Landslides (2018) 15:183–197
DOI 10.1007/s10346-017-0875-y
Received: 27 March 2017
Accepted: 3 August 2017
Published online: 15 August 2017

W. Frodella · A. Ciampalini · F. Bardi · T. Salvatici · F. Di Traglia · G. Basile · N. Casagli

A method for assessing and managing landslide residual hazard in urban areas

Abstract On February 14, 2010, a large landslide affected the urban centre of San Fratello town (Sicily Island, Southern Italy), causing severe damage to buildings, roadways, and infrastructure, as well as about 2000 evacuees. This large complex landslide, covering more than 1 km^2 in extension, represents one of the major phenomena that ever occurred in Sicily. In order to manage the landslide risk, the civil protection system was activated as part of the initial response to the emergency (the "emergency phase"). This involved the Civil Protection Departments both at national (DPC) and regional (DRPC) levels, as well as scientific institutions (namely "Competence centres", CdCs), local administration personnel, and technicians. On March 8, 2010, during the post-event recovery phase, a ground-based synthetic aperture radar (GB-InSAR) system was installed in order to monitor the ground surface deformation, assess the landslide residual risk, and analyse its displacement trend. Accurate field surveys and building inspections were also performed for a validation of the GB-InSAR data, in order to map the ground deformation, plan building evacuation-demolishment, as well as check the efficiency of the landslide mitigation works. This paper describes the outcomes of the 57 month monitoring campaign (March 2010–December 2014), reporting the use of GB-InSAR data for near real-time monitoring, mapping, and post-emergency/recovery management activities. The final aim was to provide the civil protection personnel with a reliable, rapid, and easy communication system of the monitoring results, designed to an enhance understanding of the landslide phenomena, and to support the decision-making process.

Keywords GB-InSAR · Landslide · Long-term monitoring · Post-emergency management · Residual hazard

Introduction

When landslides interact with human settlements, the availability of new remote-sensing technologies may improve the production of landslide maps, reducing costs, and optimizing field work by allowing for systematic data acquisition over wide areas (Guzzetti et al. 2012). In Italy, historical settlements are often built on hilltops suffering from stability issues, therefore requiring the implementation of monitoring systems, as well as expensive maintenance and restoration works (Ciampalini et al. 2012; Bianchini et al. 2015). In the last two decades, amongst the many new methods used in landslide investigation, terrestrial-based technologies such as digital photogrammetry (Zhang et al. 2004; Sturzenegger and Stead 2009), light detection and ranging (LiDAR; Oppikofer et al. 2009; Fanti et al. 2013), infrared thermography (Gigli et al. 2014a, b; Frodella et al. 2015), and ground-based radar interferometry (GB-InSAR) (Luzi et al. 2004; Lombardi et al. 2016) are increasingly being recognized as efficient remote surveying techniques for the characterization and monitoring of landslide-affected areas, in terms of resolution, accuracy, data visualization, management and reproducibility. GB-InSAR systems in particular, for their capability of measuring displacements with high geometric accuracy, temporal sampling frequency and adaptability to specific applications (Monserrat et al. 2014), represent powerful devices successfully employed in engineering and geological applications for detecting structural deformation and surface ground displacements (Tarchi et al. 2003; Antonello et al. 2004; Casagli et al. 2010, 2017), for the monitoring of volcanic activity (Di Traglia et al. 2014a, b), and for analysing the stability of historical towns built on hilltops (Luzi et al. 2004; Nolesini et al. 2016). 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 (Broussolle et al. 2014; Frodella et al. 2016; Bardi et al. 2017).

The San Fratello February 14, 2010 landslide

On February 14, 2010, the urban centre of San Fratello town (north-eastern Sicily, Southern Italy) was affected by a large landslide developing along the entire eastern hillslope of the town, which severely damaged the urban fabric and roadways, causing about 2000 evacuees (out of a total population of 4500 inhabitants), also disrupting the local transportation.

In this context, the civil protection system was activated in order to manage the landslide emergency phase, by involving the national (DPC) and regional (DRPC) 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). During the post-emergency phase, several remote-sensing techniques, such as LiDAR and satellite- and ground-based SAR, were used, combined with detailed field surveys, in order to provide the civil protection authorities with advanced products to be used for landslide risk management, such as the following:

- building deformation analysis (Ciampalini et al. 2014);
- basin scale landslide pre- and post-event ground deformation assessment (Bardi et al. 2014);
- implementation of an accurate geo-database to produce maps (e.g., susceptibility, ground deformation velocities, damage assessment, risk zonation) (Ciampalini et al. 2015);
- multi-temporal and spatial investigation of active and dormant landslide effects on historical buildings (Bianchini et al. 2015);
- improvement of landslide inventory (LiM) and susceptibility maps (Ciampalini et al. 2016a; Raspini et al. 2015);
- testing the effectiveness of high-resolution DEMs as tools for an accurate PSI post processing analysis (Ciampalini et al. 2016b).

This work focuses on the outcomes of the 57-month GB-InSAR monitoring campaign (March 2010–December 2014) carried out during the post-event recovery phase. In this time, span operative methodologies have been implemented to assess the landslide residual risk by the following: (i) mapping the slope surface deformation pattern; (ii) analysing the landslide deformation trend; (iii) evaluating post-emergency recovery measures (stabilisation works, products for updating landslide inventory). In this context, various field activities were carried out by local civil protection operators and technicians for a validation of the remotely sensed data (accurate geomorphological mapping and building inspections).

Such a long-monitoring campaign represents an interesting case study in order to test the potential and versatility of GB-InSAR data, applied to both short- and long-term landslide post-disaster management within a populated urban area.

Study area

The town of San Fratello is located in the north-eastern sector of Sicily, on the northern hillside of the Nebrodi mountains, a 70-km-long ridge trending ENE-WSW which is part of the Southern Apennine chain (Fig. 1a). The geomorphology of the area is characterized by steep slopes rising from the Tyrrhenian coastal plain, deeply cut by creek valleys trending N-NW (Fig. 1b). The town area stands in a mid-mountainous-hilly area at about 700 m a.s.l., on top of a N–S-oriented ridge which separates two watersheds: the Furiano creek valley to the West and the Inganno creek valley to the East (Fig. 1c). The geology of the area (part of the N-E sector of the Apennine-Maghrebian orogenic belt) is characterized by the tectonic overriding of the Kabilian-Calabrid units, occurring as dolomitic limestone and sandstone, overlaying the Apenninic-Maghrebid units, formed mainly by marlstone and claystone (Lentini et al. 1990, 2000). The San Fratello relief mainly consists of a thick terrigenous sequence (Lower Cretaceous in age) interbedded with claystone, marlstone, and sandstone (from bottom to top: Mt. Soro Flysch, Argille Scagliose unit), widely cropping out along the gentle ridge slopes (Fig. 1d). The northern sector of the town, characterized by a rough morphology, is formed by a Giurassic-Eocenic sequence of pelagic dolostone and limestone (San

