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The 2015 Scillato Landslide (Sicily, Italy): deformational behavior inferred from Satellite & Terrestrial SAR Interferometry

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SUMMARY: This paper is focused on a landslide occurred the 10th April, 2015 in Northern Sicily (Southern Italy), involving the lower portion of a slope on the left bank of the Imera River. The landslide had a great impact for the transportation network, as it produced the collapse of the Imera viaduct (Catania-Palermo Highway - A19) and it severely damaged an important connection road (SP24).
After the landslide event, a monitoring plan aimed to ensure the safety conditions during the work for the restoration of the viability has been developed. Among the activities, a continuous monitoring with Terrestrial SAR Interferometry (TInSAR) technique has been performed with the following purposes: i) control the deformational behavior of the slope, particularly in correspondence of main structures and ii) provide an alert system for the operation of the remaining viaduct.
In addition, in this paper we present the pre-failure deformations analysis of the slope retrieved by A-DInSAR (Advanced Differential Synthetic Aperture Radar Interferometry) technique, exploiting a dataset of COSMO-SkyMed images collected between 2013 and 2015.
The 2015 landslide developed in flysch deposits predominantly composed of clay materials. It has been classified as a composite landslide, triggered by heavy rainfall. The Satellite and Terrestrial InSAR analyses have allowed us to characterize the deformational behavior of the slope before and after the failure occurrence, highlighting the activity of the slope affected by the Scillato landslide.

KEYWORDS: Landslide, Monitoring, InSAR, TInSAR, A-DInSAR, COSMO-SkyMed

1 INTRODUCTION

The Scillato Landslide (Figure 1) (10th April, 2015) involved a portion of a slope located on the left bank of the Imera river between 1050 m and 240 m a.s.l. (Northern Sicily, Italy). The landslide occurred in the lower portion of the slope, at about 300 m a.s.l.. It had a great impact for the transportation network, as it produced the collapse of the Imera Viaduct (Catania-Palermo Highway - A19) and of an important connection road (SP24).

The landslide occurred in flysh deposits, mainly constituted of clays. These lithotypes are strictly connected with the geomorphological evolution of the slope, as they are very sensitive to slope instability phenomena. Indeed, the landslide inventory maps of the area, highlight the presence of several landslide phenomena (P.A.I. - *Italian Plan for the hydrogeological hazard and risk attitude*) (Figure 2). In this contest, it is worth mentioning that another landslide event occurred on April 2005 after heavy rains (Alario et al. 2005) in the same area of the 2015 Scillato landslide, producing a lot of damages to the Provincial Route SP24 (Figure 1). The 2005 landslide, characterized by a length of 200 m, a width of 250 m and a failure surface depth ranging between 2 and 5 m, involved the lower part of the 2015 landslide (Basile, 2015).

In this paper, we provide a description of the 2015 landslide event and of the monitoring plan developed in the framework of restoration works, focusing the attention on the TInSAR monitoring activity. The TInSAR monitoring has been carried out for the control of the deformational behavior of the landslide and of key structures, in order to guarantee the safety conditions during the Highway remediation works. The results of TInSAR monitoring during 22 months of activity (from May 2016 to February 2018) are presented.

In addition, in order to explore the historical deformation behavior of the slope, the A-DInSAR analysis was performed during pre-failure period, between January 2013 and March 2015, using high-resolution COSMO-SkyMed images.

