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Persistent Scatterers continuous streaming for landslide monitoring and mapping: the case of the Tuscany region (Italy)

Abstract The results of the continuous monitoring of ground deformation throughout the Tuscany region using radar images acquired by the Sentinel-1 satellite constellation of the European Space Agency (ESA) are presented here. This new monitoring approach, based on systematic imagery processing and analysis of deformation time series, is discussed at regional (for the entire Tuscany) and at local scale in the context of a case study of the Carpineta landslide, which is a large, active earth slide in the Northern Apennines (Pistoia province). The landslide registered an acceleration during the winter and spring of 2018 as a direct consequence of rainfall and snow melt. The increase in the deformation rate of the landslide, which led to the damage of several buildings, was promptly detected and monitored due to the enhanced temporal repetitiveness offered by the Sentinel-1 constellation. The results demonstrate that advances in satellite sensors, increases in computing capacity and the refinement of processing approaches and data screening tools can contribute to the development of new paradigms in satellite-based monitoring systems. Sentinel-1 data, which are systematically acquired with short revisiting times and then promptly processed, can now be used as a tool for the systematic tracking of ground deformation at the regional scale and for the continuous monitoring of slow and very slow landslides.

Keywords Landslide · SAR interferometry · Monitoring · Early detection · Sentinel-1

Introduction

Occurring in many geographical, geological and climatic environments, landslides represent a major geological hazard; they occur more frequently than volcanic eruptions and floods and are nearly as common as earthquakes (Geohazards, IGOS 2004). Landslides play an important geomorphological role in the evolution of the landscape, are a major cause of fatalities and injuries (Centre for Research on the Epidemiology of Disasters (CRED) 2015; Dilley et al. 2005) and produce direct and indirect socio-economic losses (Sidle and Ochiai 2006). Despite the ubiquitous characteristics of landslides, a reliable estimate of landslide-induced human loss is difficult to obtain (Petley 2012) because a method for systematic data collection is lacking (Petley 2010). The global impact of landslides on structures, infrastructures, economies and environments is also poorly quantified and remains largely underestimated (Schuster and Fleming 1986). The impact of landslides is often overlooked because they are sometimes associated with other major natural disasters that occur simultaneously (Hervás 2003). Although concern from individuals and authorities about landslide risk is often low (Kjekstad and Highland 2009), in some landslide-prone areas, the application of appropriate technologies for mapping, monitoring and early-warning systems is increasingly considered mandatory by authorities in charge of hydrogeological risk management.

When addressing landslide problems, mapping and monitoring rely on the analysis and comparison, at different periods, of different parameters (e.g. areal extent, state of activity, superficial and subsurface displacement, groundwater level, soil moisture) to obtain an overview of the landslide (Dai et al. 2002). Displacement monitoring, which is the systematic measurement of magnitude, rate, location and displacement vector, often represents the most effective method for defining landslide behaviour, allowing users to observe reactivation due to external triggering factors and to assess the effectiveness of mitigation measures. Real- and near-real-time landslide displacement monitoring, which relies on sensors/instruments selected according to the characteristics of slope movement, is highly valuable, especially in cases that involve strategical elements at risk, as landslide displacement monitoring can indicate where precursors of failure may occur and lead to the prediction of future landslide evolution.

Different techniques and tools are now available for the measurement of ground displacement over time, from conventional wire extensometers (Corominas et al. 2000), inclinometers (Zhang et al. 2018), GPS (Li et al. 2017) and levelling (Cotecchia et al. 1995; Colesanti et al. 2003) to more innovative approaches, such as UAV (Unmanned Aerial Vehicle) photogrammetry (Peternel et al. 2017; Rossi et al. 2018) and terrestrial laser scanning (Fanti et al. 2013; Frodella et al. 2016). These techniques rely on the materialisation of a network of geodetic benchmarks designed to cover the extent of the likely moving area. Repeat surveys allow the estimation of deformation extents and rates. These techniques, despite their robustness and reliability, in most cases provide only a static picture of the investigated area with each measurement.

Since the advent of the first interferometric satellite missions and the pioneering studies of Carnec et al. 1996, Singhroy et al. 1998, and Massonnet and Feigl 1998, Synthetic Aperture Radar (SAR) techniques have been demonstrated to be highly valuable in measuring land motion. Unlike conventional geodetic monitoring systems, SAR-based applications permit the measurement of surface deformation over vast areas with millimetre to centimetre accuracy and at a frequency varying between 1 month to several days with the earliest satellites. More recently, rapid advances in satellite technology and the development of sophisticated processing chains of radar images have made SAR techniques more effective for landslide detection, mapping and characterisation (Crosetto et al. 2016 and reference therein). Despite these advancements, the long revisit times of orbiting satellites, and the limited access to SAR data and data policy have hampered the practical use of radar satellite information as a tool for systematic monitoring of ground deformation.

In 2014, the launch of the Sentinel-1 mission provided a new opportunity for InSAR (Interferometric SAR) monitoring applications due to increased acquisition frequency and the regularity of acquisitions (Torres et al. 2012). The potential of the Sentinel-1 satellite constellation has been exploited to develop a new paradigm in monitoring systems. This new approach has been tested, tuned and refined in the Tuscany region (Central Italy), whose territory, which is mainly hilly with mountainous areas and a few plains, is highly prone to ground instability phenomena.

With more than 90,000 mapped landslides (Rosi et al. 2018), 15% of them classified as active, landslide-related risk is a challenging issue that needs to be addressed in Tuscany (Lu et al. 2012, 2014). Some landslides have been instrumented (Rosi et al. 2013), and others have been slowed through remedial efforts (Farina et al. 2006). In some other situations, extensive protective measures have been planned and carried out (D'Amato Avanzi et al. 2006), but it is not feasible to decrease all threats or protect all affected areas. For some landslides of large magnitude, stabilisation measures would be impracticable in relation to the elements at risk. In these cases, monitoring and early-warning systems are valid options to reduce risk. Considering that we can neither instrument nor prevent all landslides, a different strategy for risk mitigation must be conceived.

In October 2016, a monitoring system based on the systematic processing of Sentinel-1 images was implemented for the Tuscany region: once a new Sentinel-1 acquisition is available, it is automatically merged with the existing SAR image archive, and the new data stack is processed to create continuously updated ground deformation data. The original methodology has been firstly presented and described by Raspini et al. (2018). This manuscript includes the results obtained from October 2016, when the regional monitoring system was initiated. The application of this methodology is presented and discussed, both at the regional scale for the entire Tuscany region and at the local scale, in the context of the landslide of Carpineta (Tuscany region, Italy), which was specifically selected due to the acceleration experienced by the landslide during the wet season of 2018.