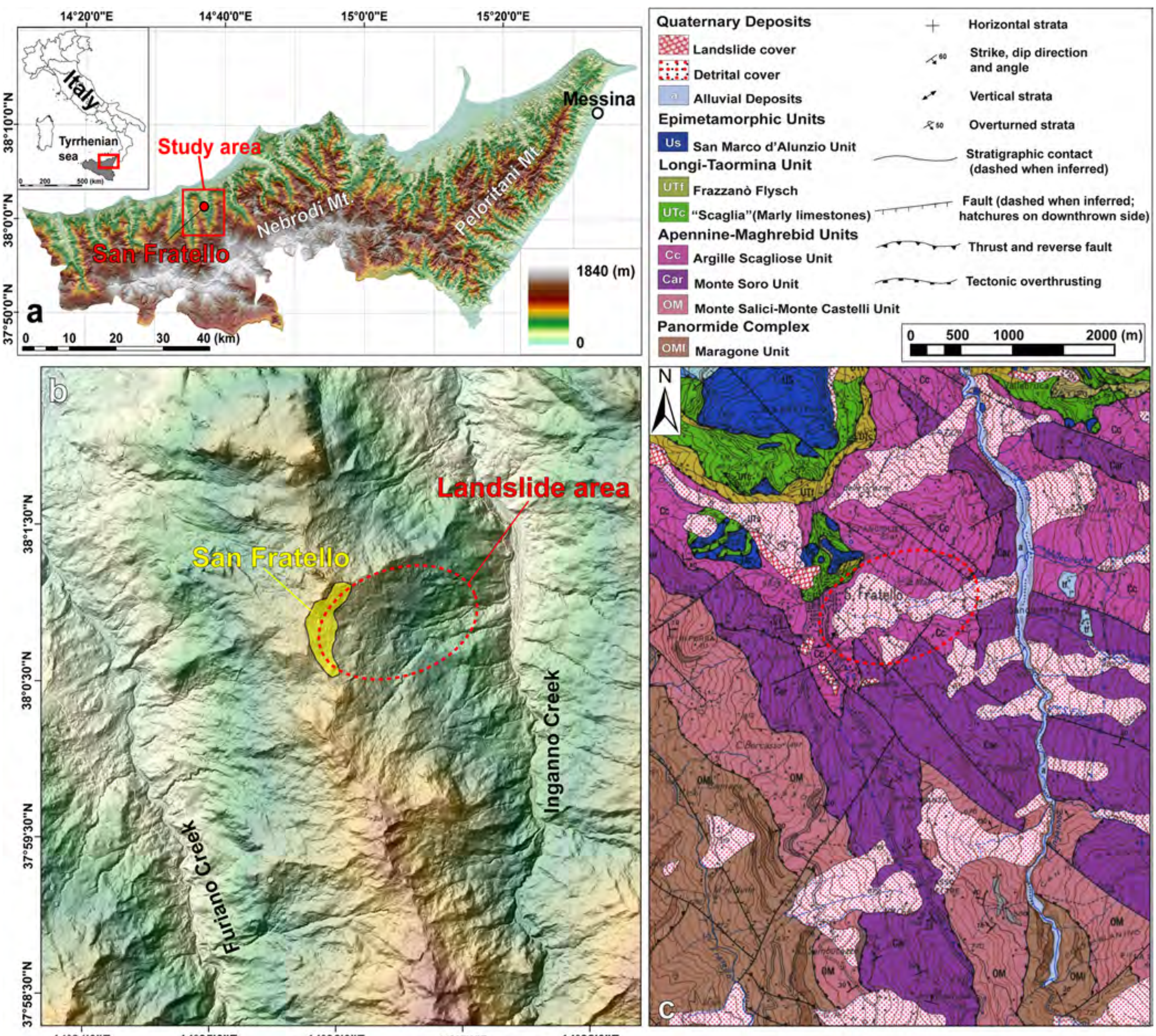

Fig. 1 **a** Location of the study area with digital elevation model of the Messina Province showing the study area. **b** DEM of the San Fratello area (2 -m cell resolution). **c** Geological setting of the study area (dotted red oval enhances the town sector; modified after Lentini et al. 2000)

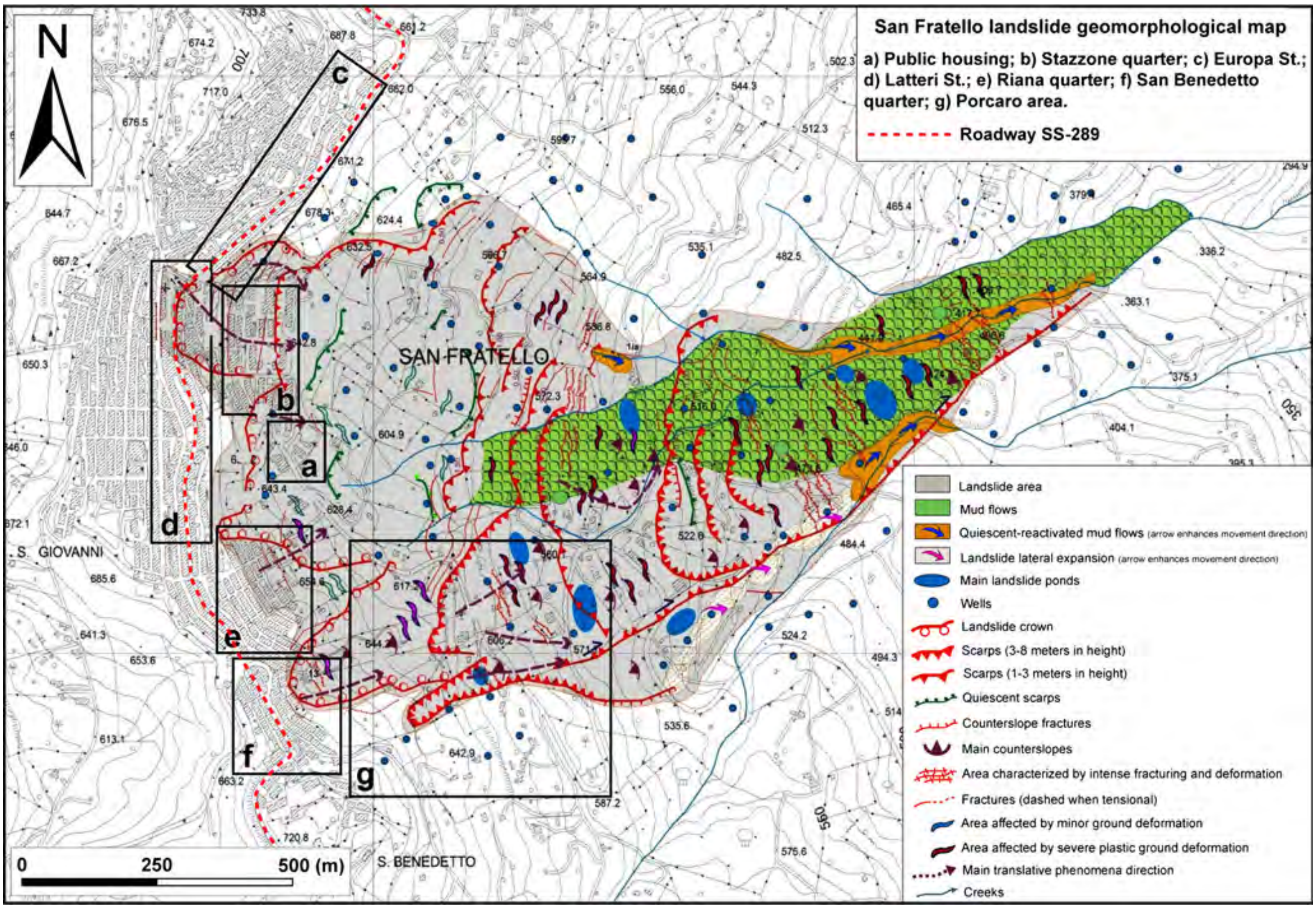

Fig. 2 Geomorphological map of the San Fratello landslide (courtesy of DRPC) and location of the affected quarters. **a** Public housing. **b** Stazzone quarter. **c** Via Europa-Via Fontana nuova. **d** Via Latteri-Via Gioberti. **e** Riana quarter. **f** San Benedetto quarter. **g** Porcaro quarter-scattered housing

Fig. 3 Example of ground deformations and damage to buildings and structure in the 2010 landslide area. Stazzone quarter: **a** oriented extensional cracks on building facades and **b** damaged asphalt road pavement; Riana Quarter: **c** landslide scarps and **d**: traction cracks in road pavement; San Benedetto-Porcaro quarters: **e** country roadway complete failure and **f** building total collapse (see also Bianchini et al. 2015 for detailed building damage description)