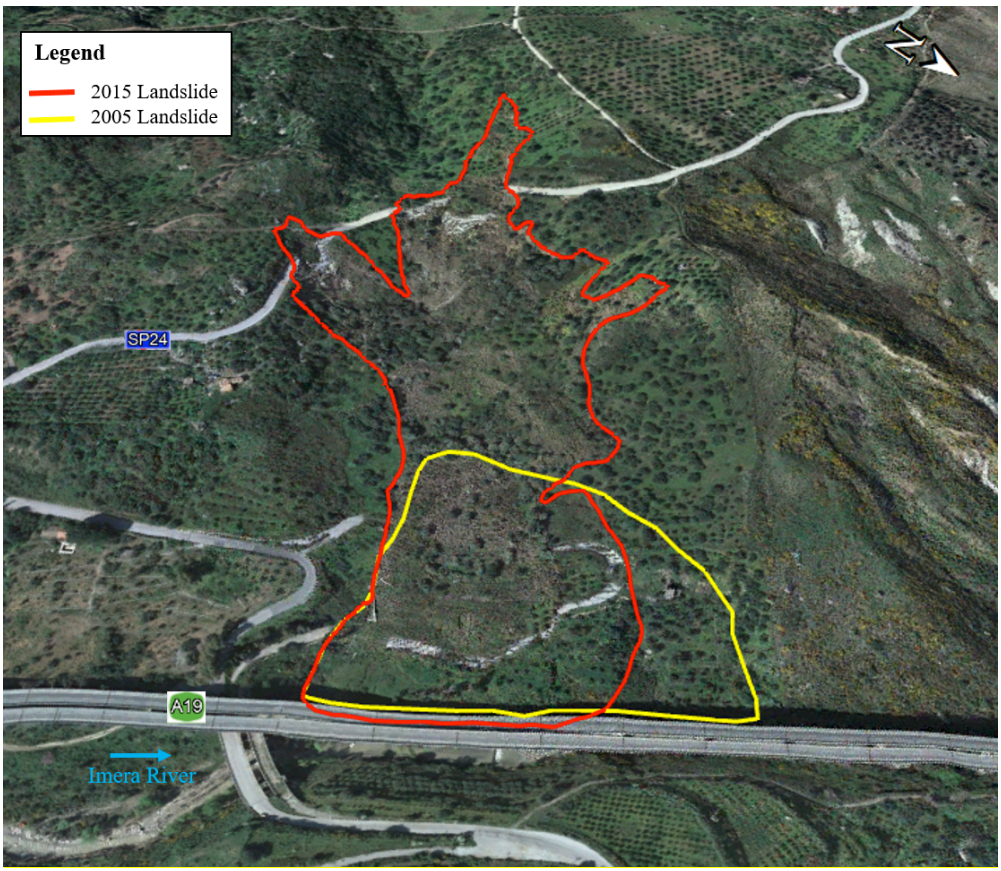

Figure 1. Overview of the 2015 Scillato landslide and the 2005 landslide reported over high-resolution aerial photos collected after the 2015 landslide event. The figure highlights the extension of the landslide events and the damages produced to the transportation corridors.

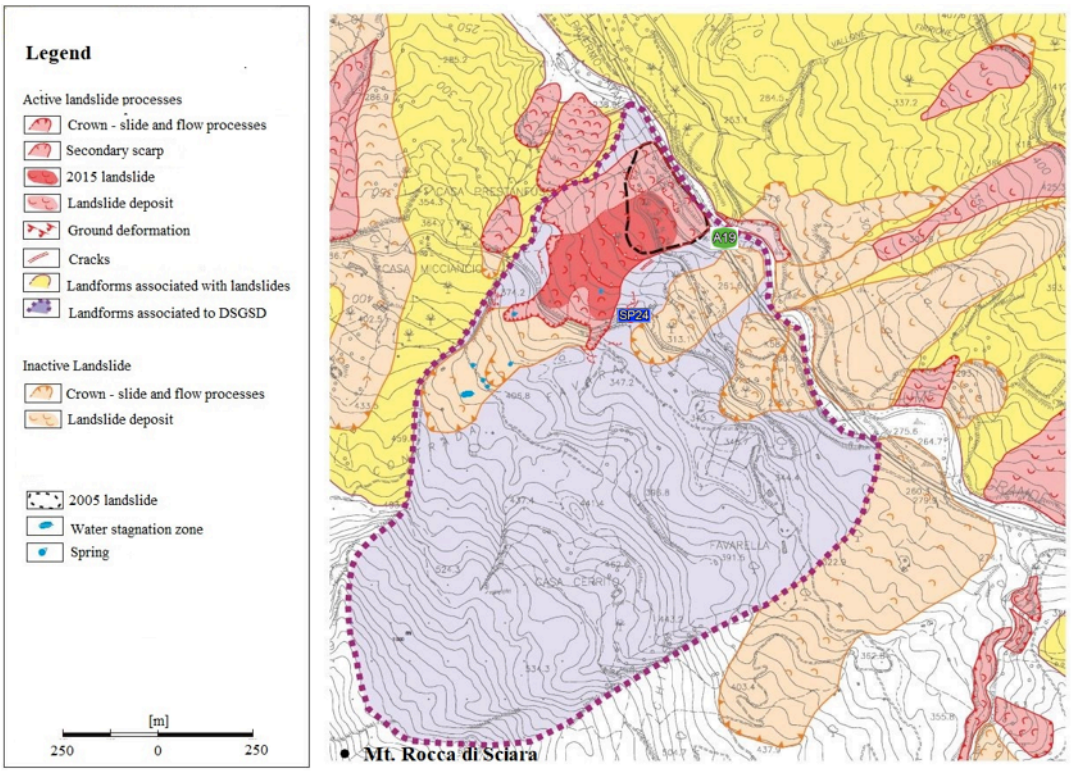

Figure 2. Geomorphological map of the area of interest, including the identification of the 2015 and 2005 landslides (from P.A.I. modified).

2 THE SCILLATO LANDSLIDE

The recent reactivation of the landslide dates back to the 10th April, 2015 (Figure 3). It occurred after heavy rainfalls, damaging about 200 m of the A19 "Palermo-Catania" highway and producing the collapse of a provincial road (SP24), causing great inconveniences for regional traffic. The landslide evolved in claystones ascribable to the Numidian Flysch Fm., specifically, the Portella Colla member (upper Oligocene – lower Miocene) (Dongarrà & Ferla 1982; Johansson et al. 1998; Gugliotta et al., 2013).

Based on field surveys and geognostic investigations, the geological setting of the area has been reconstructed by distinguishing the following geological units (Figure 4):

i) calcilutites, marly limestone ad clayey marls of the Caltavuturo Fm. (Eocene – lower Oligocene);
ii) brownish claystones ascribable to the Numidian Flysch – Portella Colla member (upper Oligocene – lower Miocene);
iii) claystones and marls belonging to the Argille Varicolori Fm. (Cretaceous – Paleocene);
iv) alluvial deposits related to the Imera River.

