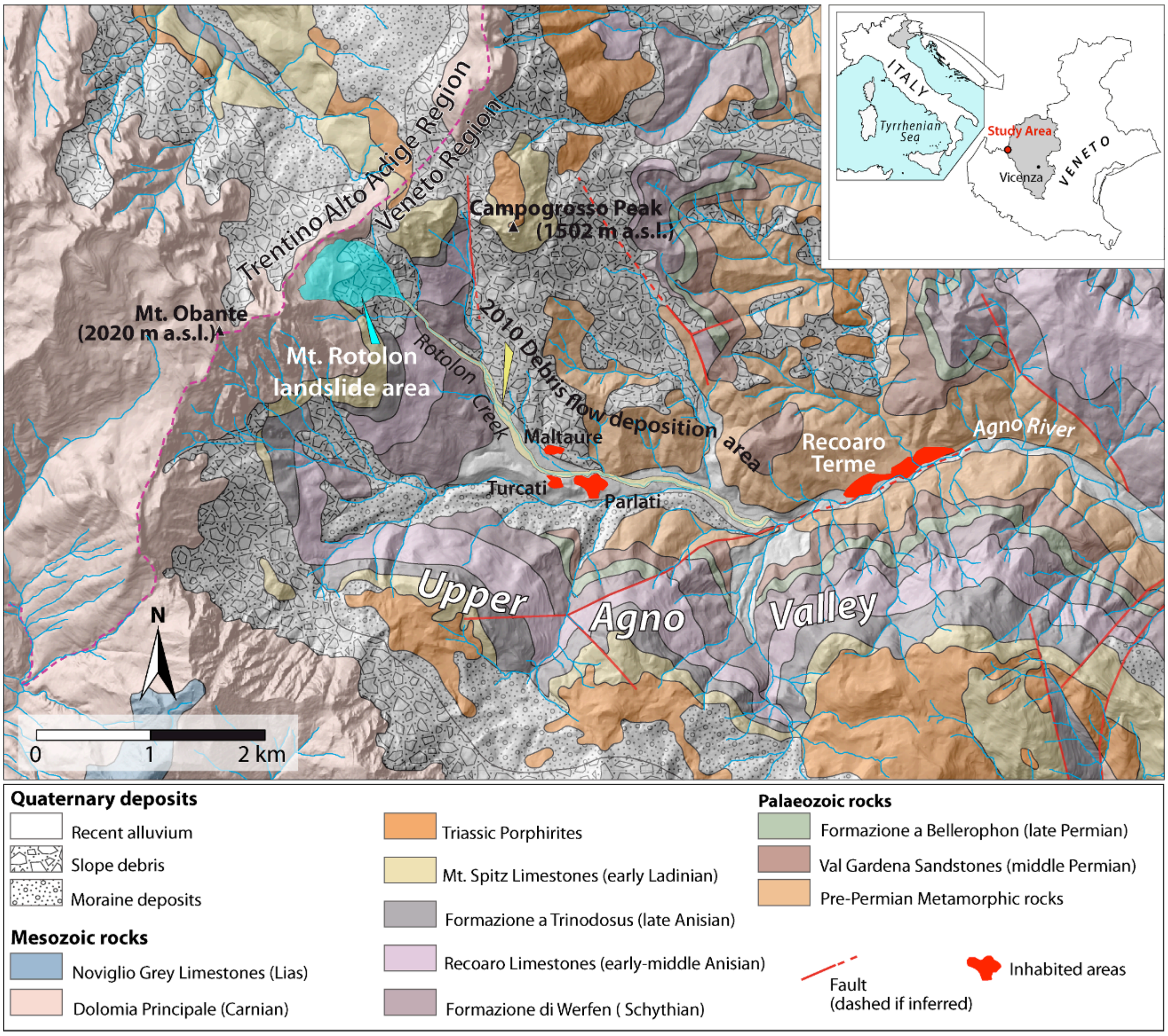

Figure 1. Geological sketch map of the Upper Agno River Valley with the location of the Rotolon landslide.

The mass movement is delimited to the NW by the ridge of the Mount Obante group and develops from about 1700 to 1100 m a.s.l., covering an area of 448000 m^2. The Rotolon DSGSD can be classified as a DSGSD ("sackung type"; Zischinsky, 1969), and characterized by a complex activity (Cruden and Varnes, 1996) causing a rough morphologywith steep scarps, trenches, crests and counterscarps (Figs. 2 and 3).

Two distinct sectors can be identified, based on the dominant slope instability processes in act: i) an upper "detachment sector", followed downstream by a ii) "dismantling sector" (Frodella et al., 2014). The detachment sector (witha mean slope of 30°), develops downstream from the main landslide crown (Figs. 2a and b; Fig. 3), and is dominated by extensional deformation causing the development of tensional fractures, resulting in alternate trenches and crests creating a very rough, stepped topographic surface. This area is affected by gravitational and erosional processes, as well as the rock mass detensioning and disaggregation, resulting in the accumulation of various depositional elements (colluvial fans, colluvial aprons, rock fall and rock avalanche deposits) formed by very coarse heterometric clasts, ranging from cobbles to boulders with scattered blocks (decimetric to decametric in size) in a coarse sandy matrix (Figs. 3 and 4).

The dismantling area (mean slope of 34°) includes sectors formed by highly weathered sub-vertical rock walls. It is dominated by surface processes (e.g., concentrated and diffuse erosion, slope-waste deposition due to gravity, detrital cover failures) that substantially cover the evidence of deeper deformations (Figs. 3 and 4). This area supplies material for debris flows, which channelize downstream within the Rotolon creek bed, representing the most critical sector for short-term hazardous phenomena.

Figure 2. The Mt. Rotolon DSGSD plan **(a)**; landslide sectors **(b, c)** and the 2010 debris flow features **(d, e)**.