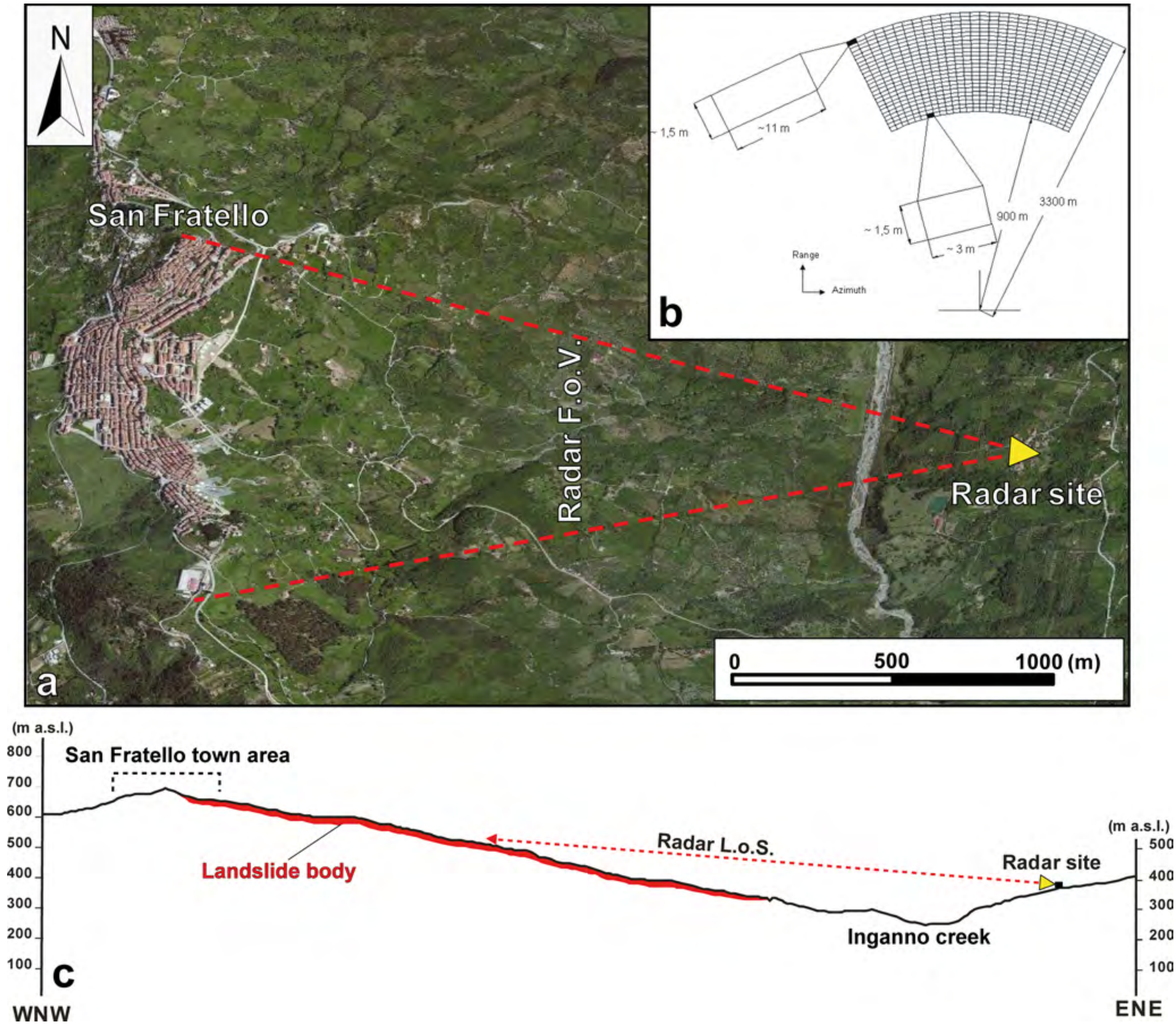

Fig. 4 GB-InSAR system features. **a** Map with the location of the monitoring system (F.O.V. field of view). **b** Resolution grid size and parameters used in the monitoring campaign. **c** Schematic cross-section representing the location of GB-InSAR system and landslide body, together with the geometry of radar LOS and landslide movement direction

Marco D'Alunzio unit), overriding sandstone and marly limestone layers (Unità Longi-Taormina) (Nigro and Sulli 1995; Lavecchia et al. 2007) (Fig. 1c, d). The landslide-affected slope is characterized by urban areas, farms, and olive groves. A silty-clayey detrital cover lies over the bedrock with an average thickness of about 10 m (DPCR 2010). This geological context causes the overlapping of hard-brittle lithotypes (San Marco D'Alunzio-Longi-Taormina units) on top of the soft erodible clayey formations (Mt. Soro Flysch-Argille Scagliose unit), deeply influencing the area landscape and causing widespread slope instability phenomena. For these reasons, the San Fratello area has been historically prone to hydrogeological hazards: during the last three centuries, two large landslides, occurring in 1754 and in 1922, respectively, had already destroyed the north-eastern and western sectors of the town (Bardi et al. 2014; Ciampalini et al. 2014; Bianchini et al. 2015).

Landslide description

In the period from October 2009 to February 2010, the Mt. Nebrodi area (Fig. 1) was severely affected by several landslides that caused widespread structural damage and casualties (Ciampalini et al. 2015).

Table 1 GB-InSAR system parameters used to monitor the San Fratello landslide

Central frequency	Band width	Synthetic aperture	Min. distance	Max. distance	ΔRr	ΔRaz (at 900 m distance)	ΔRaz (at 3300 m distance)	Scanning time
17.1 GHz	200 MHz	3.00 m	900 m	3300 m	1.5 m	3 m	11 m	14 min

Intense and exceptional rainfall events were the main factor that, combined with steep slopes and widespread clayey outcropping lithotypes, triggered several slope movements. The February 14, 2010 landslide has affected a 1.2-km^2 portion of the Inganno creek east-facing slope, developing for a 450-m level drop, with a maximum width of 1.5 km and length of 1.9 km (Bardi et al. 2014; Ciampalini et al. 2014; Fig. 2). It can be classified as a complex roto-translational mass movement (Cruden and Varnes 1996) about 20×10^6 m^3 in size, which involved mainly the silty-clayey cover for an average thickness of 10 m, and only to a lesser extent the bedrock (Bardi et al. 2014; Pagliara et al. 2014). In the upper area of the landslide, a wide crown developed (mainly in correspondence with the town quarter areas), while minor scarps and tensional/traction fractures occurred in the middle non-urbanized slope sector, and the landslide toe evolved downstream into a slow earth flow (Fig. 2). The resulting ground deformations intensively modified the topographic slope surface, producing multiple scarps (characterized by heights between 5 and 10 m) and counter-slopes, also modifying the drainage system with the formation of several landslide ponds (Fig. 2). Ground deformations intensively damaged the town structures (Fig. 3), in particular:

- the most damaged area was the Stazzone quarter, where prevalent rotational phenomena developed traction fractures in the roadways and compressive fissures on the buildings' facades (the church, the primary school, and the sewer system were heavily damaged or completely destroyed);
- in the Riana quarter, translational sliding phenomena caused the formation of sub-parallel fracture systems and secondary scarps, with the development of deep, wide ground traction fractures on the road pavement;