The rainfall records collected in the towns close to the landslide (namely, Caltavuturo and Scillato pluviographs) show that cumulated rainfall reached 600 mm in the period between January and April 2015, two times the average values of the area (Graziano, 2016). In the months after the landslide occurrence, the presence of water spills inside the landslide body was recognised in correspondence of secondary scarps, in a slope characterized by the presence of a shallow aquifer, with the piezometric level ranging between 2 and 15 meters below ground level (Sciubba & Majetta 2017). Thus, considering the groundwater asset inferred by piezometric data and field evidences and, it is reasonable to assume that the rainfalls and the consequent increase of water pressure triggered the landslide event.

The total length of the sliding body is about 600 m and the detachment areas are located between 320 m and 370 m a.s.l. with vertical slips ranging from few meters to about 10 meters along the main scarps. The deep of the failure surface, inferred by combining log-stratigraphic data and

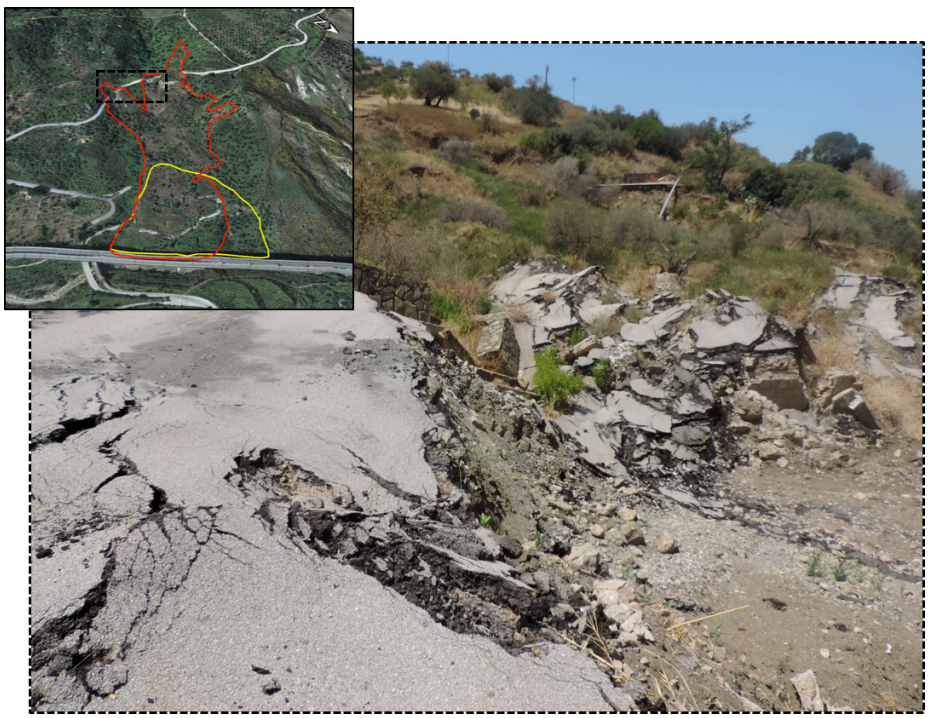

Figure 3. View of the upper part of the landslide (the picture was collected on May 2016).