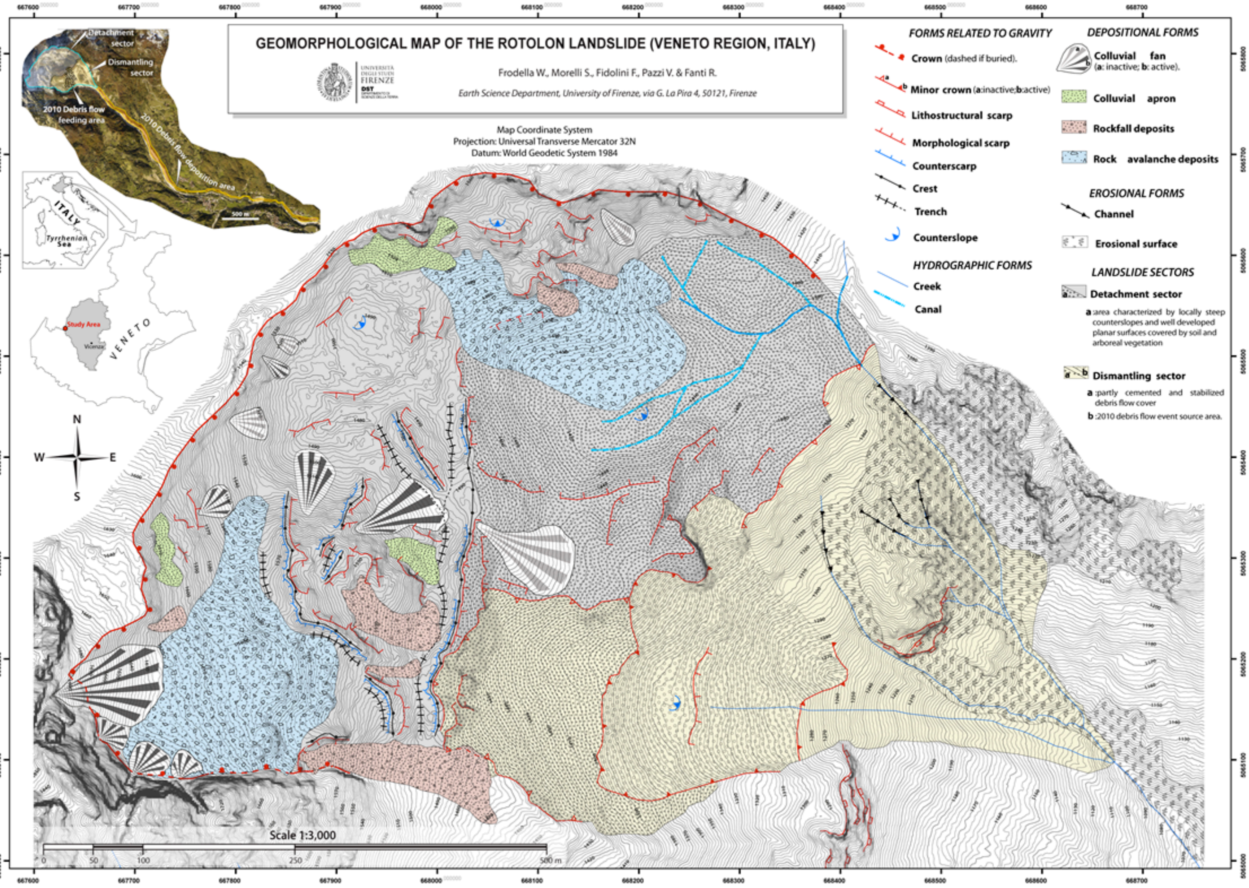

Figure 3. Geomorphological map of the Rotolon Landslide (modified after Frodella et al., 2014).

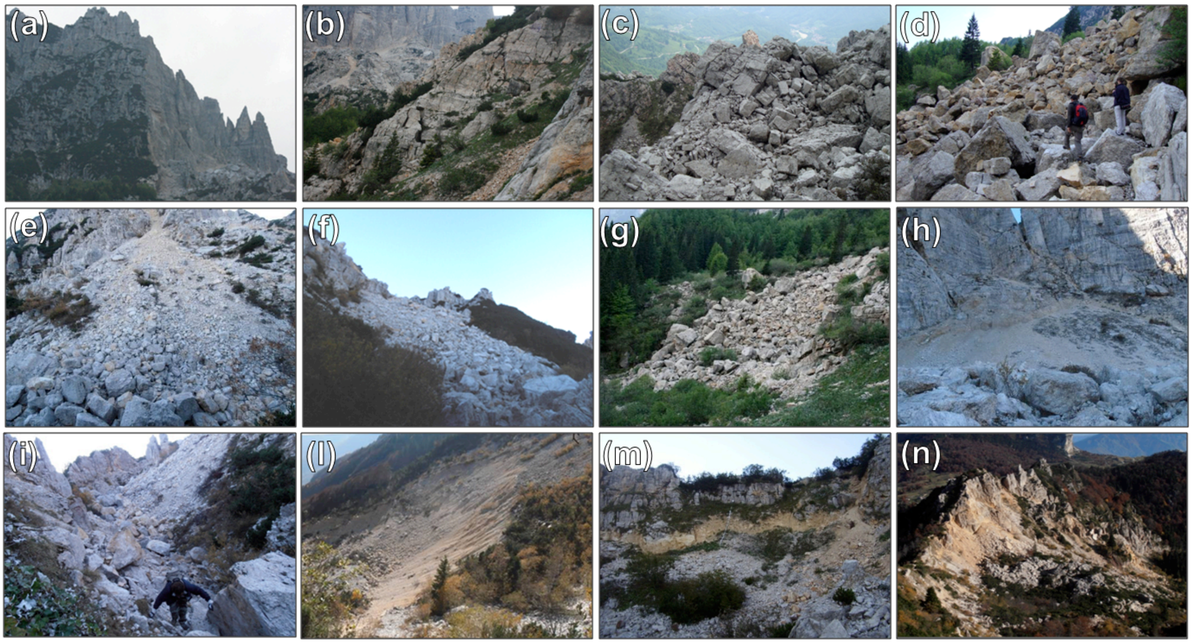

Figure 4. Geomorphic and sedimentary features of the Mt. Rotolon DSGSD detachment sector: **(a)** rock walls prone to rock falls; **(b, c)** rock mass affected by different stages of disaggregation; **(d)** plurimetric rock blocks within rock avalanche deposit. Main depositional elements within the landslide body: **(e)** colluvial fan; **(f, g)** channelized and diffused rock fall deposits; **(h)** colluvial aprons. Main landslide linear elements: **(i)** landslide trench; **(l)** 2010 debris flow detachment scarp; **(m)** DSGSD crown sector; **(n)** landslide crest.

3. The GB-InSAR technique basic theoretical principles

The GB-InSAR is a computer-controlled microwave transmitting and receiving antenna that moves along a mechanical linear rail in order to synthesize a linear aperture along the azimuth direction (Tarchi et al., 1997). The device radiates microwaves in the Ku band (12-18 GHz) and registers the backscattered signal in the acquiring time interval (less than 1 minute with the most modern systems). Each acquisition produces a complex matrix of values from which phase and amplitude information are calculated (Luzi et al., 2004; Luzi, 2010). A SAR image contains amplitude and phase information of the observed objects' backscattered echo within the investigated scenario, and it is obtained by combining the spatial resolution along the direction perpendicular to the rail (range resolution, ΔRr) and the one parallel to the synthetic aperture (azimuth or cross-range resolution, ΔRaz) (Luzi, 2010). The working principle of the GB-InSAR technique is the evaluation of the phase difference, pixel by pixel, between two pairs of averaged sequential SAR complex images, which forms an interferogram (Bamler and Hartl, 1998). The latter does not contain topographic information, given the antennas fixed position during different scans (zero baseline condition). Therefore, in the elapsed time between the ~~acquisition~~acquisitions of two or more subsequent coherent SAR images, it is possible to derive from the obtained interferograms a 2D map of the displacements that occurred along the sensor LOS (Line of Sight; Tarchi et al., 1997; 2003; Pieraccini et al., 2000; 2002). The capability of InSAR to detect ground displacement depends on the persistence of phase coherence (ranging from 0 to 1) over appropriate time intervals (Luzi, 2010). Among the technique's advantages it must be noted that GB-InSAR works: a) without any physical contact with the slope, avoiding the need of accessing the area; b) in almost any light and atmospheric condition; c) continuously over a long time; d) with millimetric accuracy (the accuracy of the measured phase is usually a fraction of the operated wavelength; Luzi, 2010); e) providing extensive and detailed near real time information of the whole visible slope.