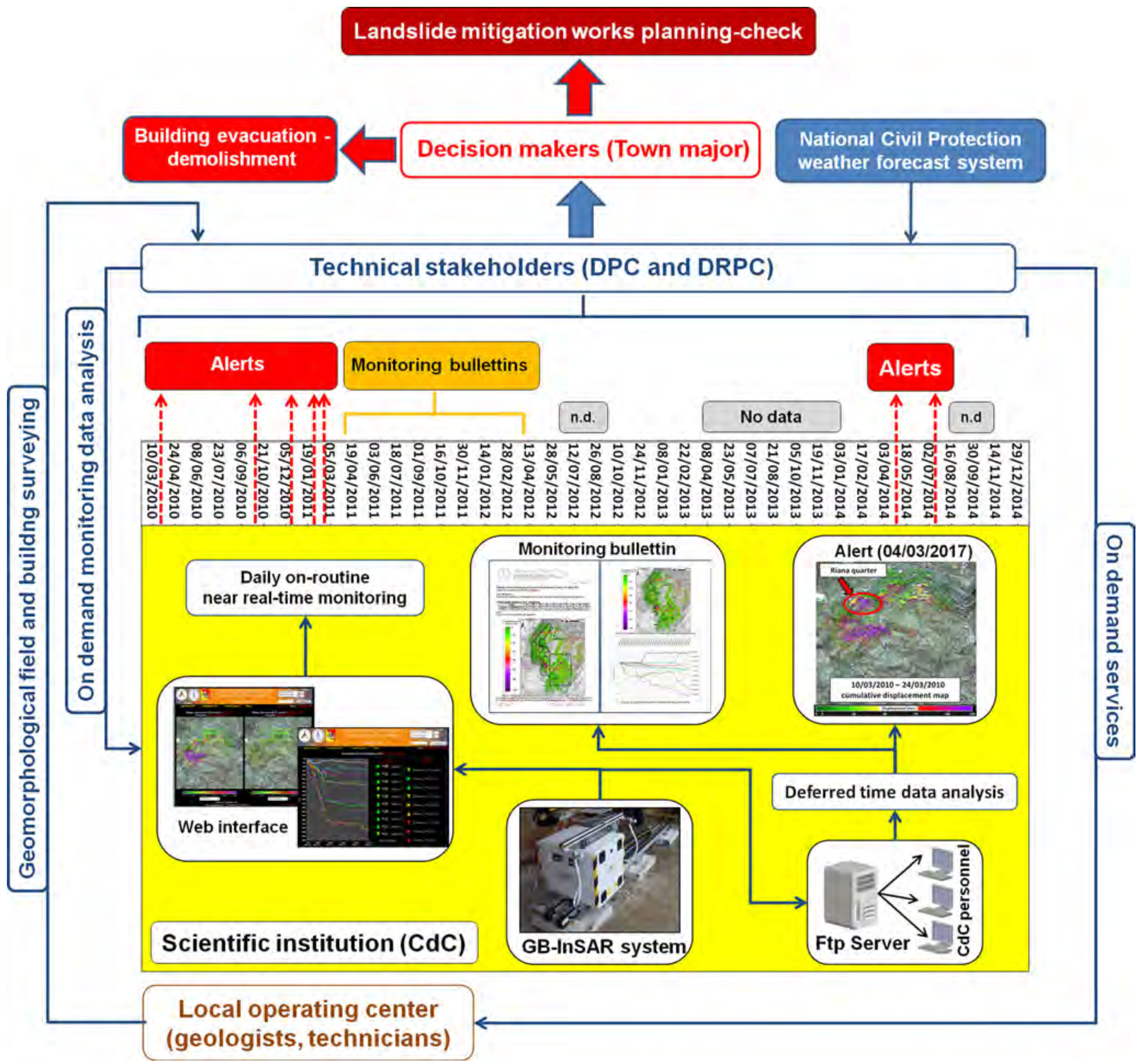

Fig. 5 Timeline rationale of the San Fratello monitoring system

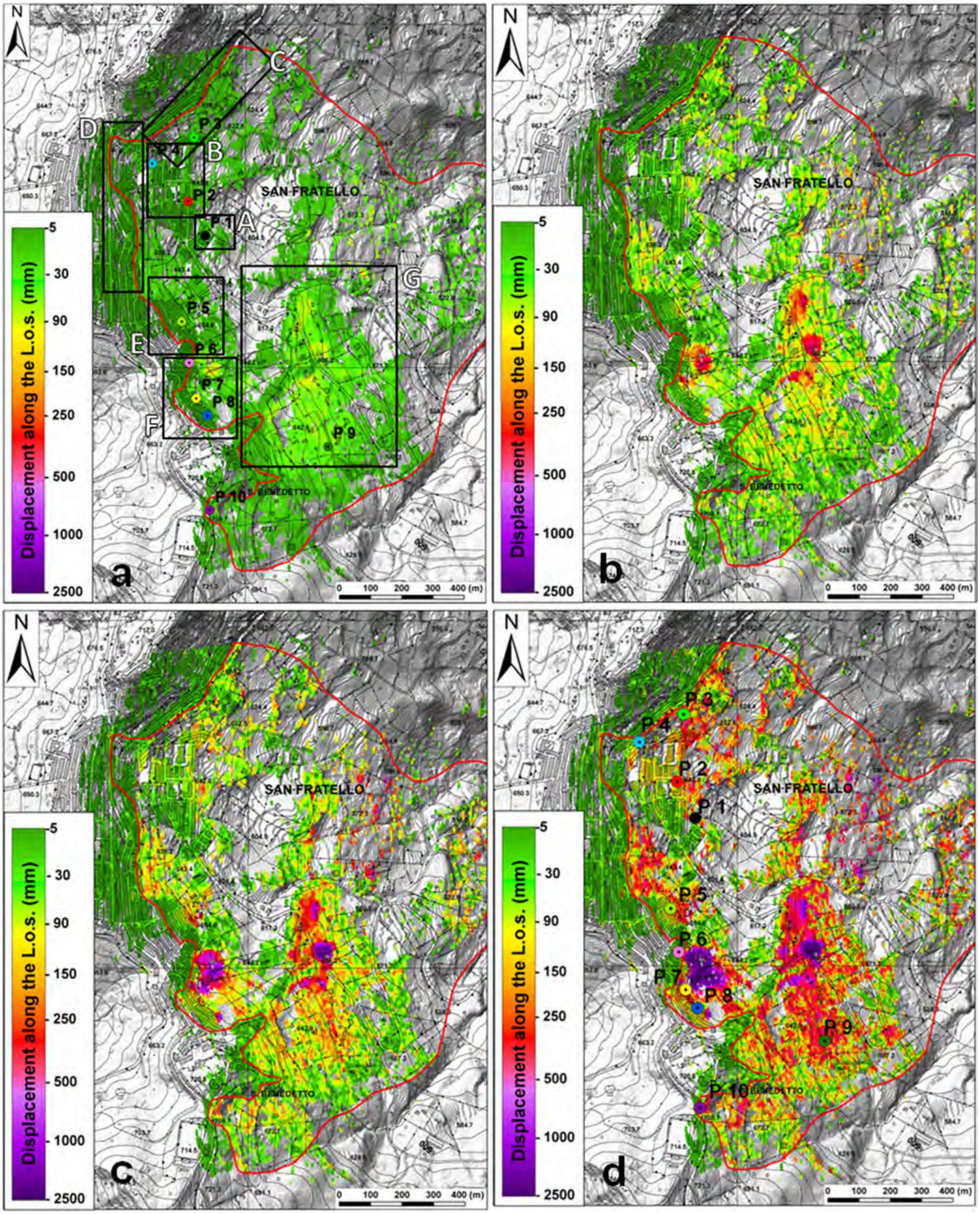

Fig. 6 Incremental cumulated displacement maps (ICD maps) of the San Fratello area. **a** March 10, 2010–April 1, 2010 (squares A–G delimit the quarter areas shown in Fig. 3). **b** March 10, 2010—November 1, 2010. **c** March 10, 2010—April 1, 2010. **d** March 10, 2010—December 2014 (P1–P10 represent the GB-InSAR measurement points in correspondence of which the displacement time series were extracted). In red which is highlighted is the landslide boundary according to Ciampalini et al. 2014 and Bardi et al. 2014