Description of the study area

The study area is represented by the entire Tuscany region in Central Italy. Located on the Tyrrhenian side of the Italian peninsula (Fig. 1), Tuscany extends over an area of 23.863 km^2 between the regions of Liguria, Emilia-Romagna, Marche, Umbria and Lazio; it also includes a small island archipelago composed of six main islands and other small rocks. Tuscany is administratively subdivided into 10 provinces, with the regional capital, Firenze, located in the northern part of the region.

The Tuscany region is characterised by extremely varied topography, including the Tyrrhenian coastal plains in the west and the Apennine ridge, with peaks that extend more than 2,000 m a.s.l. The central part of the region includes wide hilly areas and valley floors where the main rivers flow. The main elevations are located in the northern and eastern parts of the region, which feature the Northern Apennine system, an arcuate mountain chain that runs along the border of the region from NW to SE.

The Northern Apennines consist of a NE-verging fold and thrust belt whose origins date back to the Cretaceous at the time of the closure of the Jurassic Ligure-Piemontese Ocean and the subsequent collision between the Corso-Sardinian block and the Adria microplate (Boccaletti and Guazzone 1974). This collision led, during the Neogene and Quaternary (Vai and Martini 2001), to the stacking of two main paleogeographic domains: the oceanic Ligurian basin and the continental Adriatic margin. The Ligurian units are the highest units in the nappe pile and consist of the remains of the Ligurian oceanic crust and their sedimentary cover. These units overlap, from west to east, the Umbro-Tuscan unit (Bortolotti 1992) deposited on the western continental margin, which consists of a thick sedimentary sequence of carbonate and siliciclastic deposits that composes the backbone of the Northern Apennine ridge. Other high-elevation areas in the region consist of metamorphic rocks to the northwest (Apuan Alps) and volcanic rocks to the south (Mt. Amiata).

From the Oligocene to the present, the Northern Apennines have experienced eastward-migrating paired extension-compression (Elter et al. 1975): thrust stacking and shortening in the eastern external parts of the Northern Apennines has been contemporaneous with western back-arc extension and volcanism. In the internal part of the Apennines, Apennine flysch ridges alternate with several NW-SE-trending intermontane basins, which are basically grabens or semi-grabens filled with lacustrine and fluvial granular and cohesive deposits.

The present morphology of the Tuscany region is controlled by this continuous extensional-compressional migrating belt (Bartolini et al. 2003), while the typology and occurrence of surface processes are affected by the geological settings (Tofani et al. 2017). Landslide processes have pervasively shaped the Tuscan landscape. Tuscany is affected by different landslide typologies, depending on bedrock lithology and landscape morphology (Segoni et al. 2015). For instance, shallow landslides involving regolith and soil occur where flysch or schist are present (Bicocchi et al. 2016), while areas with soft rocks are mainly characterised by reactivations of rotational slides.

The village of Carpineta is located at an elevation of approximately 800–850 m a.s.l. on an eastward-exposed slope on the left riverbank of Limentra Creek, which flows, with a relatively high discharge, from south to north towards the Adriatic Sea. From a geological point of view, the area is characterised by the presence of the so-called Carigiola Formation, which consists of a succession of foredeep turbiditic deposits ranging in age from Chattian to Langhian (Oligocene-Miocene, Bettelli et al. 2002). In the study area, the lower part of the Carigiola Formation is exposed; it is made up of turbidites mostly organised into marl-sandstone megabeds (up to 10 m thick). The sandstone bedrock is covered by eluvial and colluvial deposits.

Methods

Sentinel-1 ground deformation maps and continuous streaming

To establish an initial baseline for the continuous monitoring of the Tuscany region, the existing images archive of the ESA Sentinel-1 C-band images (centre frequency 5.405 GHz and wavelength 5.6 cm) was acquired. Details of the Sentinel-1A datasets employed for the first processing step used as references are reported in Table 1. The Sentinel-1A coverage of the Tuscany region (including the main islands, Elba and Giglio) was achieved by using two different frames in both ascending and descending geometries distributed along two tracks along each geometry orbit.

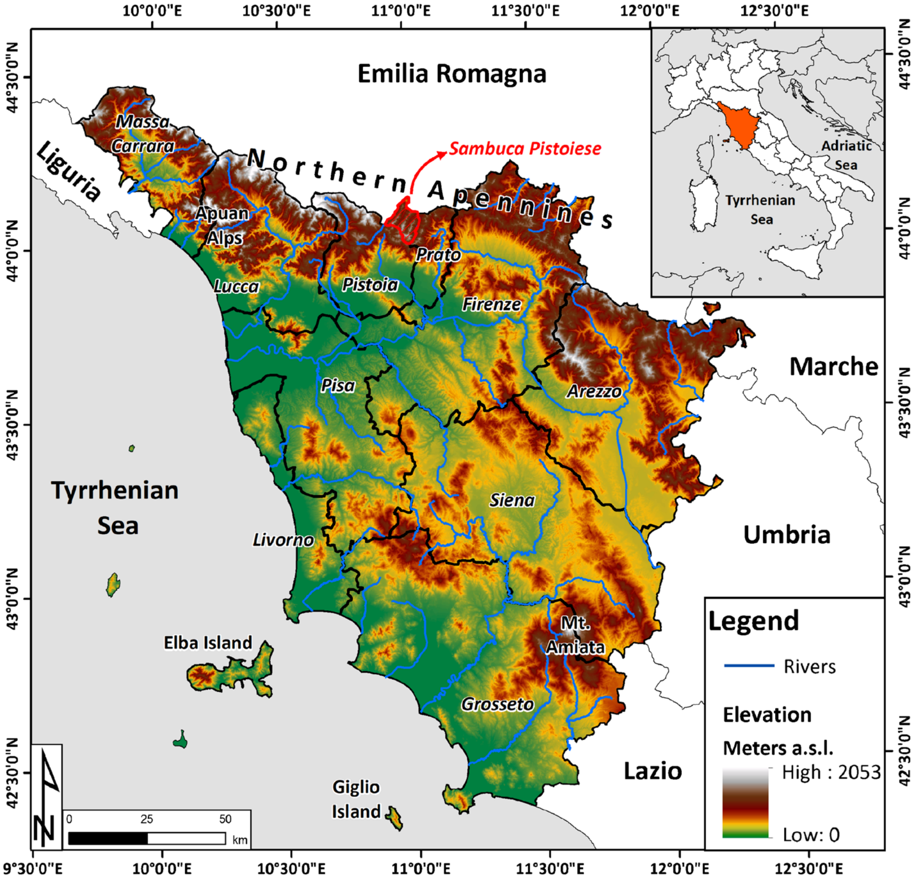


Fig. 1 Tuscany region and its main physiographic elements shown through a digital elevation model with a 10 m accuracy. The red polygon indicates the location of the Sambuca Pistoiese municipality in the Northern Apennine mountains

The datasets used for the first processing step included Sentinel-1A images only, with an acquisition frequency of 12 days.