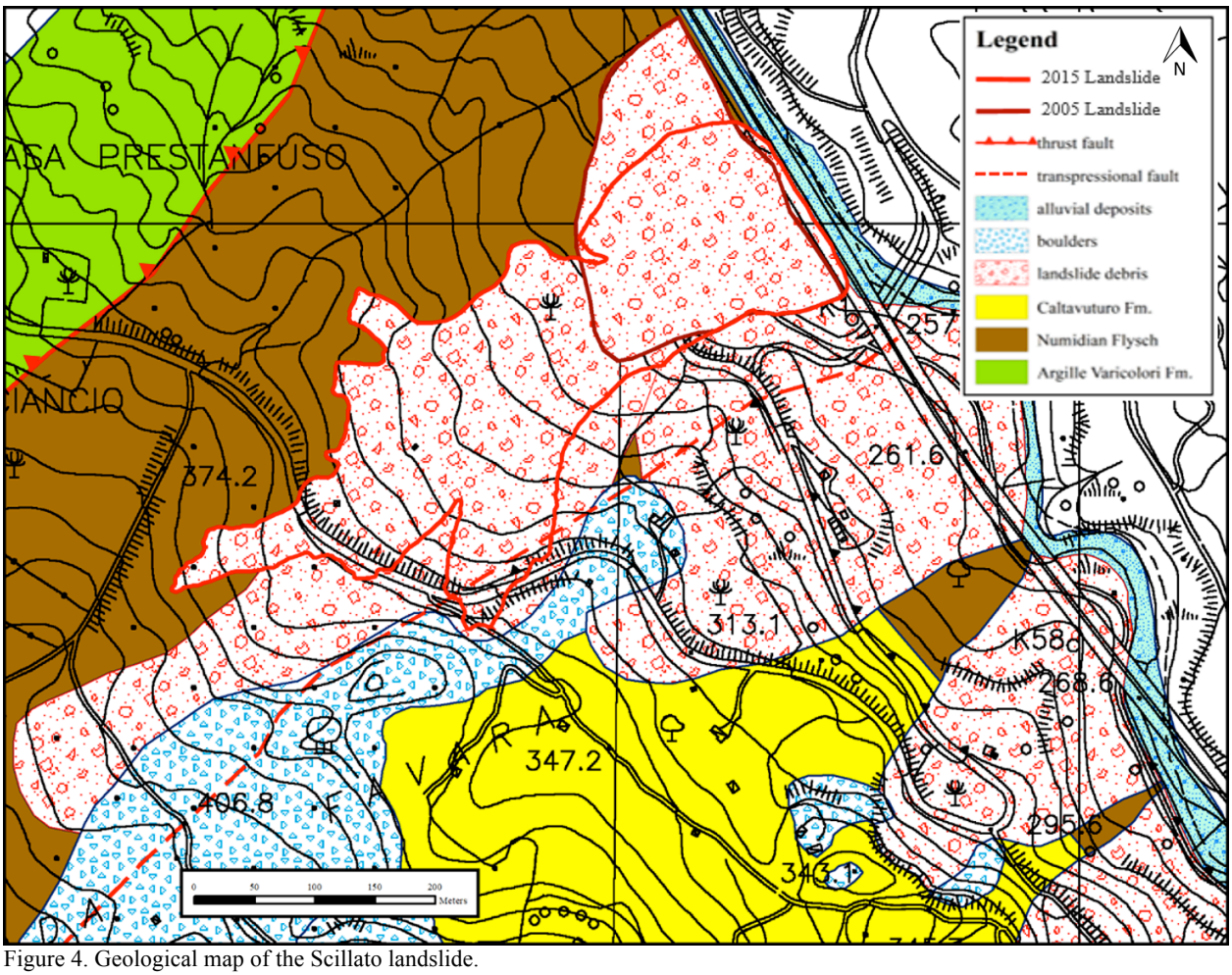

Figure 4. Geological map of the Scillato landslide.

geometrical constraints, is about 30 m. The movement was characterized by rotational features in the detachment area, such as concave crown zones and counterslopes with water stagnations, while the main movement evolved into a flow-type downslope. From the field surveys and from the exploitation of optical high-resolution aerial images, resulted that the landslide exhibited different types of movement, so that it can be classified as a composite landslide (Cruden & Varnes 1996).

3 MONITORING PLAN

The monitoring plan has been developed for knowledge and control monitoring purposes (Mazzanti 2017) and with the aim of ensuring the security conditions for the road traffic during the works for the restoration of viability of the Highway A19. The activities started before the beginning of the restoration works, in order to obtain information about the slope instability phenomena (knowledge monitoring).

The monitoring system includes both automatic and manual measurements, allowing the control of the landslide evolution and of structures located in the area of interest. The monitoring plan involves the development of four alignments of instruments over the both sides of the Imera River, located along the line of maximum slope, including (Figure 5):

Automatic systems

- N°1 rain gauge
- N° 10 in-place inclinometer systems
- N° 20 in-pressure transducers (piezometers)