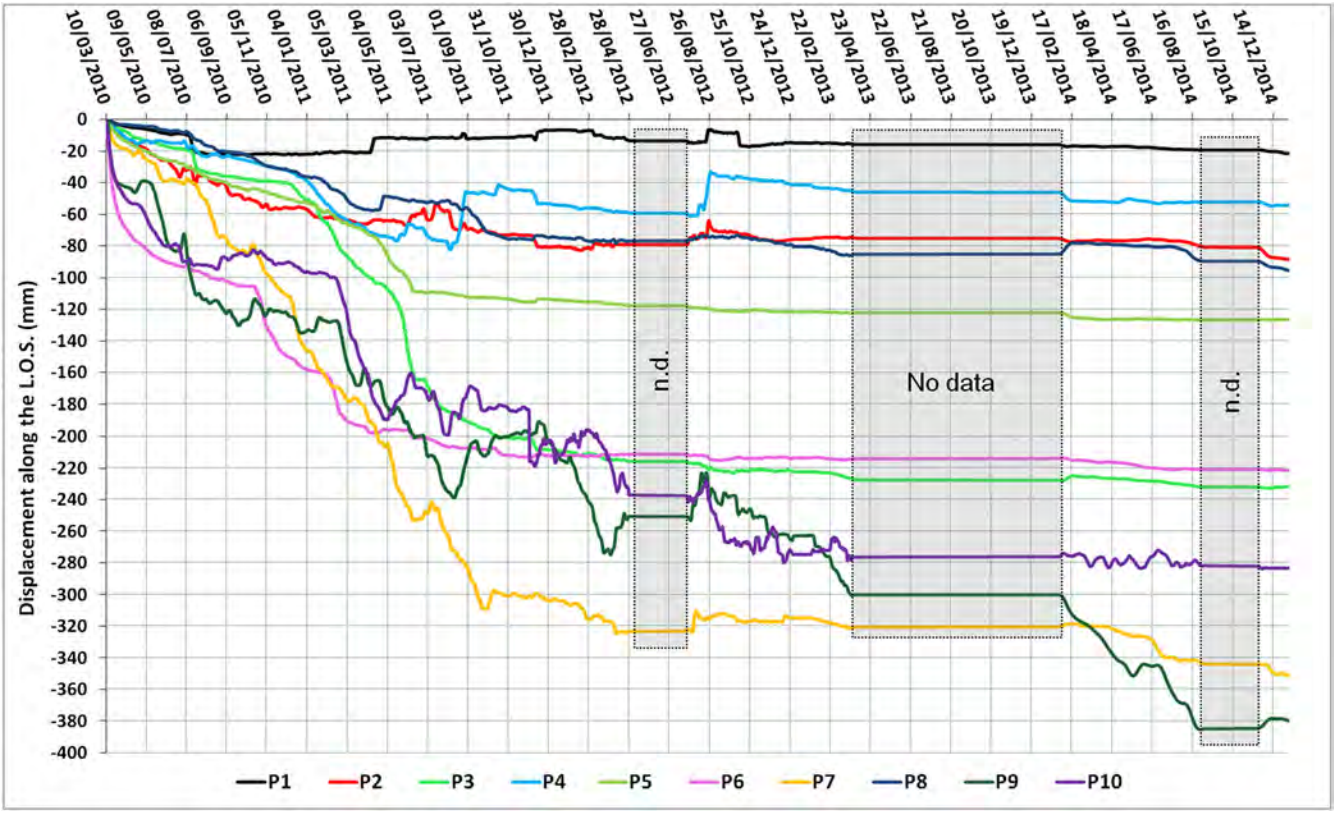

Fig. 7 Selected measuring points displacement time series of the scenario monitored. **a** Northern sector. **b** Southern sectors (see Fig. 6 for measuring points and sector location)

- in the San Benedetto and Porcaro quarters, located in the southern sector of the town, both translational and rotational phenomena and local flows caused the complete destruction of isolated buildings, roadways, water pipes, and the sewer system;
- in the upper sector of the town, a transect of the Cesarò SS 289 roadway (Fig. 2), representing one of the most important local linear infrastructures, was also damaged, causing temporary transport problems.

GB-InSAR theoretical principles

GB-InSAR system consists of a computer-controlled microwave transceiver, characterized by transmitting and receiving antennas, which by moving along a mechanical linear rail are able to synthesize a linear aperture along the azimuth direction (Tarchi et al. 1997; Rudolf et al. 1999). A SAR image is obtained by combining the spatial resolution along the direction perpendicular to the rail (range resolution, ΔRr), and that parallel to the synthetic aperture (azimuth or cross-range resolution, ΔRaz) (Luzi 2010). This image contains amplitude and phase information, measured during the acquiring time interval, regarding the backscattered echo of the observed scenario (Luzi et al. 2004; Monserrat et al. 2014). 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 constitutes 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 of two or more subsequent coherent SAR images, it is possible to derive from the interferograms obtained a map of the displacements that occurred along the sensor line-of-sight (LOS), with a millimetre accuracy in the Ku band (Tarchi et al. 1997; 2003). The ability of the technique to detect ground displacement depends on the persistence of phase coherence (ranging from 0 to 1) over appropriate time intervals (Luzi 2010). According to the specific acquisition geometry, only the displacement component along the sensor LOS can be estimated, whereas the displacements occurring along a direction perpendicular to the LOS are missed; this is one of the limitations of the GB-InSAR technique.

The radar system must be placed in order to make the sensor LOS as parallel as possible to the expected direction of the landslide motion. Nevertheless, the GB-InSAR represents a versatile and flexible technology, allowing rapid changes in the type of data acquisition, such as geometry and temporal sampling, based on the characteristics of the monitored slope failure.

The GB-InSAR monitoring campaign

On March 8, 2010, a GB-InSAR system was installed on the right flank of the Inganno Creek valley, opposite with the San Fratello town, at an average distance of 2100 m with respect to the landslide (Fig. 4; Table 1). Given the acquisition setting of the site and the civil protection needs, the radar data covers an area of about 1 km^2, corresponding to the middle-upper landslide sector and the town area. The GB-InSAR data were processed

Table 2 Features and displacement values of the selected measuring points

Measurement point	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10
Quarter area	A	B	C	B	E	E	F	F	G	South of G
Surface type	Building	Demolished building	Building	Local road	Building	Demolished building	Building	Building	Vegetated slope	Local road
Cumulative displacement (mm)	21.4	88.5	231.9	54.4	126.5	221.6	350.8	95.4	379.9	283.4
Mean velocity (mm/day)	0.014	0.058	0.152	0.035	0.082	0.145	0.229	0.062	0.248	0.182

using LiSALab software (Ellegi s.r.l.). In order to mask the noisy areas, a 0.4 coherence filter was applied. Radar images were acquired every 14 min, but for comparisons, 24-h averaged images were used. Other radar parameters used during the measurement campaign are summarized in Table 1. The radar started to acquire data 2 days after the installation and has been active for almost 5 years. In the context of the post-event recovery phase, GB-InSAR data analysis was combined with detailed geomorphological surveys and building inspections for the following:

- mapping and monitoring slope residual deformations for early warning purposes in case of landslide reactivations, so as to assure the safety of all the town inhabitants and of all the personnel involved in the recovery phase;
- selecting the buildings to be evacuated and pulled down, based on their damage conditions;
- assessing geomorphological hazard for new settlements;
- planning the landslide mitigation works (bulkheads, draining wells, and trenches) and evaluating their effectiveness;
- updating landslide inventory.

The following operative approach (Fig. 5) was adopted:

Daily on-routine near real-time monitoring

GB-InSAR data were uploaded via LAN network on a dedicated Web-based interface, which was shared with the DPC-DRPC personnel. For a clear visualization of the results and an effective data dissemination, the Web interface was organized in different sections, allowing for a near real-time on-routine visualization of the monitoring data, such as the following:

- displacement maps (spanning selectable time periods);
- displacement time series of selected measuring points;
- related trends (decreasing, stable, increasing) and criticality assessment (ordinary, moderate, high).

Due to technical problems, the system has undergone a few acquiring interruptions (Fig. 5).

On demand deferred time data analysis

The results of the on-demand data analyses were delivered to the DPC-DRPC personnel by using a remote ftp server, in the occurrence of critical weather events; based on the national civil protection weather forecast system (http://www.protezionecivile.gov.it/jcms/en/allertamento_meteo_idro.wp), GB-InSAR displacement maps (ASCII format) were integrated into a GIS environment and converted into the correct metric scale and coordinate system, overlapped to a chosen cartographic base (DEMs, topographic maps, and orthophotos), and compared with ancillary data (rainfall, geological, and geomorphological maps). Based on the surface of the deformation areas and the increasing trends of displacement time series, seven monitoring alerts were obtained (Fig. 5). This procedure allowed for the precautionary evacuation of the Riana-San Benedetto quarters on March 17, 2011, after heavy and persistent rainfall events and three monitoring alerts, starting from February 1, 2011 to March 4, 2011. Following the evacuation, a monthly bulletin phase