This latter feature in particular gives a strong advantage with respect to traditional ground surface methods (like inclinometers, extensometers, total stations), which on the contrary provide single-point information in accessible area, and are generally not sufficient to evaluate the kinematics and potential behaviour of a complex landslide. The main drawback of the technique is the logistics of the installation platform, both because the GB-InSAR system measures only the displacement component parallel to ~~the line of sight (L.O.S.)~~LOS, and because the azimuth resolution (the ability to separate two objects perpendicular to the distance between the sensor and the target) lessens with the increase of the distance from the target (Fig. 5). Moreover, vegetated areas can be another drawback of the technique since they are commonly characterized by signal low coherence and power intensity.

4. The GB-InSAR monitoring strategy in the Rotolon early warning system~~The adopted monitoring system~~

The GB-InSAR system was installed in the Maltaure village, at an average distance of 3 km from the landslide, pointing upwards to NW (Fig. 5). The radar parameters are summarized in Fig. 5. Given the acquisition setting of the site and the civil protection needs, the radar data covers an area of 1.2 km^2. The logistics of the GB-InSAR system installation favoured a good spatial coverage of the data on the monitored area, especially with regards to the dismantling sector. Nevertheless, shadowing effects, due to the slope roughness, crests and counter-slope surfaces affect the detachment sectors (Figs. 5 and 7).

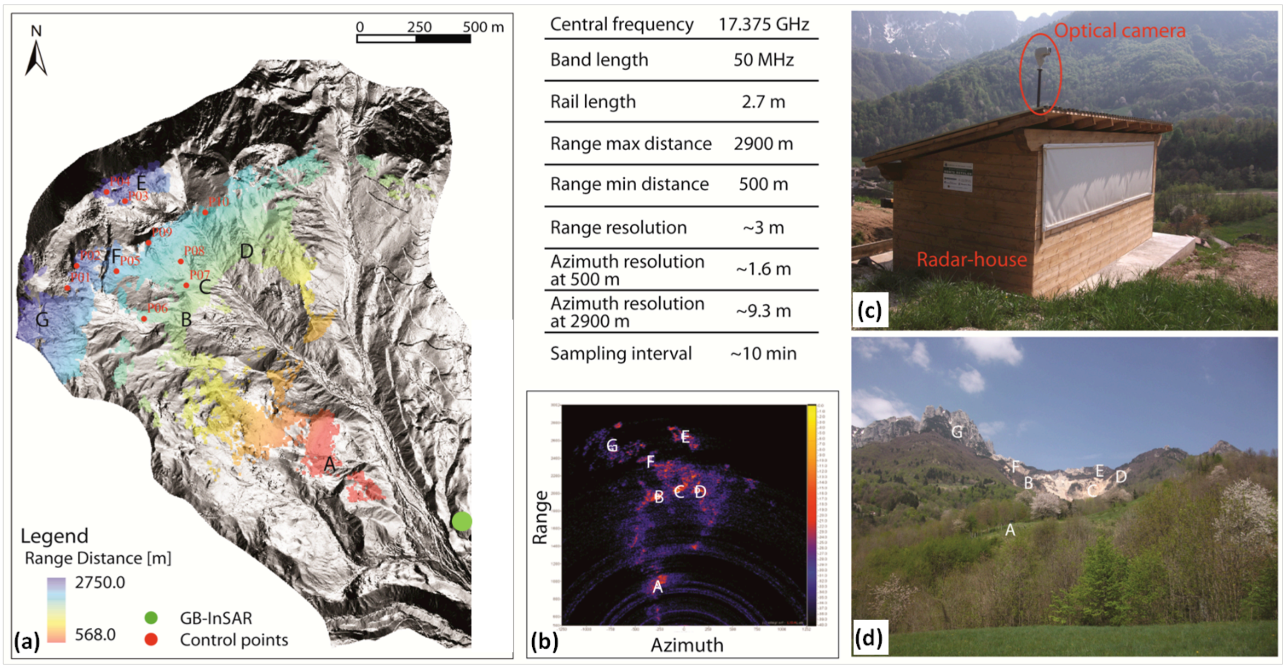

Figure 5. The adopted monitoring system: **(a)** Location of the GB-InSAR system and radar data coverage features (A-G=recognized landslide sectors); **(b)** the adopted monitoring parameters and radar power image, displaying the correspondent recognized landslide sectors; **(c)** the radar system hut setting; **(d)** picture of the monitoring optical system scenario (A-G=corresponding sectors).

The radar system acquired GB-InSAR data every 10 minutes, from which cumulated 2D displacement maps, and displacements time series of 10 measuring points (Fig. 5) were obtained. GB-InSAR data were processed using LiSALab software (Ellegi s.r.l.) and uploaded via LAN network: i) on a dedicated Web-based interface, allowing for a near real time data on-routine visualization; ii) on a remote ftp server (in ASCII format), in order to perform on demand analysis in case of critical weather events forecast by the national civil protection weather system (Fig. 6). The latter were performed integrating into a GIS environment the displacement maps and comparing them with ancillary data (rainfall, geological and geomorphological maps). In addition, a remotely adjustable robotized high resolution optical camera (Ulisse Compact model produced by Videotec S.p.A, digital zoom 10x - 36x), ~~manouverable~~manoeuvrable via IP-Ethernet interface, was installed in correspondence with the radar system, acquiring data every 60 minutes and allowing for programmable zooms. The objective of this device was to check the hazardous and inaccessible ~~Dismantling~~ dismantling sector of the landslide (Figs. 5 and 6).

Based on these displacements acquisition modes, a local scale early warning system (Intrieri et al., 2012; 2013) was implemented considering three different levels of attention: ordinary, pre-alarm and alarm levels (Figure 5). In order to support the Civil Protection decision making, hourly displacement thresholds were adopted. The level change occurred if the following thresholds were surpassed: i) ordinary: <0.1 mm/h; ii) pre-alarm: 0.1 mm/h to 0.5 mm/h; iii) alarm level: >0.5 mm/h. For each threshold different actions were planned: i) regular monitoring but no additional actions; ii) on demand monitoring data and analysis, and four-hours bulletins; iii) integration with other external monitoring data and activation request of the alert system once false warnings are prevented. This last point was achievable thanks to the ability of the radar output data to be integrated and promptly analysed in a commensurable manner with records from different devices. In this specific case they were represented by traditional instruments (1 total station with a benchmarks network, 1 rain gauge and 6 extensometers; Frigerio et al., 2014) operated by the Research Institute for Geo-Hydrological Protection of the Italian National Research Council (IRPI-CNR). To define these stability thresholds, since there was no a previous knowledge of the phenomenon behaviour, a deeper inspection of cumulated images (incremental method) and interferograms (rolling method) were carried out in the first month of activity in 7 sectors visible from the station and characterized by high reflectivity (mainly rocky and bare terrains), including the landslide area and all the surrounding slopes which were considered stable (A-G in Fig. 5). This double analysis, useful to overcome possible misinterpretations caused by noise signal, was finally refined in relation to expected dynamics of the investigated instable slope. During of all the monitoring period, communication with the deputy commissioner and cooperators was operated through the dispatch of informative bulletins every week and whenever the warning thresholds were exceeded. The time line rationale of the monitoring system and emergency management procedures is summarized in Fig. 6.