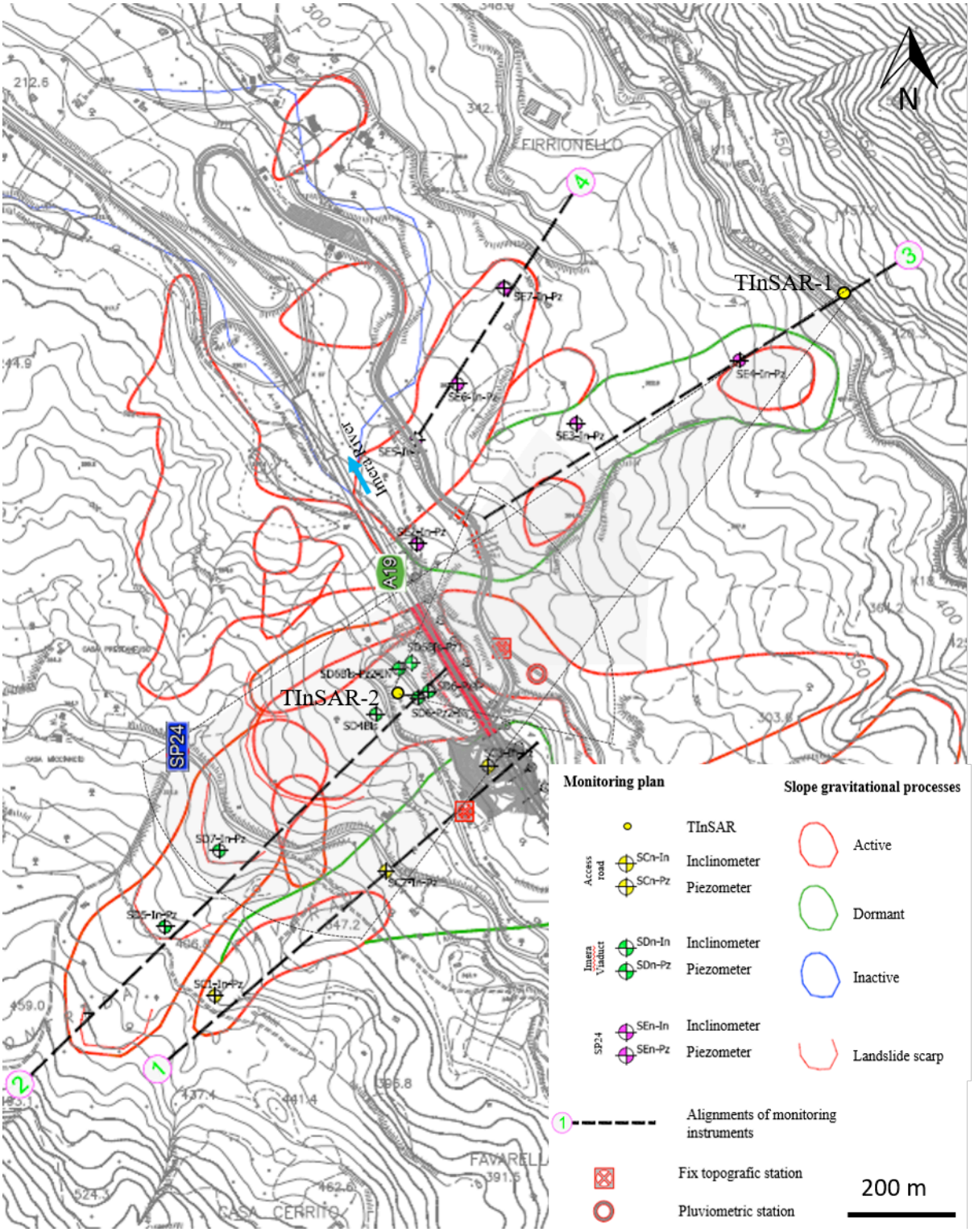

Figure 5. Scheme of the monitoring plan developed after the 2015 landslide. The landslide developed where the TInSAR-2 is located, including the SP24 route and the A19 Highway. The collapsed part of the Imera viaduct is highlighted with red (from ANAS SpA technical attachment modified).

- N° 3 robotic total stations (with 33 optical targets installed on the viaduct)
- N°2 TInSAR systems (including 20 corner reflectors)

<u>Manual systems</u>

- N°7 inclinometer boreholes

- N° 13 piezometer boreholes

The automatic systems are connected and controlled by a Data Acquisition Units, for the automatic measurements at scheduled time and data transfer. All the acquired data are validated by standard procedures regarding the management of emergency scenarios and are collected by the on-line platform specifically developed for this monitoring program, allowing for real time consultation of data (data visualization, data interrogation, data management, etc.). Specific alert procedures are also defined based on predefined thresholds for each monitoring systems.
The monitoring platform allows achieving the following goals:

1) continuously monitoring the horizontal deep movements, including the identification of potential failure surfaces;
2) continuously monitoring the surficial displacements of ground and structures;
3) detection of subsidence processes and settlements;
4) reconstruction of groundwater asset.

3.1 TERRESTRIAL InSAR

One year after the Scillato landslide occurrence, two TInSAR monitoring systems have been installed to capture the possible occurrence of displacements inside the landslide body, interesting strategic structures, the remaining part of the viaduct and the slopes around the Imera River (Figure 5). In order to improve the signal to noise ratio of some key points, 20 corner reflectors have been installed, 11 of which are placed inside the landslide body.
This paper is focused on the results collected by the TInSAR-1 (the location is reported in Figure 5), which consists of an IBIS-L interferometer by IDS S.p.A. installed in May 2016 in order to monitor the slope affected by the 2015 landslide event and the viaduct 24/7. The TInSAR-1 is located on the opposite slope with respect to 2015 landslide at about 400 m a.s.l., at a distance of 950 m from the Imera Viaduct. The interferometer has been set up using a QUIB^{TM} (*Quick Installation Basement*) system, designed and realized by NHAZCA S.r.l. with the aim of enabling rapid installation and guaranteeing the restoration of the original site conditions at the end of the activities. The TInSAR system is characterized by a sampling period of 10 minutes and it is able to reach a resolution of about 0.75 m in range and 4.38 mrad in azimuth (equal to 8 m at a distance of 1800 m). According to the site-specific conditions, the accuracy of measurements ranges between 0.1 mm to 2 mm.

3.2 SATELLITE InSAR

In addition to the monitoring plan developed in the framework of the Highway remediation works, satellite InSAR has been used in order to investigate the pre-failure deformational behavior of the slope involved in the 2015 landslide process. The basic principle of the Satellite InSAR technique is the same of the Terrestrial SAR system, where the SAR principle is reached using the motion of the sensor along the satellite orbit. In order to obtain the displacement information of the observed scenario, A-DInSAR methods based on the PSI (Persistent Scatterers Interferometry) technique (Ferretti et al. 2001, Kampes 2005) have been used, allowing to obtain the time series of displacement along the LOS for the coherent targets considered as PSs (Persistent Scatterers).