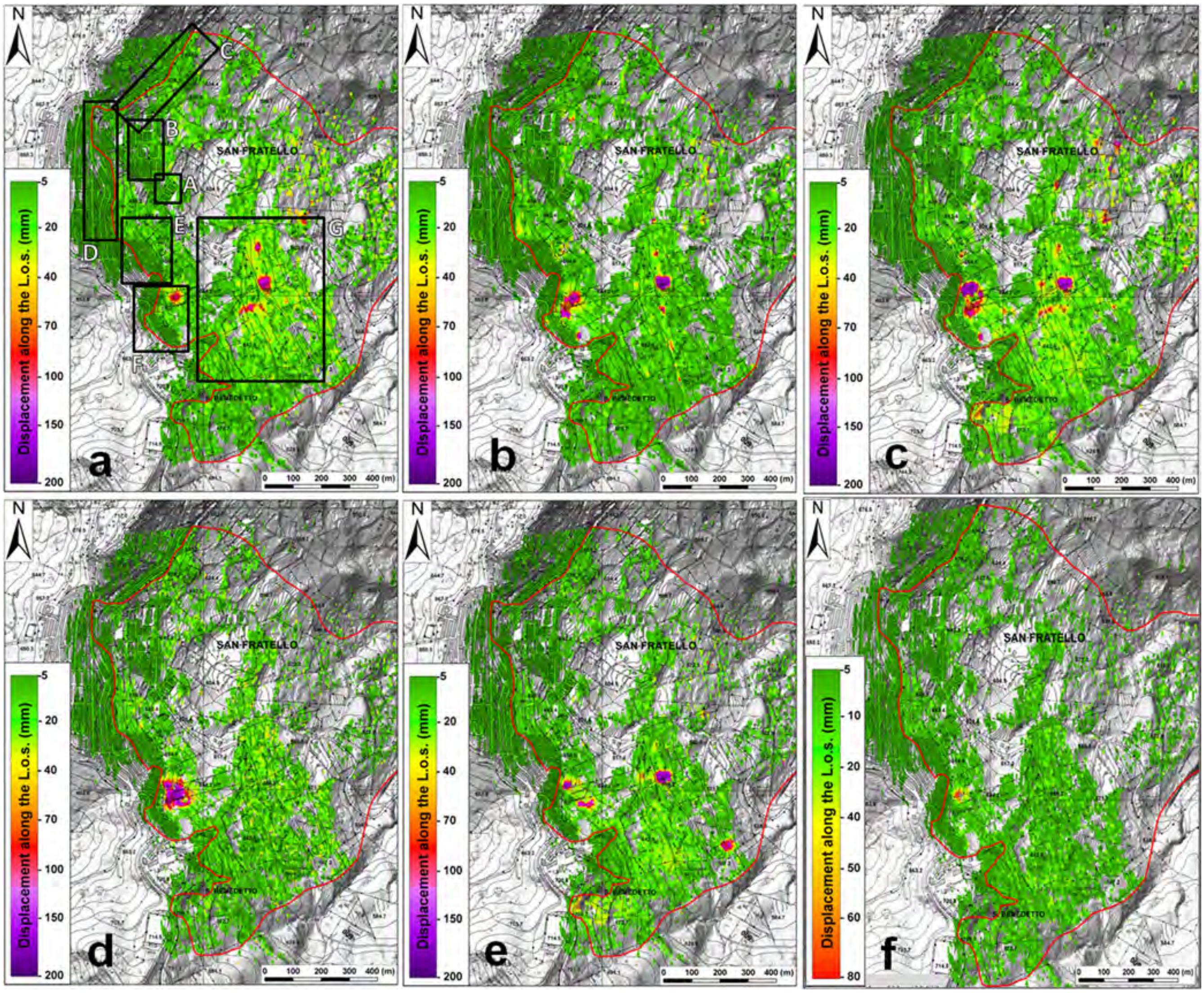

Fig. 8 Selection of monthly cumulated displacement maps (MCD maps). **a** April 2010 (91 mm). **b** December 2010 (184 mm). **c** March 2011 (139 mm). **d** October 2011 (160 mm). **e** February 2012 (133 mm). **f** July 2014 (65 mm). In red which is highlighted is the landslide boundary according to Ciampalini et al. 2014 and Bardi et al. 2014

(April 2011–March 2012) was planned as a strategy for landslide residual risk prevention.

Monitoring data analysis

GB-InSAR incremental cumulative displacement maps and displacement time series

The collected GB-InSAR dataset, consisting in incremental cumulative displacement (ICD) maps and displacement time series of 10 selected measuring points, are shown in Figs. 6 and 7, respectively. The obtained radar maps show the global increase of the slope surface deformation, starting from March 10, 2010 up to the first day of each successive month of the monitoring campaign. The ICD maps are shown as a function of the displacement measured along the device LOS (the negative displacement values indicate movements approaching the sensor) (Fig. 6). In order to evaluate the deformation rates and provide easily interpretable data, a traffic light type colour scale was adopted. From the analysis of ICD maps and displacement time series, two areas characterized by the highest residual displacement were identified, falling within the San Benedetto (sector F; 2524 mm) and Porcaro quarters (sector G; 2259 mm) (sectors F and G in Fig. 6a). Minor ground deformations were measured within the Riana (sector E) and Stazzone quarters (sector B), where cumulated displacements reached 664 and 450 mm, respectively. The displacement time series of the measurement points (P1–P10 in Fig. 6a; corresponding to a 5×5 pixel size area) were selected in correspondence with sectors with high stability of the radar signal i.e. high signal/noise ratio in SAR power image and high coherence (> 0.40), in order to accurately monitor the deformations of structures and buildings (Fig. 7). The displacements recorded in correspondence with the measurement points are related to their specific location; thus, they do not necessarily reflect the maximum displacement of the whole area investigated (Table 2). The analysed displacement time series confirmed the deformation trend highlighted by the cumulated maps (Fig. 7). In particular, in the northern sector of the town, represented by the public housing area (sector A in Fig. 6a) and Stazzone quarters (sector B in Fig. 6a), P1, P2, and P4 points recorded low cumulative displacements, while