Ground deformation maps for the Tuscany region were obtained using the SqueeSAR technique (Ferretti et al. 2011), a second-generation PSInSAR algorithm (Ferretti et al. 2001) that involves the processing of long temporal series of co-registered SAR images acquired over the same target area and with the same acquisition geometry. The main idea behind PSInSAR is to identify point-like targets (PS, Permanent Scatterers corresponding to single pixels or groups of a few pixels) that exhibit good phase coherence over the entire observation period. PS targets have a stable radar signature and usually correspond to natural objects (rock outcrops, boulders) and anthropic objects (buildings, metallic structures), which are common in cities but less common in non-urban areas.

Unlike the PSInSAR approach, the SqueeSAR technique exploits both point-wise coherent scatterers (i.e. the PS) and partially coherent Distributed Scatterers (DS) to determine surface displacement. DS correspond to homogeneous groups of pixels sharing similar radar returns and typically coincide with medium reflectivity areas, such as scattered outcrops, bare soil, debris-covered zones and non-cultivated land (rangeland, pasture, shrubs).

The SqueeSAR analysis is designed to identify a sparse grid of measurement points (MP) for which it is possible to estimate, with millimetre accuracy (Ferretti et al. 2011; Crosetto et al. 2016), displacement time series (TS) along the satellite line of sight (LOS) and the mean yearly velocity. Multi-interferometric approaches have been widely used and validated by geoscientists in different fields of landslide analysis, such as detection and mapping (e.g. Bardi et al. 2014; Bianchini et al. 2012), characterisation of mechanism (Tofani et al. 2013; Del Soldato et al. 2018) and modelling (Berardino et al. 2003); through the analysis of deformation time series, it has been used in the identification of velocity changes in landslide evolution (Berti et al. 2013, Solari et al. 2018a, 2018b) and in the a-posteriori prediction of failure time (Intrieri et al. 2018; Carlà et al. 2017).

The first ground deformation maps obtained through the processing of the Sentinel-1A archives are shown in Fig. 2. PS and DS were detected and classified according to their mean annual LOS velocities. Positive values correspond to motion towards the satellite, whereas negative values correspond to motion away from the satellite. Each measurement temporally and spatially refers to a unique reference image and a stable reference point. All points within each frame share the same reference point and reference date. Apart from the phase stability throughout the dataset, the reference points of the stacks are chosen in areas that are assumed to be unaffected by ground motions and that are temporally coherent throughout all the images.

With almost one million points for each geometry of acquisition, these maps include information that can be exploited to scan

Table 1 Details of the Sentinel-1 data used for the first processing step (in green) and for the following updates (in red). Details refer to the update # 40 of mid-September 2018. Sentinel-1 data are freely accessible through the Sentinels Scientific Data Hub (https://scihub.copernicus.eu)

		Archive analysis (initial baseline creation)		Continuous monitoring (systematic update)	
Track number	Geometry	# of images	Time period	# of images	Time period
15	Ascending	36	23/03/2015-01/09/2016	139	23/03/2015-03/09/2018
117	Ascending	48	12/12/2014-08/09/2016	154	12/12/2014-10/09/2018
168	Descending	41	22/03/2015-12/09/2016	148	22/03/2015-14/09/2018
95	Descending	45	12/10/2014-07/09/2016	151	12/10/2014-09/09/2018

wide areas, flag unstable zones and reconstruct the deformation histories of observed areas back to 2014. However, despite the reliability of this information, these maps are unsuitable for monitoring the deformation occurring in observed areas because they simply provide a static and retrospective view of areas affected by ground motion.

To achieve the transition from the historical satellite analysis of radar imagery to the dynamic streaming of displacement information at the regional scale, specific processing chains for both ascending and descending geometries have been established (Table 1). Once a new Sentinel-1 image is available, it is automatically downloaded and added to the existing archive. The new data stack is then entirely reprocessed to generate new ground deformation maps and updated displacement TS. A series of subsequent updates is created every 12 days using Sentinel-1A images. Sentinel-1B became fully operational in January 2017, and its images were included in the processing chain, reducing the time interval between two acquisitions to 6 days and permitting full exploitation of the satellite constellation's potential.

Analysis of displacement time series

In addition to the simple use of mean annual LOS velocities, landslide analysis can frequently benefit from the information provided by the deformation time series of each MP, in which ground movements are recorded with millimetric precision, acquisition by acquisition. TS represent the most advanced SqueeSAR product and provide a deformation history over the observed period; they are fundamental for studying the kinematics of a given phenomenon and highlighting any changes that may have occurred during the monitoring period (Tomás et al. 2016), such as sudden accelerations prior to a landslide failure (Sun et al. 2015).

Rigorous approaches have been proposed to exploit TS to their full potential (Notti et al. 2015). Visual (Cigna et al. 2011), semi-