The COSMO-SkyMed dataset used is composed by 30 SAR images, acquired in the ascending acquisition geometry with a right-looking configuration. The LOS angle with respect to the North is -168.8 degrees and the incidence angle is 26.5°. The A-DInSAR analysis has been performed during the two years preceding the slope failure, analyzing the period between January 2013 and March 2015.

4 MONITORING RESULTS

4.1 Terrestrial InSAR Monitoring

During the 22 months of monitoring, localized discontinuous displacements have been detected in correspondence of the route SP24 (Figure 6) (i.e., the crown area - Sector A) and in the central sector of the landslide body (Sector B), while the viaduct resulted to be stable during all the monitoring period. The major displacements have been recorded at the beginning of the monitoring activity, between the middle of May and July 2016 (as reported in the 2D displacement map in Figure 6). During this period, a sector moving with a constant velocity trend has been identified in the central part of the landslide body (Sector B) with an extension of 40x40 m, featured by a displacement rate of 1.2 mm/day.

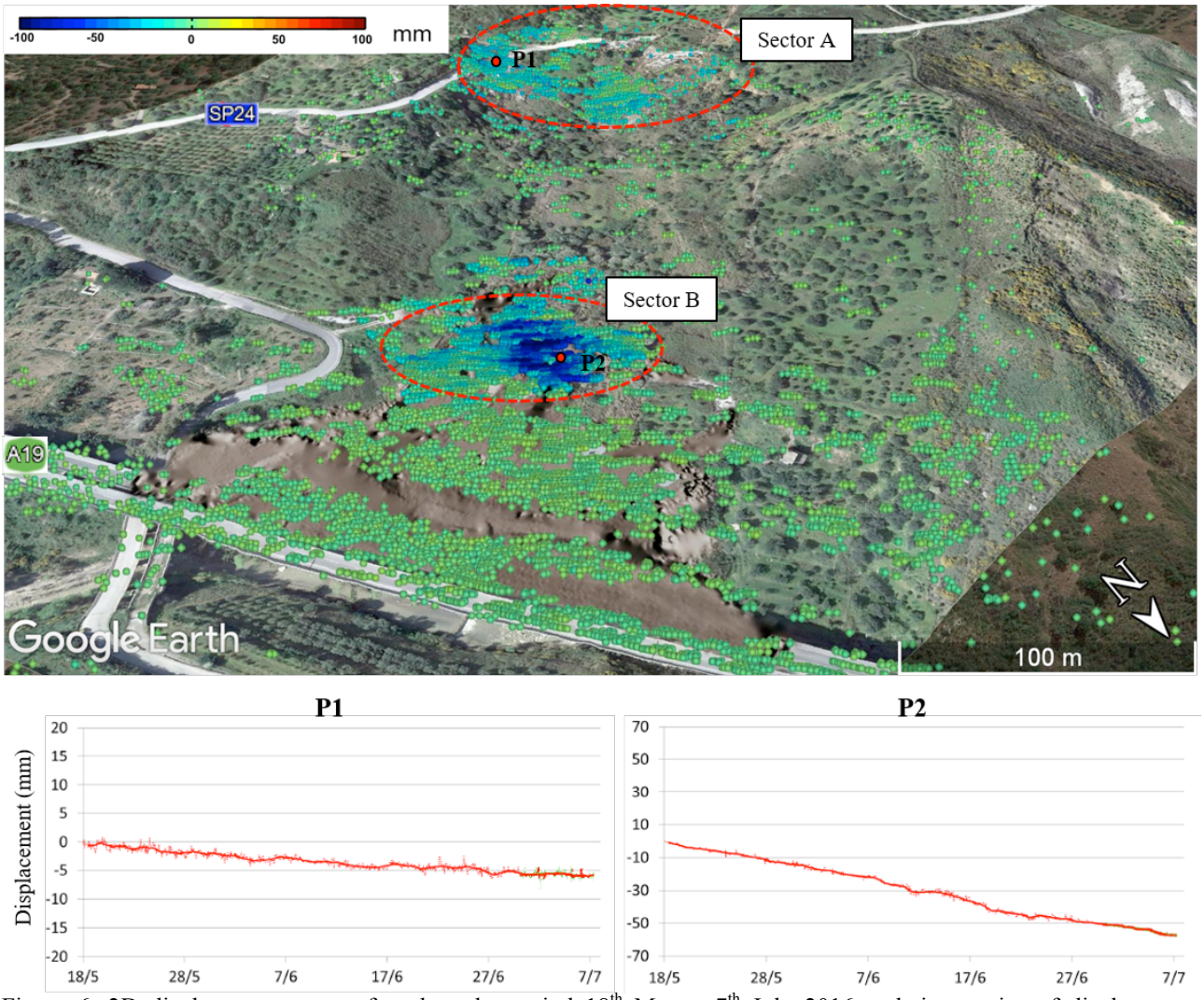

Figure 6. 2D displacement map referred to the period 18th May – 7th July 2016 and time series of displacement representative for the moving sectors. The colour of the point indicates the intensity and the direction of displacement. Specifically, negative values (light blue to dark blue) are points that moves towards the sensor, positive values (yellow to red) are points that move in the opposite direction with respect to the sensor, while green points are considered stable.