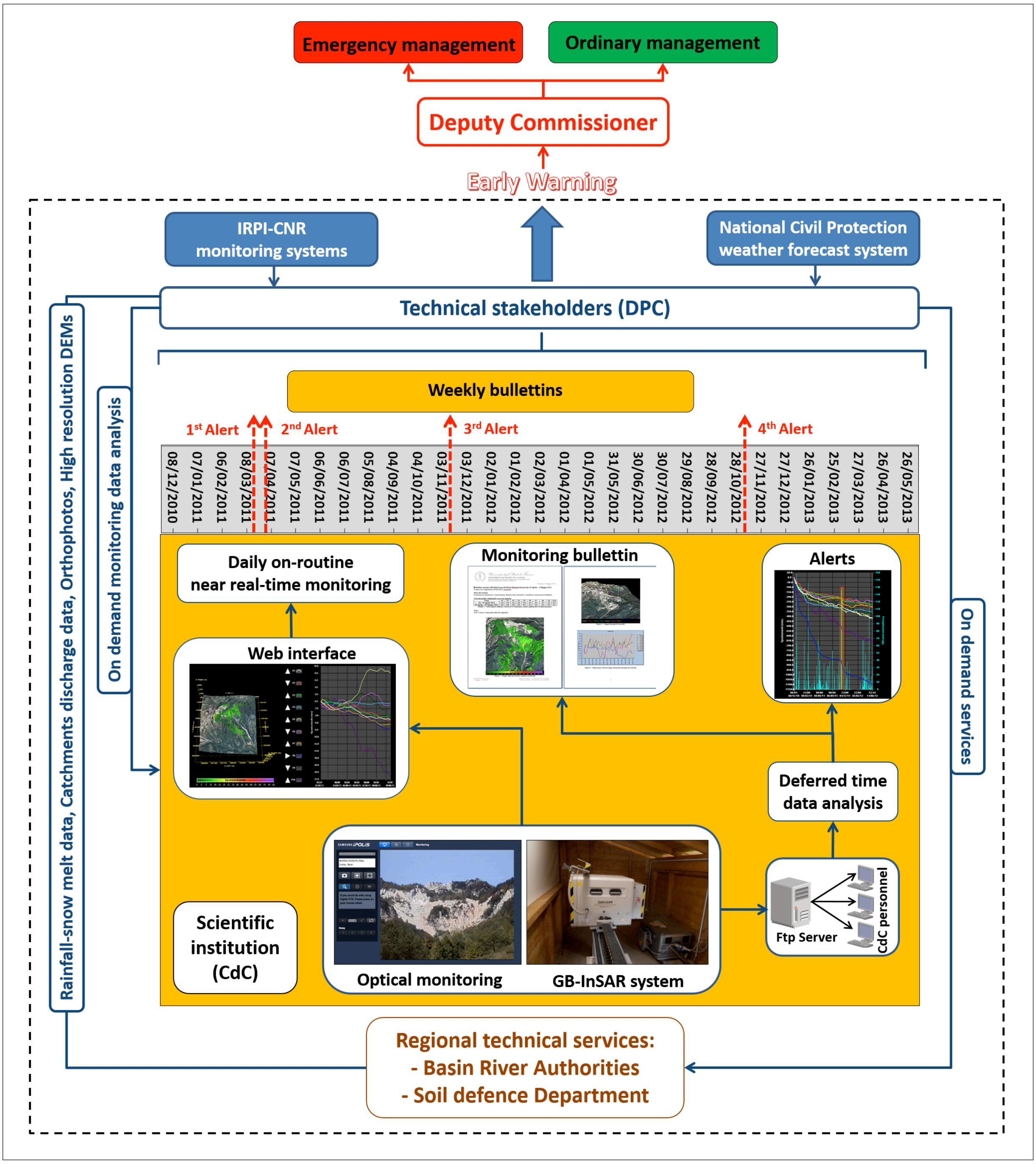

Figure 6. Time line rationale of the Rotolon monitoring system and emergency management procedures. The black dashed box include the early warning system.

5. GB-InSAR data analysis

The GB-InSAR incremental cumulative displacement (ICD) maps and the displacement time series of the measuring points obtained are shown in Figs. 7 and 8, respectively. By using a selected colour scale, the radar maps obtained are displayed as a function of the displacement measured in the period spanning from December 8th 2010 up to the beginning of each month of the monitoring campaign, (the negative displacement values indicate movements approaching the sensor; Fig. 7). In order to evaluate the deformation rates and provide easily interpretable data, a traffic light-type colour scale was applied in all the displacement maps.

GB-InSAR measuring points (corresponding to a 5 x 5 pixel size area) were selected in correspondence with sectors where the radar signal is characterized by high stability, in order to monitor the landslide kinematics and characterize the various landslide physiographic features (Fig. 7). Furthermore, with the aim of performing a temporally detailed displacement analysis and detecting the spatial pattern of residual landslide deformation, monthly cumulated displacement (MCD) maps were also selected and analysed from the collected GB-InSAR dataset (Fig. 9).