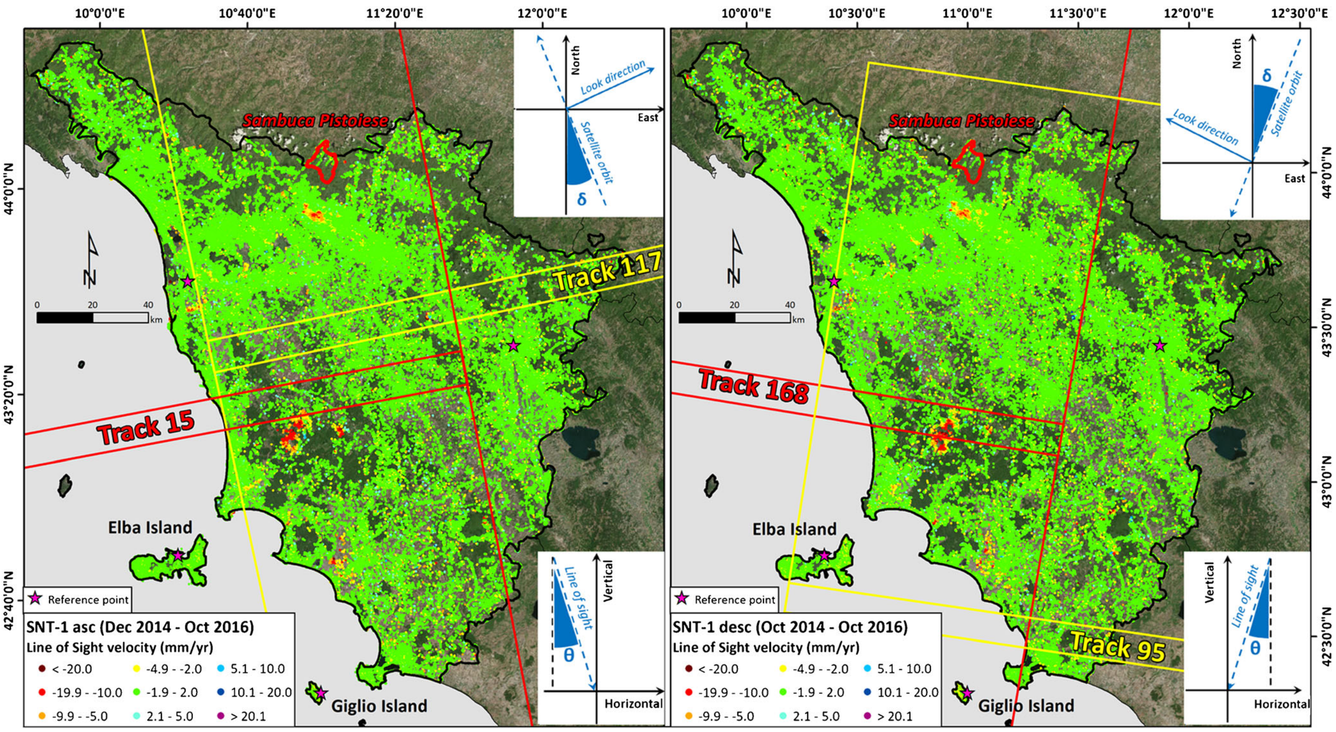


Fig. 2 Archive (2014–2016) ground deformation maps for the Tuscany region obtained with SqueeSAR processing with ascending (left) and descending (right) geometry. Acquisition geometries are shown in the insets

automatic (Cigna et al. 2012; Tapete and Casagli 2013) and automatic (Berti et al. 2013) methods for trend recognition have been presented and successfully tested, but they have been applied to only the historical archives of SAR data (e.g. ERS1/2, RADARSAT and ENVISAT). Our monitoring system relies on a continuous analysis of TS, which is regularly performed following each satellite acquisition. To enhance the information included in the SqueeSAR ground deformation maps, the displacement TS of each measurement point for both ascending and descending geometries are automatically analysed to identify, in the last 150 days of the TS, any change in the deformation pattern (Raspini et al. 2018). When a change is identified, a breaking point (Tb) is set. The average deformation rates before and after the breaking point are recalculated; when their difference $|\Delta V|$ is higher than 10 mm/year; the point is highlighted as *anomalous*. The selected temporal window and the velocity threshold represent the best options for limiting false positives/negatives and have been defined on the basis of an iterative procedure that considers both longer and shorter periods and lower and greater velocity thresholds. The automatic analysis of TS presented here provides a comprehensive picture of the evolution of recent ground movements and replaces the manual, tedious and time-consuming process of identifying trend deviations; a task that is usually performed by radar interpreters on the basis of their eyesight and expertise. Automatic identification of trend variations within TS enhances the radar interpretation of ground movements at the regional scale and offers significant advantages over conventional analyses solely on the basis of the mean deformation velocity.

Points whose time series are not affected by any trend changes are stable or characterised by linear deformation trends, away or towards the satellite (Fig. 3 above). An MP is considered without anomalies of movements if it registers random fluctuations of displacement values around zero, if it does not register appreciable movements during the monitoring period or if it registers a linear trend with a constant rate over the entire monitoring period.

In contrast, the TS of anomalous points (Fig. 3 below) denote a variation in their temporal behaviour. The sign of ΔV coupled with the slope and slope aspect derived from the digital elevation model (DEM) enables further evaluation of this result, supporting the identification of the triggering cause and the kinematics of the anomaly (accelerating or decelerating). Basically, four different changes in the displacement rate are identifiable:

- 1) TS with $\Delta V > +10$ mm/year with accelerating trend: corresponding to slope instability with an increasing displacement rate moving towards the satellite's LOS (i.e. westward movements measured from the ascending geometry and eastward movements from the descending geometry)
- 2) TS with $\Delta V < -10$ mm/year with accelerating trend: corresponding to slope instability with an increasing displacement rate moving away from the satellite's LOS (i.e. eastward movements measured from the ascending geometry and westward movements from the descending geometry)
- 3) TS with $\Delta V < -10$ mm/year with decelerating trend: corresponding to slope instability with a decreasing displacement rate moving towards the satellite's LOS (i.e. westward movements measured from the ascending geometry and eastward movements from the descending geometry)
- 4) TS with $\Delta V > +10$ mm/year with decelerating trend: corresponding to slope instability with a decreasing displacement rate moving away from the satellite's LOS (i.e. eastward movements measured from the ascending geometry and westward movements from the descending geometry).

Results at the regional scale

The deformation monitoring approach described in this paper has been used to scan the entire Tuscany region since October 2016, searching for anomalous points to indicate a change in the

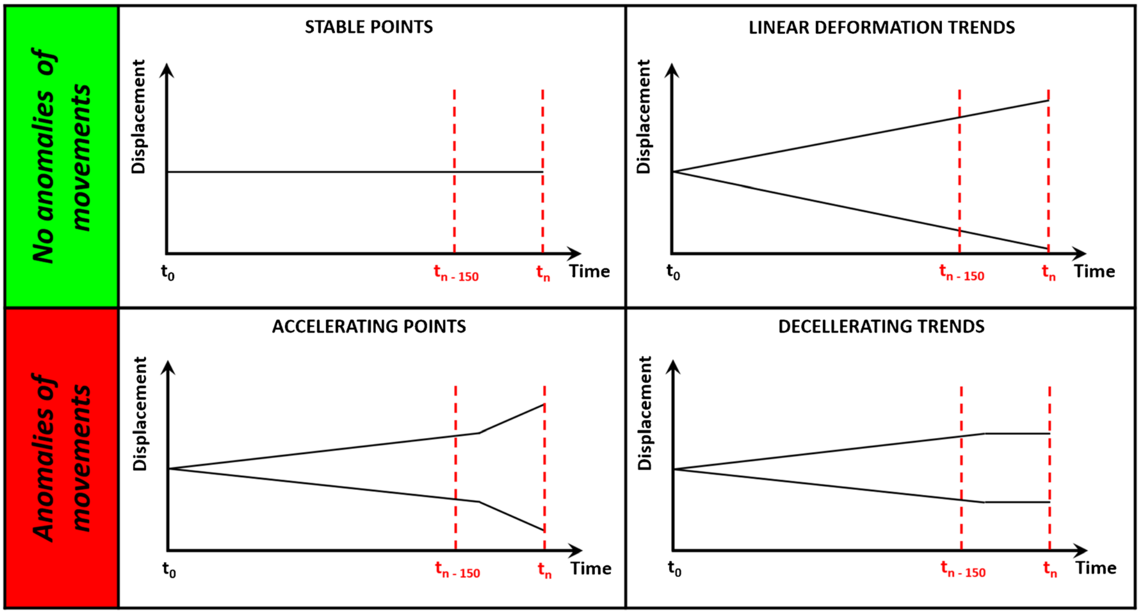


Fig. 3 Classification of time series with respect to the absence (above) or presence (below) of trend changes within the last 150 days

dynamics of motion. When detected, changes in the deformation pattern have been analysed and interpreted.