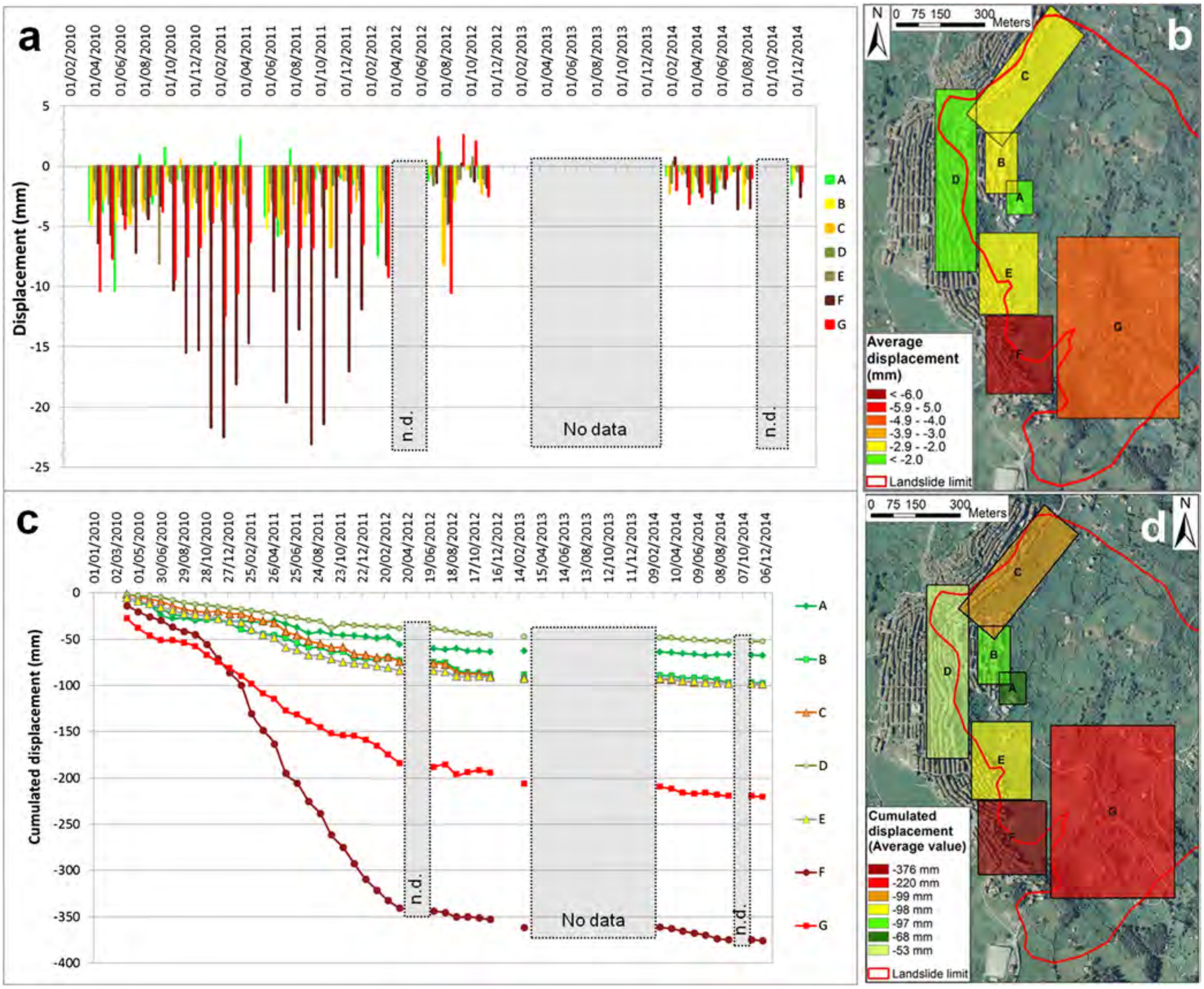

Fig. 9 Average displacement estimation in correspondence of each town quarter. **a** Monthly average displacement values measured in correspondence of each of the San Fratello quarters. **b** Average displacement map within the quarter areas during the whole monitoring period. **c** Cumulated displacement time series (monthly cumulated average values of each town quarter area). **d** Map of the maximum displacement values registered in correspondence of each quarter during the whole monitoring period

moderate values were measured in correspondence with P3 point (Via Europa area, sector C in Fig. 6a). Slope deformations are more relevant in the town's southern sector, in correspondence with P5 point within the Riana quarter (sector E in Fig. 6a), and especially regarding P6, P7, and P8 points in the San Benedetto quarter (sector F in Fig. 6a).

The peak cumulative displacements recorded within all of the measuring points correspond to P9 and P10 points, which fall within uninhabited areas in the Porcaro quarter-scattered housing area (sector G in Fig. 6a).

GB-InSAR monthly cumulated displacement maps

Moreover, so as to perform a temporally detailed displacement analysis (from the beginning to the end of each month) for detecting residual landslide hazard areas, monthly cumulated displacement (MCD) maps were also selected and analysed from the dataset (Fig. 8). The comparison amongst these emphasized that displacements are particularly relevant during the winter-fall season, ranging from the maximum measured value of 184 mm in correspondence with area G (December 2010; Fig. 8b) to 133 mm in correspondence with area F (February 2012; Fig. 8e). On the contrary, the summer periods highlighted lower displacement values, from a maximum of 69 mm (July 2014; Fig. 8f) to the lowest value in the overall monitored period (a few millimetres; August 2012 and September 2012). In order to enhance the areas affected by higher/lower displacement values, MCD maps were also used as input data for average displacement estimation in correspondence with each town quarter (Fig. 9). Average values are usually affected by lower noise than "raw" values and are more representative of the general displacement trend in the selected area. The analysis was performed in a GIS environment, by means of the "zonal statistic" tool (Fig. 9). The average displacement was calculated on each single monthly cumulated displacement map (Fig. 9a), showing that the areas G and F in particular are affected by the highest slope deformation trend, as also confirmed by the spatial representation of the cumulated and average values for each quarter (Fig. 9b). In Fig. 9c, the cumulated displacement time series is

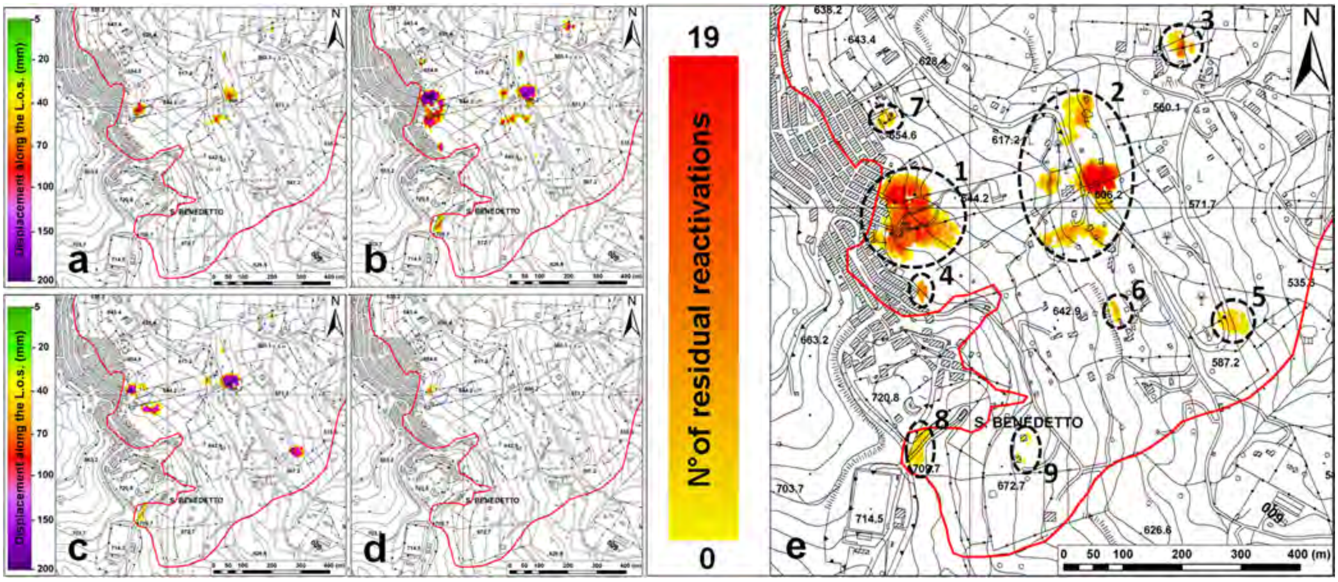

Fig. 10 Results of the employed MATLAB code applied to the GB-InSAR dataset. Residual reactivation maps obtained from selected MCD maps. **a** April 2010. **b** March 2011. **c** February 2012. **d** July 2014. **e** Frequency map of the reactivation of the critical residual displacement sectors, classified basing on their activation frequency from 1 (most active) to 9 (least active)

reported by calculating the monthly cumulated average values in correspondence with each town quarter area. While in Fig. 8d, the quarter areas' maximum displacement map is reported, enhancing 220 mm for area G and 376 mm for area F. Spatial average values can imply the underestimation of localized peak displacements; therefore, in order to automatically extract the most critical residual displacement sectors, the data were also analysed by means of a MATLAB code (Salvatici et al. 2017) (Fig. 10). The code extracts from the MCD maps dataset all of the areas affected by deformation higher than a selected threshold value (= 32 mm; being the minimum displacement amongst all the maximum monthly values; Fig. 8). The results are displacement maps highlighting only the areas with such selected displacements (Fig. 10a, d). The second operation of the employed code consists in the frequency calculation of displacement occurring (the code computes how many times each pixel has recorded the selected displacement during the monitoring period) (Fig. 10e). By using this method, nine critical areas characterized by repeated residual reactivations were detected.

Discussion

Assessment of landslide residual hazard

Successful strategies for landslide residual hazard assessment and risk reduction imply integrated methodology for instability detection, mapping, monitoring, and forecasting (Confuorto