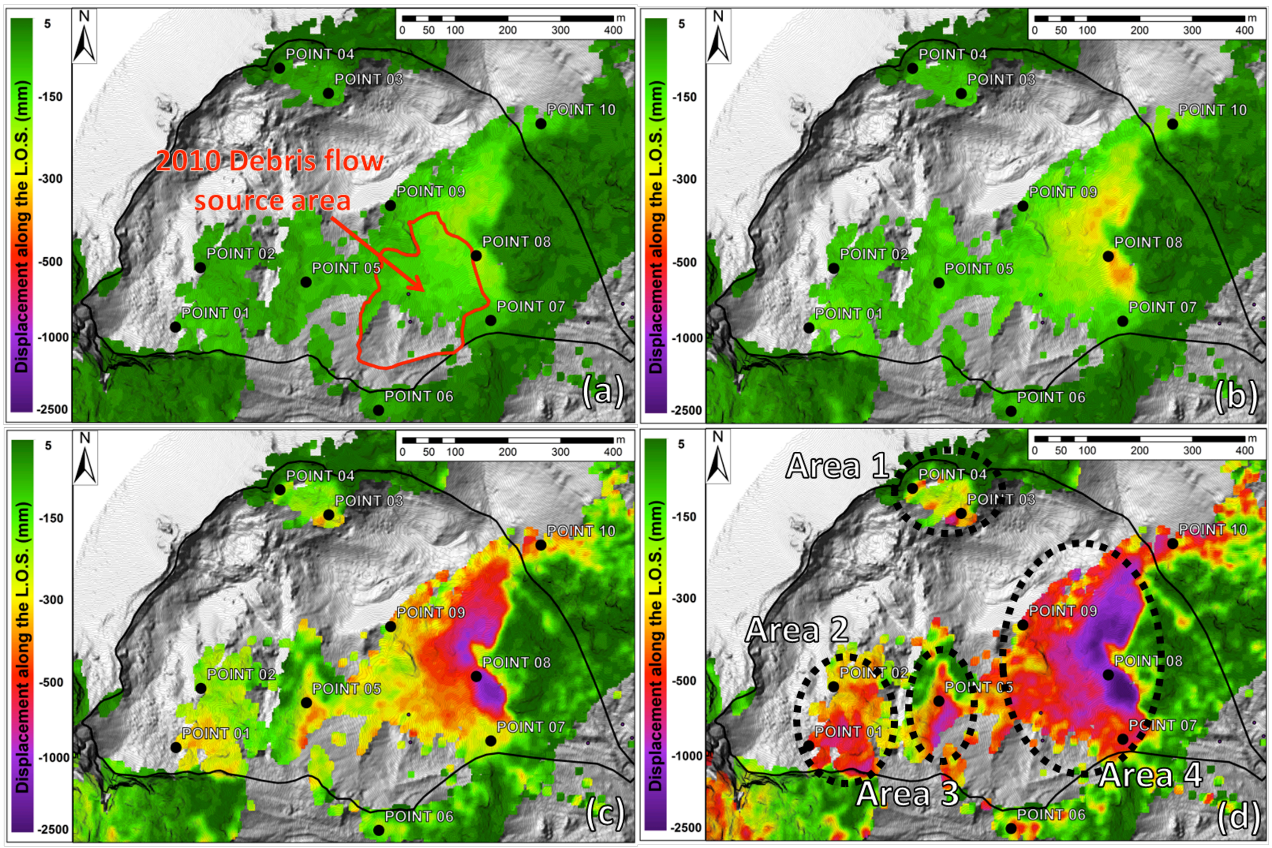

Figure 7. ICD maps of the Rotolon landslide: (a) December 8th 2010 - January 1st 2011; (b) December 8th 2010 - February 1st 2011; (c) December 8th 2010 - December 1st 2011; (d) December 8th 2010 - December 31th 2012 (Point 1-10 represent the GB-InSAR measurement points in correspondence of which the displacement time series were extracted).

From the analysis of the collected GB-InSAR dataset of the ICD maps (Fig. 7) four distinct areas characterized by relevant residual cumulated displacement were identified (Fig. 7d):

- Area 1 (ICD=737 mm, about 12500 m^2 in extension) and Area 2 (ICD=751 mm, area of 28000 m^2), corresponding to the material infilling the detachment sector (Fig. 2), such as minor rock fall and rock avalanche deposits;

- Area 3 (ICD=960 mm; 12000 m^2 in extension) and Area 4 (ICD=2437 mm; 88000 m^2 coverage), both falling within the dismantling sector detrital cover (Fig. 2) which was not affected by the 2010 debris flow detachment.

The measuring points time series (Fig. 8) display cumulated displacements ranging from 337 mm (Point 6) to 595 mm (Point 4, located in Area 1); Point 8 in particular (falling within Area 4) displays the monitored area cumulated peak displacements (ICD=1476 mm), showing two acceleration periods (middle March 2011 and beginning of November 2011), alternating with a more linear trend. The comparison amongst the MCD maps highlighted a first phase of widespread residual displacements (December 2010, Fig. 9a), which gradually decreased from the following month (Fig. 9b). In the subsequent period ground deformation took place in correspondence with limited sectors within Area 4 (May 2011 in particular shows higher MCD up to 244 mm; Fig. 9d), except for a widespread reactivation recorded in November 2011 (Fig. 9e).

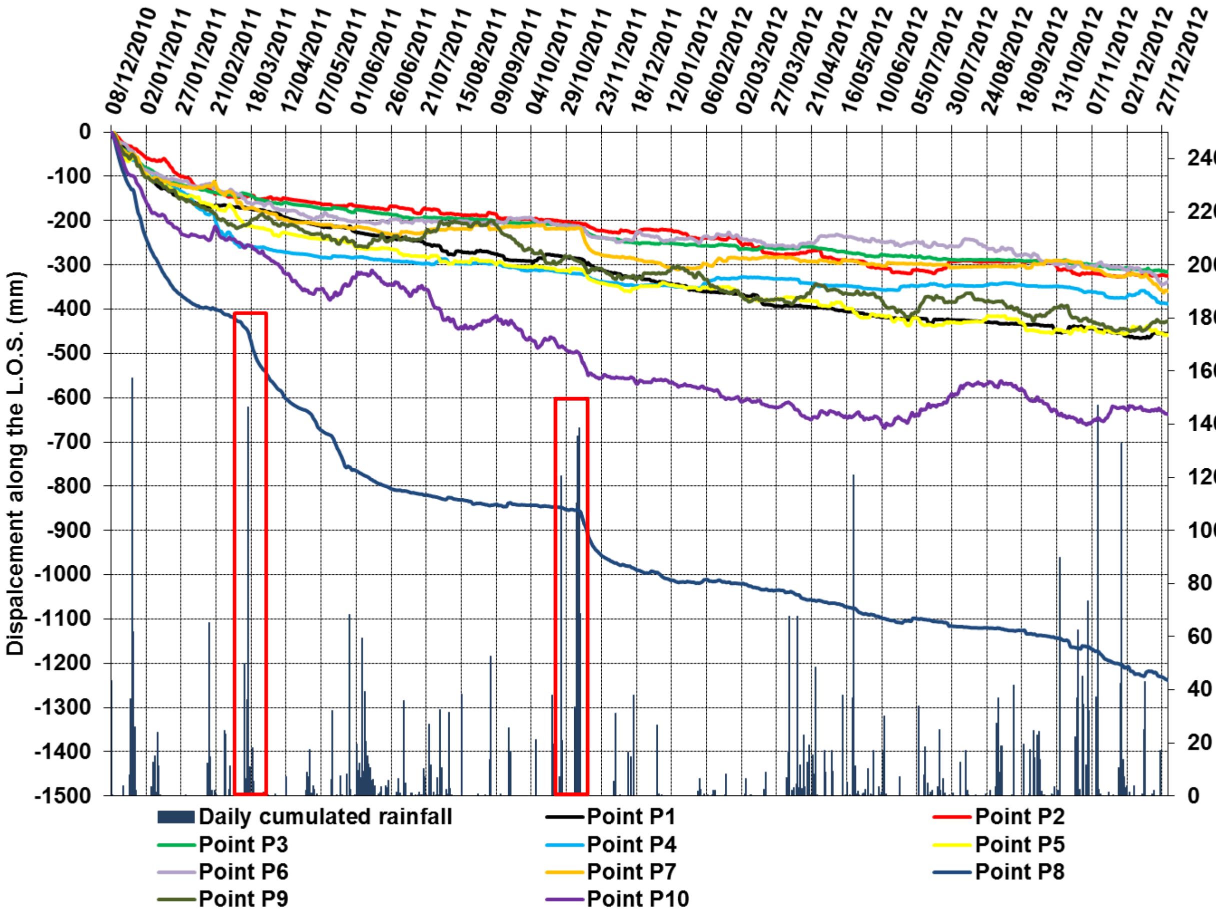

Figure 8. Selected measuring points displacement time series of the monitored scenario (red squares enhance Point 8 accelerations).