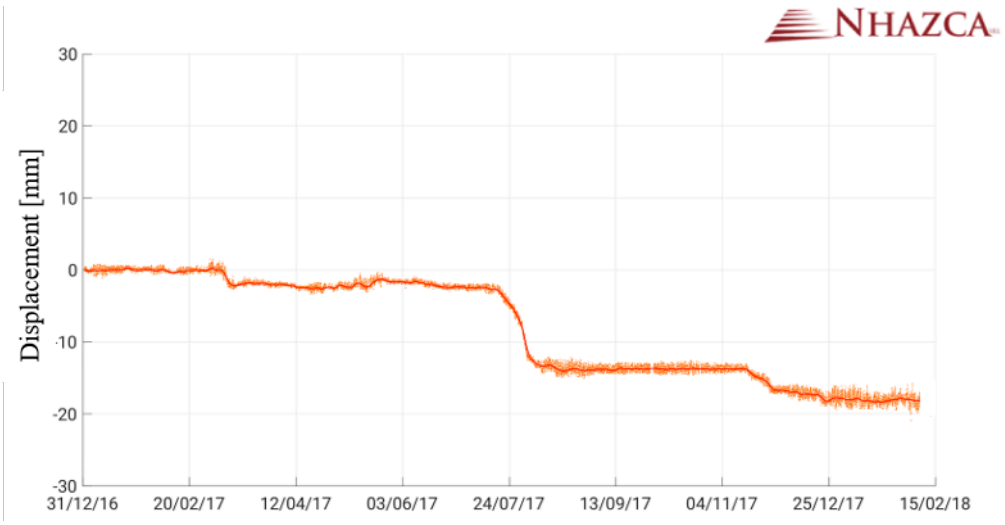

Figure 7. Example of time series of displacement of a measurement point in sector A, showing the intermittent deformation behavior of the sector.

The highest displacements were recorded in correspondence of the P2, with a total of 50 mm of cumulative displacement along the LOS towards the sensor direction. Minor displacements were registered in correspondence of the crown area (Sector A), where 5 mm of cumulated displacement was recorded in P1 (Figure 6). Considering the monitoring period from May 2016 to February 2018, the Sector A reached 100 mm of cumulative displacement, while the Sector B reached 300 mm. Overall, the deformational behavior in these two sectors is featured by the intermittent occurrence of surficial displacements, mainly observed in correspondence of major rainfall events (Figure 7).

4.2 Satellite InSAR Monitoring

Figure 8 shows the results obtained by processing 30 CSK images acquired between January 2013 and March 2105 with A-DInSAR technique. In particular, Figure 8 represents the average velocity map obtained in correspondence of the area involved in the Scillato landslide.

Inside the landslide area, displacements have been recorded in two different sectors (A and B in Figure 8). The major displacements were reached in the upper scarp of the landslide, in correspondence of the route SP24 (Sector A), where velocity trends ranging from -2 to -8 mm/year have been measured. The Sector B, is featured by the presence of deformations with an average velocity -3 mm/year, capture mainly in correspondence of the SP24 route, while the viaduct resulted stable during the 2-year monitoring period. The time series of displacement inside the landslide area are characterized by a linear deformational behavior, not showing evidences of an acceleration phase prior to the slope failure.

Outside the landslide area, two different sectors involved in deformation processes have been detected: i) the Sector C, affected by linear slope deformations up to -8 mm/year and i) Sector D characterized by deformations with an average velocity of about -2 mm/year.

8 CONCLUSIONS

Geological surveys and borehole log-stratigraphies allowed us to reconstruct the geometry and the type of the 10th April landslide event, classified as a composite movement which involved claystones ascribable to the Numidian Flysch (Portella Colla member). The rainfall records, coupled with groundwater monitoring data available and field evidences, suggested the main role played by the pore water pressure in triggering the 2015 landslide.

The past slope deformational behavior has been analyzed with COSMO-SkyMed images using multi-image processing techniques. The results highlight the occurrence of displacements in the area subsequently involved in the landslide process. The major displacements have been retrieved in correspondence of the higher sector of the landslide (Sector A), characterized by a linear deformational behavior with deformation trends ranging between -2 and -8 mm/year. Minor deformations have been collected in the lower part the landslide body (Sector B), with an average deformation trend of -3 mm/year. However, an acceleration phase before the failure was not captured from the satellite InSAR analysis, so that it would not be possible to appreciate the critical conditions of this portion of the slope before the failure occurrence.

The recent slope activity in terms of deformations has been derived by Terrestrial InSAR, that shown the presence of localized slope deformations in the central sector of the landslide body and over the crown area, in correspondence of the route SP24, ascribable to surficial movements that did not raise particular concerns among decision makers. It is worth mentioning that the surficial character of deformation phenomena has been also confirmed by inclinometer data, that highlighted the occurrence of deformations constrained in few meters below ground level (Sciubba & Majetta 2017).