The interpretation of anomalous points requires a proper analysis strategy supported by thematic information (i.e. topographic, geomorphologic, geological and land use maps), optical images and in situ data that can assign a geomorphological meaning to the scattered point-wise ground displacement measurements. It should be emphasised that the monitoring operation described in this paper does not directly generate any alert or early warning to deliver to regional and local authorities. Anomalous points are analysed by a group of radar interpreters to decide whether an anomalous pattern is consistent with real slope dynamics and worth reporting to regional authorities. For proper use, the interpretation of the deformation TS and trend variations should stand on two pillars:

i. spatial consistency: a single, isolated measurement point showing an anomalous deformation pattern offers no reliable information. Only grouped measurement points sharing similar TS trend variations and behaviour (i.e. cluster of anomalies) can be interpreted as indicators of an actual change in the kinematics of a landslide
ii. temporal persistency: only anomalies repeated in at least two consecutive updates are considered representative of an actual change in the deformation TS. In contrast, anomalies identified in only one single update are discarded from further interpretation because they are likely related to data noise or processing artefacts (e.g. uncompensated orbital phase ramps, phase unwrapping errors, atmospheric disturbances, thermal effects on targets). It is also worth recalling that TS are a product without redundancy (Crosetto et al. 2016), i.e. they contain one deformation measurement per SAR acquisition, and for this reason, they are particularly sensitive to the noise inherent in any acquisition system>

The presence and temporal persistence of clusters of anomalies are the most important parameters linking registered trend changes to landslide reactivation. Figure 4 shows the Tuscany municipalities classified according to the total number of persistent anomalies detected from the beginning of the project to September 2018. The most consistent clusters of anomalies related to slope instability are associated with hilly and mountainous areas or rocky coasts. With more than 700 persistent anomalies, the territories of Santa Fiora and Arcidosso, located on the southern flank of the Monte Amiata volcanic cone (between the provinces of Siena and Grosseto), Montalcino, located on the northern flank, and the territory of Cavriglia (western margin of the Arezzo province) are the municipalities with the highest number of anomalies related to slope instabilities. These municipalities are located in the most landslide-prone areas of the region, and, as calculated by Rosi et al. 2018, they have very high sliding indices.

Clearly, the mere number of persistent anomalies is not an indicator of a potential threat. For instance, most of the persistent anomalies found in the municipalities of Arcidosso, Montalcino and Santa Fiora are related to the minor seasonal acceleration of shallow flows affecting nothing but grassland and bare soil. The same observation can be made for the municipality of Cavriglia, where a consistent number of persistent anomalies are related to the seasonal acceleration of well-known landslides affecting a former coal mining area, without any effects on anthropic structures. In contrast, the small cluster of anomalous points (few per update) that appeared during the winter of 2018 in the village of Carpineta (in the municipality of Sambuca Pistoiese in the northern part of Tuscany, Fig. 4 for location) is a representative case of persistent and significant anomalies of movement. This cluster of persistent and significant anomalies is in an area with elements that are at risk (urban areas, roads, infrastructures), indicating a significant level of risk that is considered worth relaying to the authorities, with the need for further analysis and on-site validation surveys.