Furthermore, in order to automatically extract the most hazardous residual displacement sectors, the MCD dataset was analysed by means of a MATLAB code (Salvatici et al., 2017) (Fig. 10). The code extracts from the dataset all of the areas affected by deformation higher than a selected threshold value, set equal to 92.3 mm, being the minimum displacement among all the maximum MCD values. The results are displacement maps showing only the areas with such selected displacements (Fig.10 a-d), confirming the trend highlighted by the MCD maps (Fig. 9). The second operation of the employed code consists in the frequency calculation of the displacement occurred (the code computes how many times each pixel has recorded the selected displacement during the monitoring period) (Fig. 10e). By using this method, three critical areas characterized by repeated residual reactivations were detected: Area 2, Area 3 (1 reactivation) and especially Area 4 (8 reactivations).

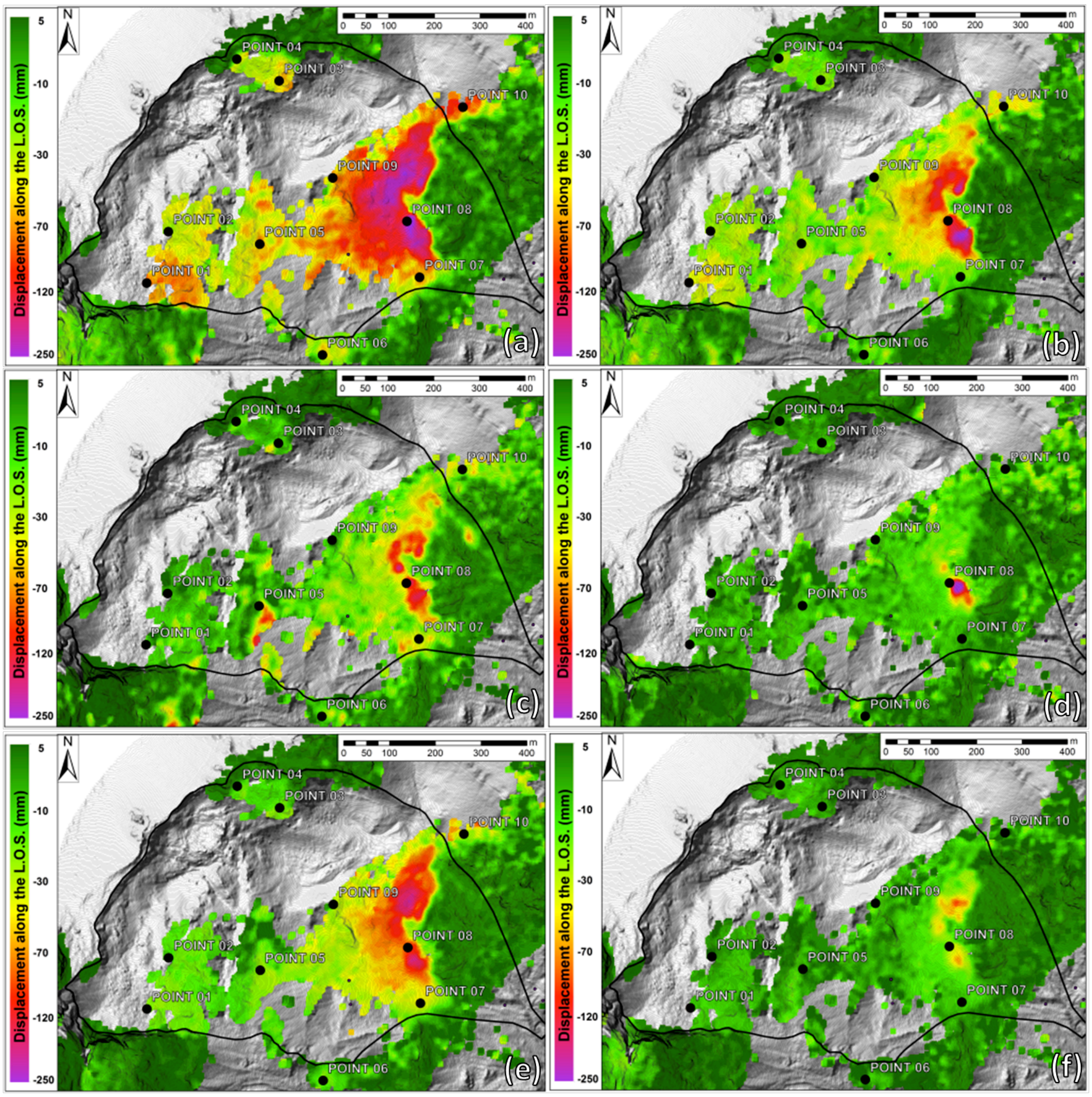

Figure 9. Selection of MCD maps from the GB-InSAR dataset: (a) December 2010 (232 mm cumulated peak displacement); (b) January 2011 (214 mm); (c) March 2011 (173 mm); (d) May 2011 (244 mm); (e) November 2011 (174 mm); (f) November 2012 (106 mm).

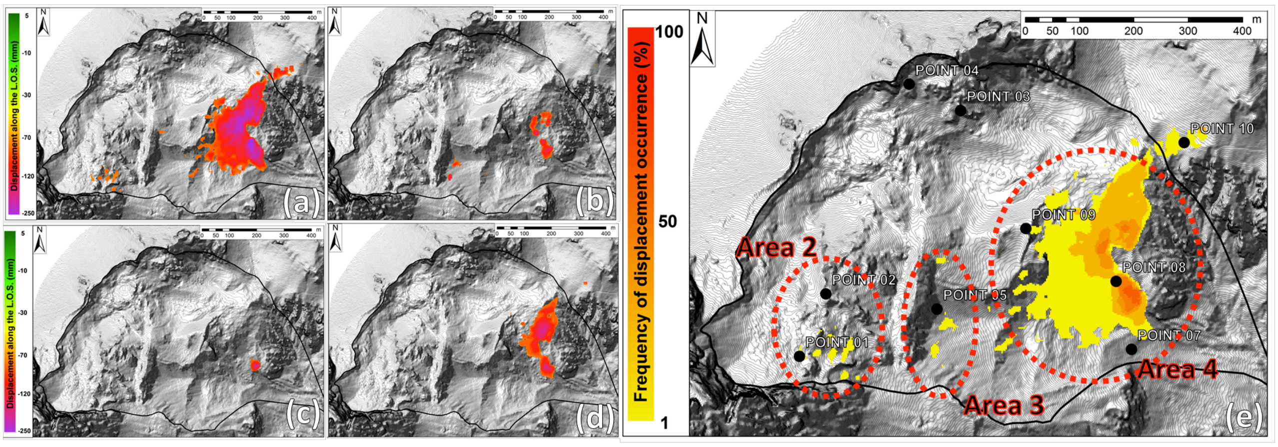

Figure 10. Residual reactivation maps obtained from selected MCD maps by means of the employed MATLAB code analysis: a) December 2010; (b) March 2011; (c) May 2011; (d) November 2011; (e) frequency map of the reactivation of the critical residual displacement sectors, classified based on their activation frequency.