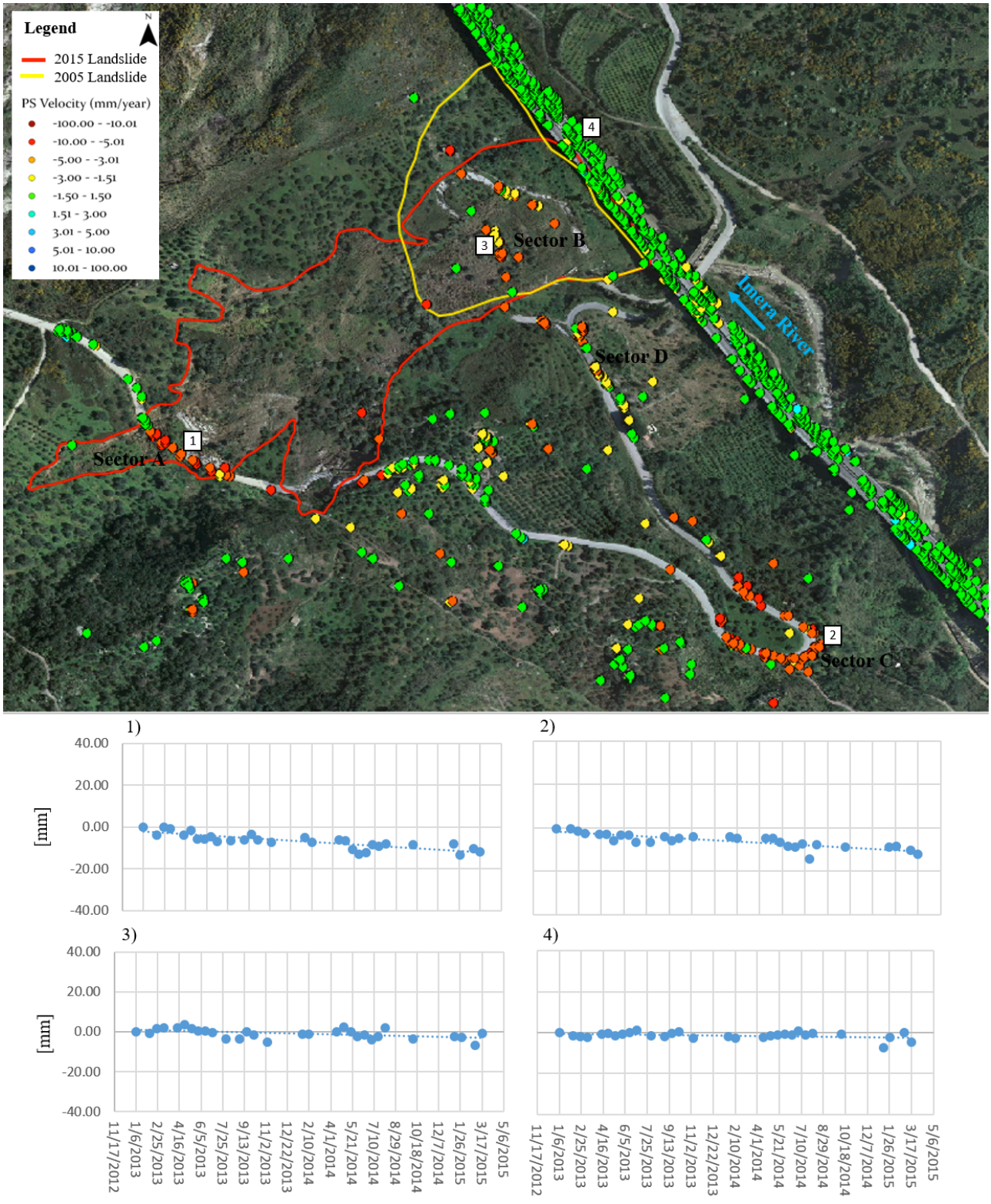

Figure 8. A-DInSAR results during the pre-failure period over a georeferenced high-resolution optical aerial image. The negative values indicate movement away from the sensor (yellow-red color), while positive values represent movement towards the satellite (blue color). (COSMO-SkyMed Product - ©ASI - Agenzia Spaziale Italiana - (2017). All rights reserved).

Inside the landslide body, the InSAR monitoring highlighted the presence of two sectors of interest (Sector A and B in Figure 6 and Figure 8), characterized by the occurrence of deformations both before and after the 2015 landslide.

Outside the landslide body, the slope morphology is mainly related to the occurrence of several landslide events, as it can be observed from the geomorphological and geological maps (Figure 2 and Figure 4). In particular, in the lowest section of the slope, along the Imera River, several landforms reflect the occurrence of past landslide processes. In this scenario, the A-DInSAR analysis highlighted the active state of two landslides mapped in correspondence of the sectors C and D in Figure 8, that were classified as inactive in the geomorphological map reported in Figure 2.

Overall, the Satellite and Terrestrial InSAR analyses confirmed the deforming attitude of the lithologies outcropping in the area of interest (i.e., claystones and marls), highlighting the landslide-prone features of the slope affected by the Scillato landslide and of the surrounding area.

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