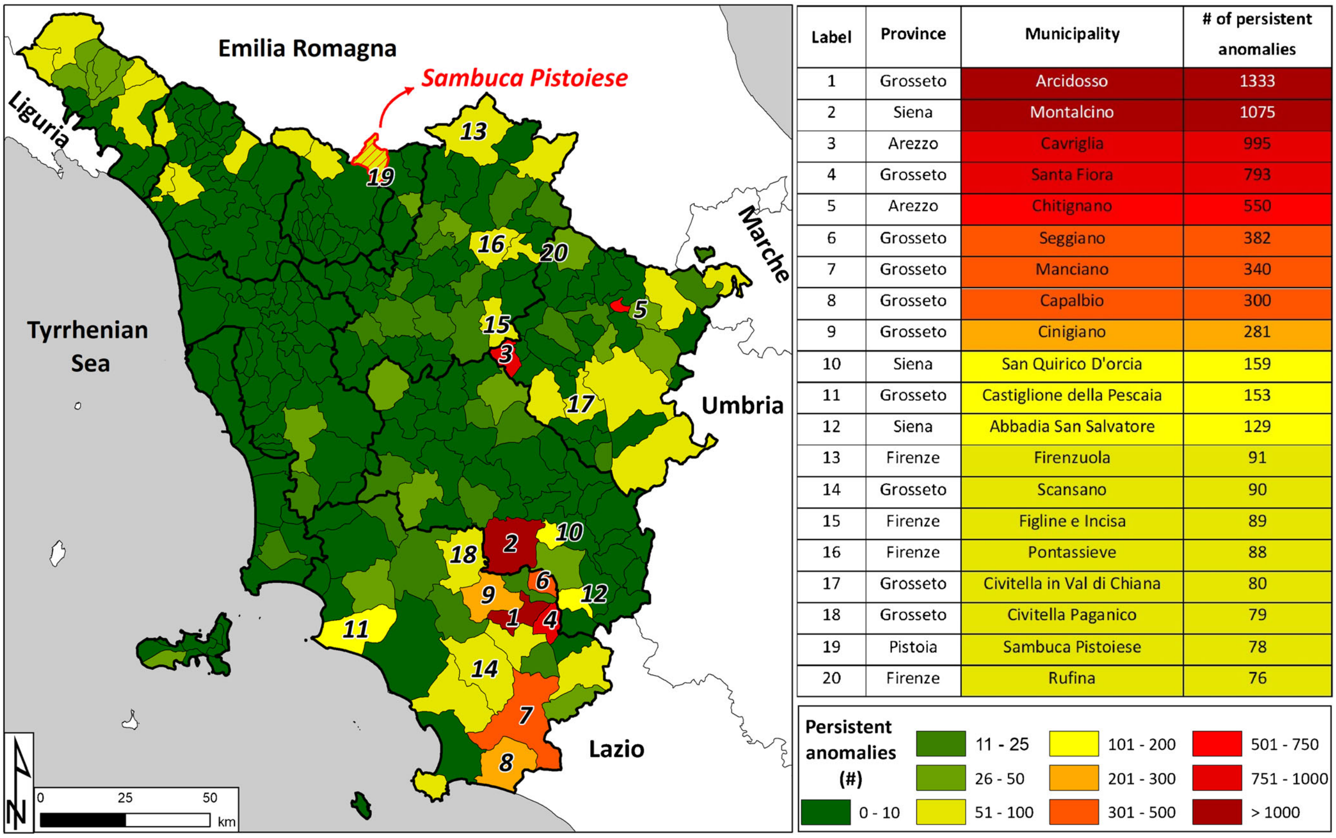
Results for the Carpineta landslide

SqueeSAR results, covering the time interval from December 2014 to February 2018 (Fig. 5), highlight the presence of active deformation affecting the village of Carpineta. Considering the acquisition geometry (ascending) and the slope orientation (east-facing slope), the deformation data are consistent with the occurrence of gravitational movements with a main eastward component. A geomorphological analysis using a LiDAR-derived DEM with a 1-m resolution highlighted the presence of several morphological indications of surface deformation, which led to the mapping of a large earth slide (Fig. 5) that is affecting the entire slope on the left riverbank of Limentra Creek, including the village of Carpineta. The DEM analysis, supported by a field survey, allowed the identification of different sectors within the main landslide body.

The highest deformation rates (dark red points in Fig. 5) were recorded in the central part of the slope, where the village is located. Here, velocity values range from − 20 to − 25 mm/year. In the upper part of the landslide, NW of the hamlet of Carpineta, lower deformation rates are recorded (approximately − 7.5 mm/year). In the lower part of the landslide, SE of the hamlet of Carpineta, a few isolated measurement points show deformation rates of approximately − 12 mm/year. Values of deformation are consistent with the eastward movement of the slope.

The central and lower part of the landslide, where the village of Carpineta is located, experienced a significant acceleration during the winter of 2018. Analysis of the three deformation maps shown in Fig. 5 indicates that the effects of this acceleration in terms of variation of the mean annual deformation rate (calculated as the linear interpolation of the measured displacement over the entire monitoring period) are quite limited in the three intervals. Deformation rates increased, in approximately 6 months, by a few mm/year. Sector 1, with values increasing from − 24.6 mm/year to − 30.2 mm/year, is the landslide sector where the greatest variation is registered ($\Delta V = 5.6$ mm/year). Analyses of deformation based on velocity maps alone are clearly insufficient to identify landslide acceleration in a timely and correct manner. This means that the acceleration registered by the landslide of Carpineta could be totally undetected (i.e. missed), by visual analysis performed by an operator.

Systematic analysis of continuously updated deformation time series (Fig. 6) offers several advantages compared with the simple use of the average yearly motion rate in landslide analysis. In addition to the progressive increase in displacement, the time series indicated that the acceleration affected different parts of the Carpineta landslide at different times, confirming the partitioning of the large earth slide into



Label	Province	Municipality	# of persistent anomalies
1	Grosseto	Arcidosso	1333
2	Siena	Montalcino	1075
3	Arezzo	Cavriglia	995
4	Grosseto	Santa Fiora	793
5	Arezzo	Chitignano	550
6	Grosseto	Seggiano	382
7	Grosseto	Manciano	340
8	Grosseto	Capalbio	300
9	Grosseto	Cinigiano	281
10	Siena	San Quirico D'orcia	159
11	Grosseto	Castiglione della Pescaia	153
12	Siena	Abbadia San Salvatore	129
13	Firenze	Firenzuola	91
14	Grosseto	Scansano	90
15	Firenze	Figline e Incisa	89
16	Firenze	Pontassieve	88
17	Grosseto	Civitella in Val di Chiana	80
18	Grosseto	Civitella Paganico	79
19	Pistoia	Sambuca Pistoiese	78
20	Firenze	Rufina	76

Fig. 4 Classification of the municipalities of the Tuscany region according to the number of persistent anomalies of movement related to slope instability from October 2016 to September 2018. The table includes the 20 municipalities with the highest number of anomalies

different sectors, as evidenced by field survey information and DEM analysis. Figure 6 shows that the continuous screening of time series allows the early detection of anomalous variations, whose appearance, persistency and disappearance follow a precise timing. Specifically, measurement points become anomalous after the start of acceleration. This period, defined as the latency of the anomaly, may vary from 3 to 5 acquisitions, depending on the intensity of the acceleration itself. The period of latency is designed to identify only measurement points with a consolidated trend variation and disregard temporary changes in the time series, which are likely due to errors in data processing or intrinsic noise and are not related to real ground motion. After its appearance, the anomaly persists for a certain number of updates. This period of persistency, added to the latency time, covers a period of approximately 150 days, corresponding to the time interval selected for the detection of the anomaly. After 150 days, the anomaly disappears, reappearing only in the case of a new variation (acceleration or deceleration) in the time series.

The acceleration of the Carpineta landslide occurred after a period of persistent rainfall in the area. Due to the lack of rain gauges within the landslide's perimeter, the rainfall data used here were recorded at the Treppio hamlet, 1.2 km south of Carpineta. This rain gauge is the only available rain gauge in the area and is close to the landslide; it is installed at an elevation (726 m a.s.l.) similar to the altitude of Carpineta (850 m a.s.l.), along the same valley flank. From a climatic point of view, the highest rainfall periods in this part of the Apennine range are recorded in autumn (October–November) and spring (March–April). In addition to rainfall, another important factor is rapid snow melting, whose effect on the displacement time series is clearly visible in the form of a reduced signal-to-noise ratio from late February to mid-March (see the blue bars in Fig. 6). Analysis of the rainfall data allows the identification of intense rainfall events that occurred before landslide acceleration, confirming rainfall as the main triggering factor. Before landslide acceleration occurred in January 2018, 30-day and 60-day accumulated rainfalls of 179.6 mm and 578.0 mm, respectively, were registered by the Treppio rain gauge. This pluviometric regime surely contributed to the complete saturation of the slope and consequently triggered the acceleration of the landslide.