6. Discussion

Successful strategies for landslide residual hazard assessment and risk reduction would imply integrated methodologies for instability detection, mapping, monitoring and forecasting (Confuorto et al., 2017). In order to provide information on the nature, extent and activation frequency of ancient landslides, standard detection and mapping procedures need a combination of field-based studies and advanced techniques, such as remote sensing data analysis and geophysical investigations (Ciampalini et al., 2015; Lotti et al., 2015; Del Soldato et al., 2016; Morelli et al., 2017; Pazzi et al., 2017a, b). In this context GB-InSAR represents a versatile and flexible technology, allowing for rapid changes in the type of data acquisition (geometry and temporal sampling) based on the characteristics of the monitored slope failure, which is capable of assessing the extent and the magnitude of the landslide residual hazard (Di Traglia et al., 2014; 2015; Carlà et al., 2016a, b). In the presented case study the 2 year continuous GB-InSAR monitoring campaign made it possible to measure the slope displacement with millimetric accuracy over a 1.2 km square landslide area, enabling the analyses of the evolution pattern connected to the landslide residual hazard. The measured deformation pattern ~~is~~ was almost always consistent, in terms of extent and values, with the results obtained in some specific benchmark by an automated total station monitoring network (Frigerio et al., 2014; Bossi et al., 2015), working approximately in parallel with the GB-InSAR system. ~~(Frigerio et al., 2014; Bossi et al., 2015)~~.

By comparing the landslide geomorphological map (Frodella et al., 2014) with the ICD displacement map of whole monitored period (Fig. 11), the four critical areas shown in Figure 7 are analysed in detail:

- Area 1, including measuring Points 3 and 4, is located in the northern side of detachment sector (Fig. 11a). In the first few months (between December 2010 and March 2011) the points recorded a peak of displacements of about 260 mm (Point 4) and 150 mm (Point 3); after this period the displacement decreased up to 8th November 2011. Between November 8th and 12th, during a major rainfall event (68 mm), the displacements increased again (Fig. 11b). The displacements recorded by the points within Area 1 may be related to deformations affecting the deposits placed along the steep scarp connected to the main crown delimiting the DSGSD (Fig. 4).

- Area 2 is located in the detachment sector (SW side of the DSGSD). Two measuring points (Points 1 and 2) therein located (Fig. 11d) recorded a peak of displacement of about 170 mm (Point 1) and 130 mm (Point 2) respectively, between December 2010 and March 2011. The ground deformations recorded by these points are related to slope waste deposition due to the gravity affecting the coarse material infilling this sector, such as ancient rock avalanche deposits (Point 1) and detensioned rock mass portions (Point 2) (Fig. 4).

- Area 3 represents the border between detachment and dismantling sectors, and is located upstream of the 2010 event scarp (Fig.11c). Its kinematics is represented by Point 5 behavior, showing a trend similar to P1, which may be associated with the sliding of the partly cemented and stabilized detrital cover material (Figs. 4-11d).

- Area 4 represents the lowermost portion of dismantling sector. Three measuring points are therein located: Points 7, 8 and 9 (Figs. 11e and 11f). Points 7 and 8 display the kinematics the detrital cover surrounding the 2010 debris flow triggering area. Both control points show acceleration periods alternating with periods of stability. In particular, the trend of P8, located near the Rotolon creek ephemeral springs and channels (Frodella et al., 2014; 2015) shows a correlation with cumulative precipitation above a threshold value of about 100 mm (Fig. 11f), which contribute to the sub-surface water circulation within the detachment sector's loose detrital cover.

This suggests that the recorded displacements may be associated to the spring erosion within the detrital cover. This point records the maximum displacement of the entire area (about ICD=1236 mm) monitored by GB-InSAR system. The area is apparently dominated by superficial processes, such as widespread soil erosion and slope-waste deposition due to gravity. Measuring Point 9, located near the dismantling sector upstream limit, records cumulative displacement of 445 mm and shows an irregular trend mainly due to its location near vegetated areas (Figs. 4-11f).

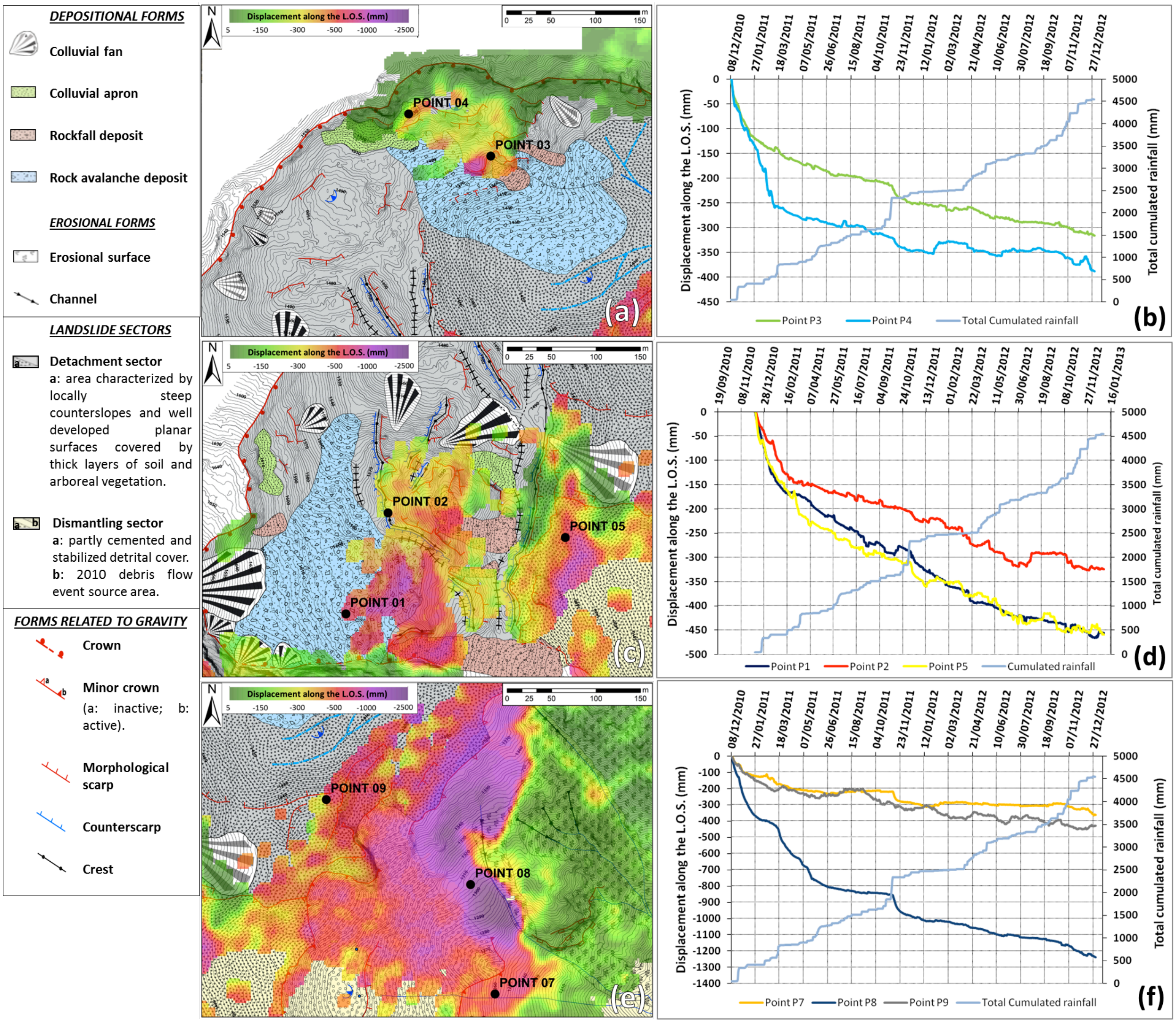

Figure 11. Integration between geomorphological map (modified after Frodella et al., 2014), the ICD maps displacement maps of whole monitored period, and the control points displacements time series: (a) the zoom of the Area 1 shown in Figure 7d; (b) the displacements time series of P4 and P3; (c) zoom of the Area 2 and Area 3 shown in Figure 7d; (d) the displacement time series of Points 1, 2 and 5; (e) zoom of Area 4 shown in Figure 7d; (f) the displacement time series of Points 7, 8 and 9.