A notification of the persistent anomalies affecting the village of Carpineta was promptly delivered to regional authorities in charge of geohazard management at the end of February 2018. A joint field survey was conducted a few days later. Field investigations were performed to evaluate the main morphological indicators of surface deformation, to support the production of a geomorphological map of the landslide and to highlight the presence of damaged buildings or infrastructures. Activities then focused on the areas where the anomalies were detected, that is, within and around the village of Carpineta, to validate SAR measurements. A field survey identified buildings with diffuse factures that were

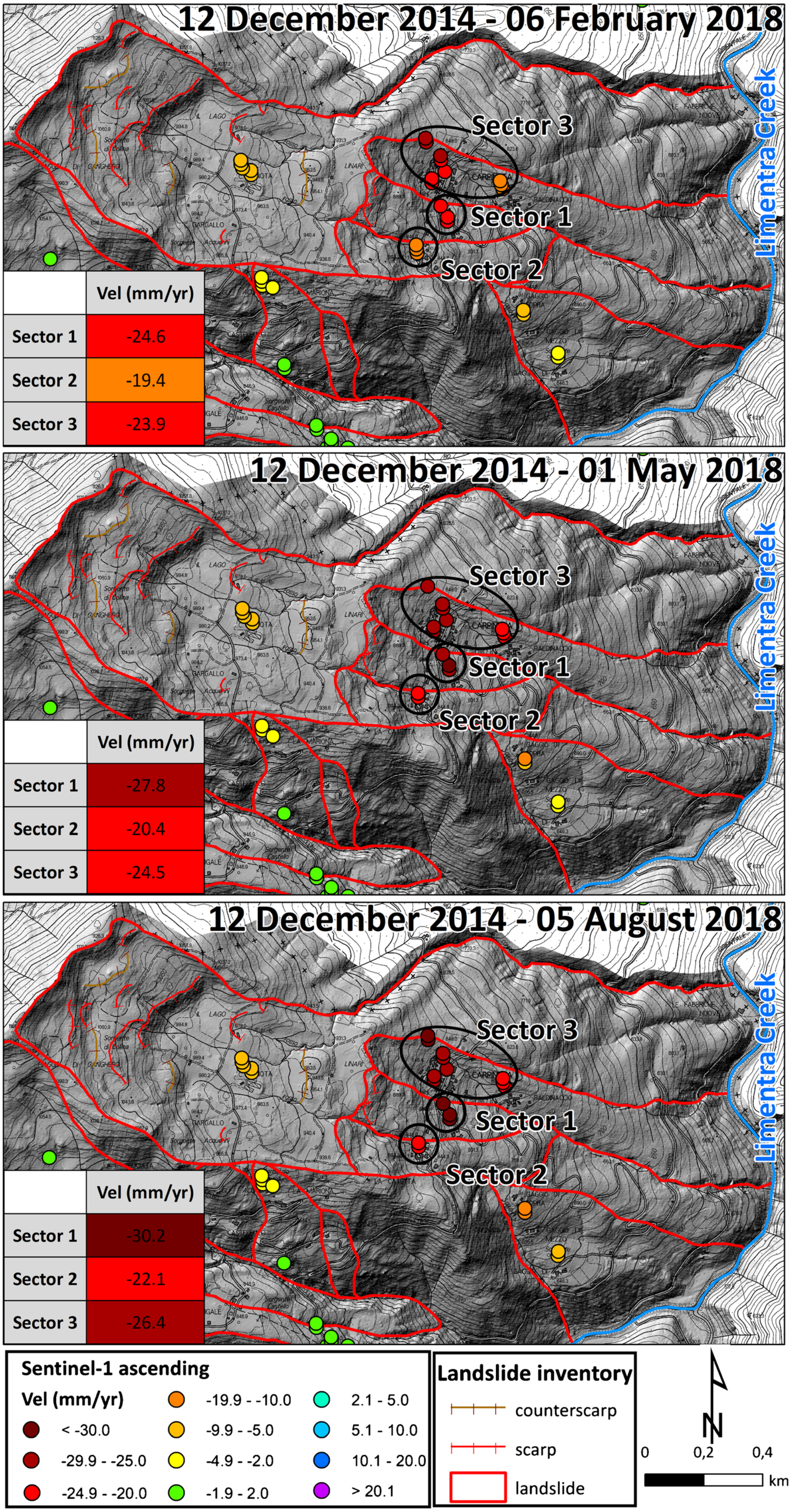
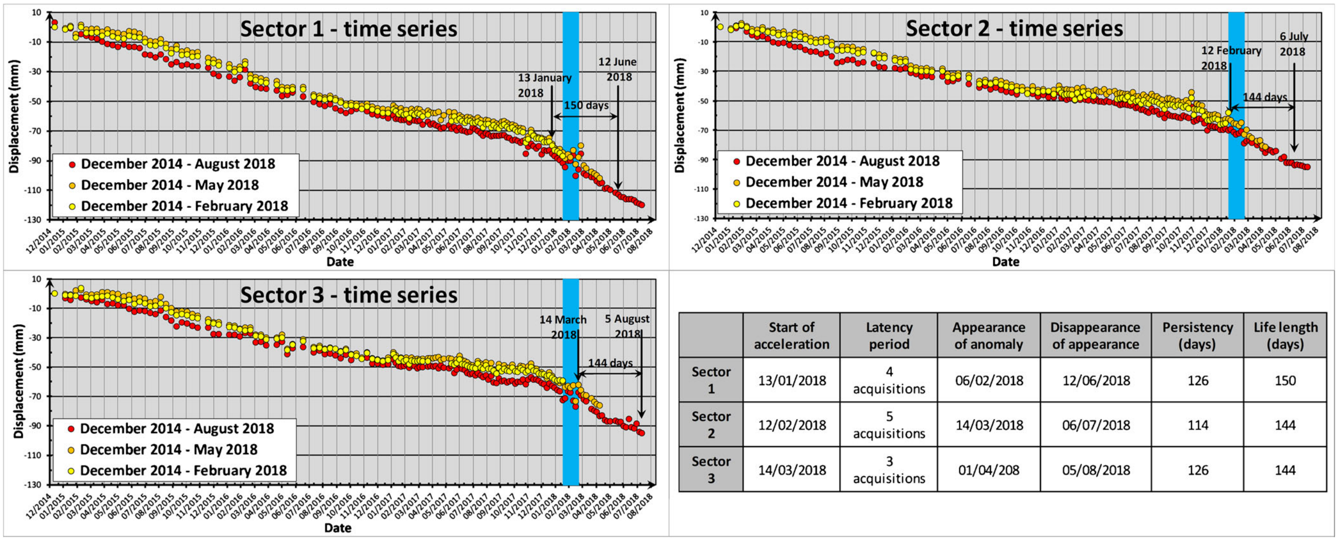


Fig. 5 Mean annual deformation rates of the Carpineta landslide obtained through the continuous processing of Sentinel-1 data acquisition. In the lower left insets, the increase over time of mean deformation velocities for the different sectors is shown



	Start of acceleration	Latency period	Appearance of anomaly	Disappearance of appearance	Persistency (days)	Life length (days)
Sector 1	13/01/2018	4 acquisitions	06/02/2018	12/06/2018	126	150
Sector 2	12/02/2018	5 acquisitions	14/03/2018	06/07/2018	114	144
Sector 3	14/03/2018	3 acquisitions	01/04/208	05/08/2018	126	144

Fig. 6 Displacement time series for the three sectors of the Carpineta landslide in three different time intervals (the same as in Fig. 5). The blue bar indicates the presence of snow on the ground. A summary table of the appearance, persistence and disappearance of anomalies in the three sectors of the Carpineta landslide is also shown

induced by long-term landslide movement. The acceleration of the landslide caused both the worsening of pre-existing damage patterns on various structures and the opening of new vertical cracks in the southern part of the village (Fig. 7).