The use of GB-InSAR ICD maps and the integration with geomorphological field surveys proved its usefulness in recognizing Area 4 (located within the DSGSD dismantling sector; Figs. 3 and 7) as the most hazardous sector within the monitored scenario, due to the widespread and intense recorded cumulated displacements (2437 mm), and its geomorphological features (steep slope, loose very coarse debris and widespread surface erosional processes in act due to the presence of ephemeral springs), and frequency of reactivations (Fig. 10).

The main triggering factor for these shallow remobilizations ongoing in this area is intense rainfall events, as highlighted by measuring point 8 time series (Fig. 8). Area 3 (recording 960 mm of total cumulated displacements) falls as well within the ~~Dismantling~~ dismantling sector detrital cover, and was considered the second most hazardous landslide sector within the monitored scenario. Other areas characterized by relevant residual cumulated displacement were identified in Area 1 (737 mm) and Area 2 (751 mm), corresponding to the material infilling the ~~Detachment~~ detachment sector (Fig. 2), but they were not considered hazardous due to a 300 meter long and 20 meter high N-S trending trench acting as a physical barrier separating the upper detachment sector from the lowermost dismantling sector. Furthermore, the comparison amongst the MCD maps (Fig. 9 and 10) highlighted widespread and frequent residual displacements taking place in Area 4 during the wet autumn-winter months (December 2010=232 mm; January 2011=214 mm; March 2011=173 mm; November 2011, 2012=174 and 106 mm respectively). Nevertheless, in May 2011 Area 4 reached the highest MCD in the monitored period (244 mm), although concentrated in a limited sector located near the measuring Point 8 (Fig. 9d).

~~A simplified local scale early warning system (Intrieri et al., 2012) was implemented based on three different warning levels: ordinary, pre-alarm and alarm levels (Figure 5). In order to ensure the safety of the post-recovery management personnel, hourly displacement thresholds were adopted: the level change occurred if the following thresholds were surpassed (i) ordinary: <1 mm/h; ii) pre-alarm: 1.0 mm/h to 5.0 mm/h; iii) alarm level: >5 mm/h). Communication, which is a fundamental issue of every early warning system (Intrieri et al. 2013), was operated through the dispatch of monitoring bulletins every week and whenever the warning thresholds were exceeded~~In this framework, based on the surface of the deformation areas and the increasing trends of displacement time series, 4 ~~monitoring~~ alert~~s~~ messages were obtained and communicated: i) March 19th 2011 (pre-alarm condition); ii) April 7th 2011 (alarm condition); iii) 8-12th November 2011 (pre-alarm condition); iv) November 10-12th 2012 (pre-alarm condition, ~~(~~Fig. 6). All these events were located in the area monitored by measuring Point 8, but under none of these circumstances, the debris developed in~~.~~ ~~Inspections carried out by the optical monitoring device and by means of field surveys from safe viewing points, assessed that the detected accelerations did not generate~~ significant slope failures and runout, although rainfall comparable to that of November 2010 had hit the area every time. ~~Following the second alert, a weekly bulletin phase (May 2011 - September 2012) was planned for a residual risk prevention strategy.~~ In any case, the GB-InSAR, benefiting from extensive coverage of the observations, registered in details a brief dislocation of surficial material and followed the gradual return to the stability conditions up to the most critical observed pixels that from time to time appeared irregularly dislocated around point 8.

7. **Conclusions**

In the context of the 2010 hazardous events affecting the Rotolon creek valley, a local scale GB-InSAR system was implemented for: i) mapping and monitoring slope landslide residual deformations; ii) early warning purposes in case of landslide reactivations. The objective was to assure the safety of both the valley's inhabitants and the personnel involved in the post-event recovery phase. The radar system acquired GB-InSAR data every 10 minutes, from which cumulated 2D displacement maps, and displacements time series of 10 measuring points were obtained. The analysed GB-InSAR data were uploaded both on a dedicated Web-based interface and remote ftp server, allowing for: i) a daily near real time and on-routine data visualization; ii) on demand analysis in case of critical weather events. In this context, based on the surface of the deformation areas and the increasing trends of displacement time series, 4 monitoring alerts were obtained and a 16 month weekly monitoring bulletin campaign was performed (May 2011-September 2012). All of the monitoring data were shared with the technical stakeholders and decision makers involved in the emergency management.

Given the recorded residual deformations, four critical sectors were identified in the monitored scenario on the basis of the measured cumulated displacements, frequency of activation and geomorphological features. Amongst these sectors Area 3 and in particular Area 4 (recording respectively 960 mm and 2437 mm of total cumulated displacements) were considered the most hazardous for potential debris flow reactivations. The latter areas are in fact located within a steep landslide sector characterized by loose detrital cover, affected by soil erosion and slope-waste deposition (~~Dismantling~~

dismantling sector). The displacement time series of the GB-InSAR measuring points provided information on the landslide kinematics: displacements range from 337 mm (Point 6) to 1476 mm (Point 8). This latter point displays the monitored area's cumulated peak displacements, showing two acceleration periods (mid March 2011 and beginning of November 2011) triggered by intense precipitations, alternating with a more linear trend. The kinematics of the other representative measuring points, is related either to deformations affecting the deposits placed along the steep scarp connected to the main DSGSD (Points 3-4), or to slope waste deposition due to gravity affecting the coarse material infilling the ~~Detachment~~ detachment sector (Points 1-2-5).

The comparison amongst the MCD maps highlighted a first phase of widespread residual displacements (December 2010). In the following period, ground deformation took place in limited sectors within Area 4, except for a widespread reactivation recorded in November 2011. The acquired radar data suggest a complex nature of the monitored landslide: its geomorphological features (e.g., rough topography, stepped profile in its upper sector, showing scarps, counterscarps, ridges, trenches and counter slopes, toe bulging) documents the activity of deep-seated long-term processes. The radar data also recorded the wide spectrum of short-term secondary instability phenomena, probably related to erosional-depositional gravitational processes (detachment sector), and soil erosion/slope-waste deposition (dismantling sector). Although this latter sector represents the most hazardous area within the landslide, the displacements acting therein during the analysed time span, appear to be related to ephemeral spring erosion located within the loose detrital cover. This suggests that these processes are only the surficial and secondary expression of a more complex deep-seated landslide system.

The monitoring system adopted provided all of the technical personnel and decision-making local authorities involved in the post-crisis management activities with a reliable, rapid and easy communication system of the results of the monitoring campaign. This favoured an enhanced understanding of such a critical landslide scenario (a populated mountainous area particularly devoted to touristic activities), during the post-emergency management activities. Furthermore, the methodology could be profitably adapted, modified, and updated in other geological contexts.

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