Discussion

In the last two decades, multi-temporal InSAR techniques have experienced major developments and gained increasing attention within the scientific and end users' communities. Despite the maturity of interferometric techniques, most studies have focused on post-event reconstructions, concentrated on the spatial analysis of ground movement, and, possibly retrospectively, looked for precursory signals of already established motion. The enhanced temporal repetitiveness of the COSMO-SkyMed satellite constellation and the flexibility of the mission's configuration partially filled this gap and offered a new opportunity to effectively employ radar imagery to support operational programmes (Raspini et al. 2014).

Designed to provide timely and accurate data for decades to come, Sentinel-1 satellites support the development of a new approach in the field of InSAR analysis and foster the use of SAR data for long-term operational programmes. Benefitting the enhanced imaging capabilities of Sentinel-1, Barra et al. (2017) proposed an approach, based on the spatial filtering of ground deformation maps, to detect unstable areas at wide scale. Treasuring this approach, procedures for deriving impact assessment maps have been presented at wide (Solari et al. 2018b) and local scale (Béjar-Pizarro et al. 2017). Exploiting the operational readiness of Sentinel-1, the monitoring system active over the Tuscan region provides regional authorities with continuous information on where and how fast the ground is moving and, more importantly, offers early indications of non-linear ground motions. The approach is designed to identify different trends in time series, distinguish different components of motion and detect different phases in the evolution of a hydrogeological process: acceleration and deceleration, seasonal oscillation, changes in motion, or trend inversion. In this monitoring approach, which is operative at the regional scale, satellite radar data feed a decision chain for hydrogeological risk mitigation; this means that prioritisation and mitigation strategies for landslide risk reduction can start with satellite radar data and prioritise those slope instabilities that represent a major threat and are deemed to be most urgent. In particular, the focus of the proposed monitoring system is the detection of accelerating areas, as they can be directly related to precursory movements that indicate possible future landslide failure.

When a landslide is close to collapse, it may experience power-law acceleration (called tertiary creep) characterised by an increasing soil strain rate. The most popular prediction methods thus far have relied on the use of monitoring data acquired by ground-based devices and have plotted the inverse of the slope velocity against time (e.g. Fukuzono 1985). To this end, Sentinel-1 satellites offer systematic InSAR measurements for landslide monitoring at a wide scale in places where installation of ground-based systems would be unfeasible or at sites where accessibility is difficult. This monitoring approach mainly applies to those landslides experiencing a progressive acceleration that is long enough to be effectively registered with the current sampling frequency (6 days for Sentinel-1) and that does not suffer from the intrinsic limitations of any of the interferometric approaches (e.g. N-S exposure, vegetation cover, steep topography, snow cover).

In the case of the landslide of Carpineta, the increase in deformation went completely unnoticed, as no systematic remote sensing was being carried out in the area. Information on persistent anomalies affecting elements at risk is promptly delivered to the regional authorities in charge of geohazard management. The identification of an acceleration, even if it does not lead to complete failure, draws the attention of regional and local authorities, highlighting the need for further analysis to assess the severity of the hazard, define risk management strategies and decide the most appropriate actions to mitigate the posed risk. Field investigations are performed in areas at potential risk; these areas may also be

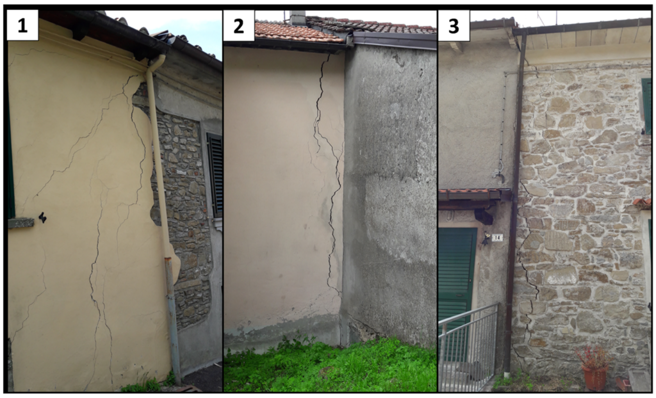


Fig. 7 Damage identified during the field survey of Carpineta hamlet. (1) Cracks in the external wall of a building in the central part of the village (sector 1). Front (2) and back (3) part of the same building affected by a vertical fracture in the southern part of the village (Sector 2)

targets for detailed analysis using high-resolution sensors (e.g. COSMO-SkyMed) or ground-based monitoring, which increases, if necessary, the temporal frequency of the observations and the spatial resolution of the data.

In April 2018, also the Valle d'Aosta Region started monitoring its territory adopting an approach similar to Tuscany (Solari et al. 2019). Outputs of this monitoring systems may seed future European activities, such as the scheduled European–wide Copernicus Ground Motion Service (EGMS), treasuring thematic information already available, such as the landslide database compiled by Herrera et al. (2018). Finally, experiences and protocols resulting from the current activity may enrich the web-based platforms and collaborative projects, such as the Geohazard Exploitation Platform (GEP) (Galve et al. 2017).

Conclusions

A new monitoring system based on the systematic processing of Sentinel-1 data acquisitions has been active since October 2016 over the entire Tuscany region. This system, which provides a continuous stream of processed data, marks the transition from retrospective satellite analysis to the timely monitoring of ground displacement at the regional scale. Following every new Sentinel-1 acquisition, automatic tools of data mining and screening are applied to the updated dataset, which consists of millions of measurement points, to highlight anomalies of movement, i.e. points where a change in the dynamic of motion is occurring. The results show that relevant clusters of persistent anomalies related to slope instability correspond to the most landslide-prone areas of the Tuscany region. During the winter of 2018, a small cluster of anomalous points appeared in the village of Carpineta in the Northern Apennines; these anomalous points reflected the acceleration of a large, active earth slide as a consequence of rainfall and snow melt. Systematic analysis of updated deformation time series allows the prompt identification of a landslide's acceleration, which could be underestimated or, even worse, totally undetected by a visual analysis performed by an operator on the basis of velocity maps only. Advances in the performance of satellite systems, processing algorithms, data mining tools and computational capabilities allow the design of new paradigms for monitoring ground deformation at the regional (or wider) scale, exploiting SAR data to feed a decision support system for hydrogeological risk mitigation strategies.

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