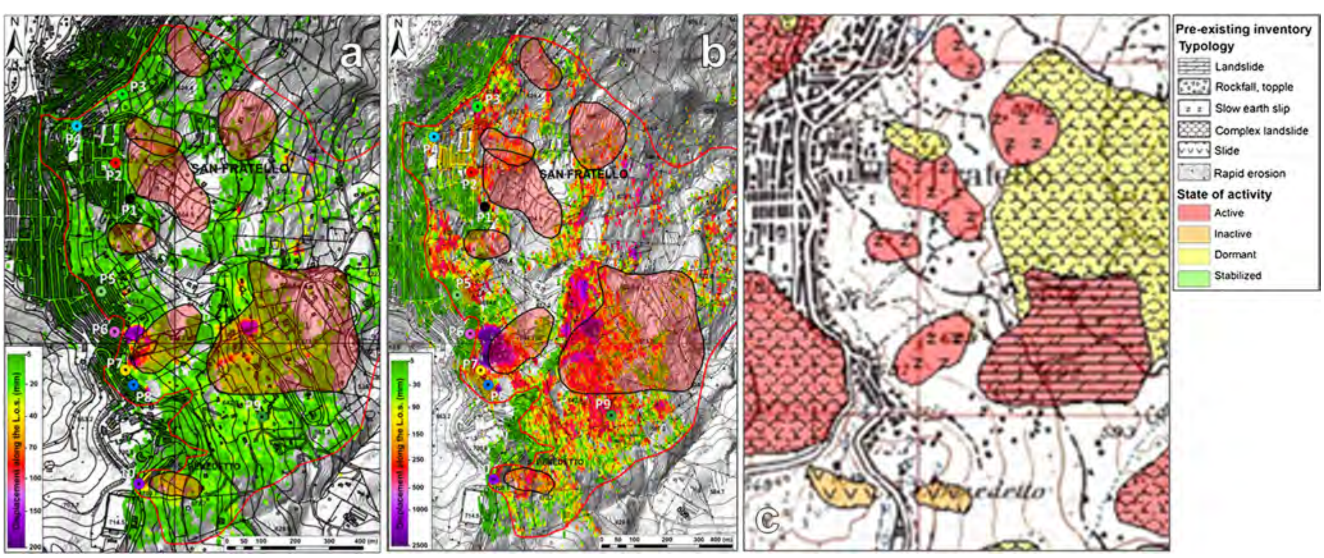

Fig. 11 Comparison between radar maps and landslide inventory of San Fratello area. **a** March 2011 MCD map. **b** December 13, 2014 ICD map A. **c** Landslide inventory map from PAI (Piano di Assetto Idrogeologico—hydrogeological setting plan; AdB 2012)

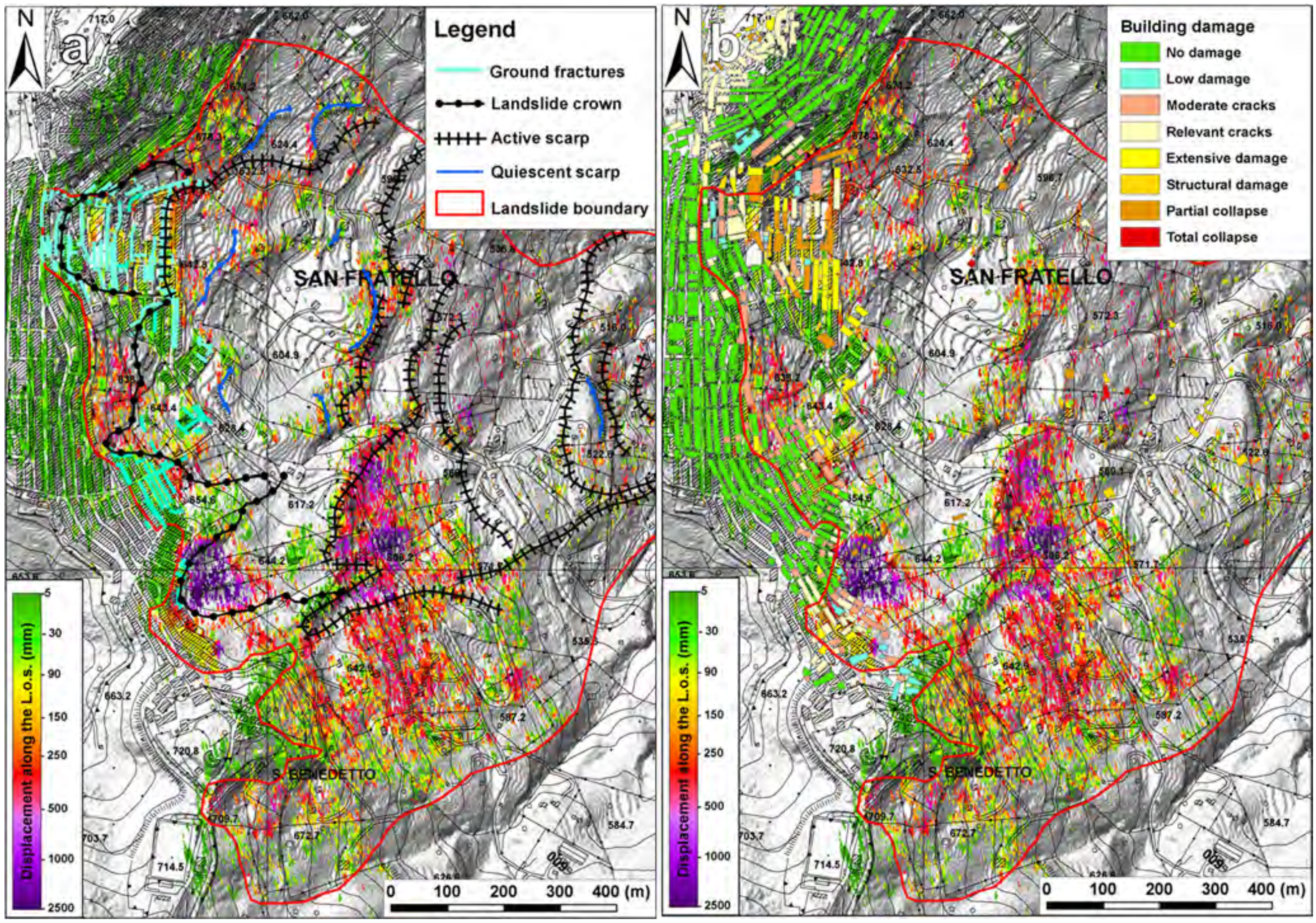

Fig. 12 Comparison between ICD map of the total monitoring period and field surveys. **a** Slope fracture field mapping (courtesy of DRPC). **b** Building damage assessment map (modified after Ciampalini et al. 2014)

et al. 2017). Detection and mapping need a combination of the "classical" approach providing information on the nature, extent, and frequency of past landslide events (i.e. field-based studies, standard geomorphological mapping) and advanced techniques, such as remote-sensing data analysis and geophysical investigations (Frodella et al. 2014; Ciampalini et al. 2015). In particular, the extent and the magnitude of the landslide residual hazard could be successfully assessed using ground-based monitoring techniques, and of these, the one giving best results appears to be GB-InSAR (Di Traglia et al., 2014a, b; 2015; Carlà et al. 2016a, b). In the study area, the 57 months of continuous GB-InSAR data acquisition enabled the measurement of the slope surface deformation pattern with millimetre accuracy over a 1.2-km^2 landslide area. This allowed the analyses of the landslide residual hazard evolution during the post-2010 event phase. The GB-InSAR system requires the user to choose the optimal radar location for measuring the most significant displacement signal, providing the most suitable resolution and allowing for continuous monitoring of ground deformation (Di Traglia et al. 2015), also in the case of unstable slopes with mitigation works (Bozzano et al. 2011). In the San Fratello area, the logistics of the GB-InSAR system installation favoured a good data spatial coverage on the monitored slope, especially with regard to the town's inhabited quarter sectors (areas A–G in Figs. 3, 6a, and 8a), with the exception of the western town area where shadowing effects did not allow for measurement (Fig. 6).

Moreover, the system narrow field of view prevented the middle-lower slope landslide monitoring (Fig. 4). The use of ICD maps proved its usefulness in recognizing an overall stability for the town's uppermost sector (area D), in correspondence with the slope divide. Furthermore, areas affected by the most relevant residual hazard were detected: the peak deformations are located in the southern sectors of the monitored slope, such as area F (2524 mm) and area G (2259 mm), whereas in the northern sector of the town peak cumulated ground deformations vary from 465 mm (area A) to 664 mm (area B) and 550 mm (area C), respectively (Fig. 6d).

Comparing remotely sensed data and field evidence

The comparison between field surveys and GB-InSAR data in the San Fratello area provided useful information for analysing and interpreting the pattern and kinematics of the detected slope deformations. In particular, by comparing ICD and MCD maps with previous landslide inventories (PAI 2004; AdB (2012), it was noticed how several slope areas characterized by intense residual deformation fall within shallow minor instability processes (such as slow earth slips, slides, and complex landslides) (Fig. 11). This suggests the effectiveness of GB-InSAR for mapping refinement of slope scale inventories. Furthermore, by comparing the ICD map of the total monitoring period with field evidence

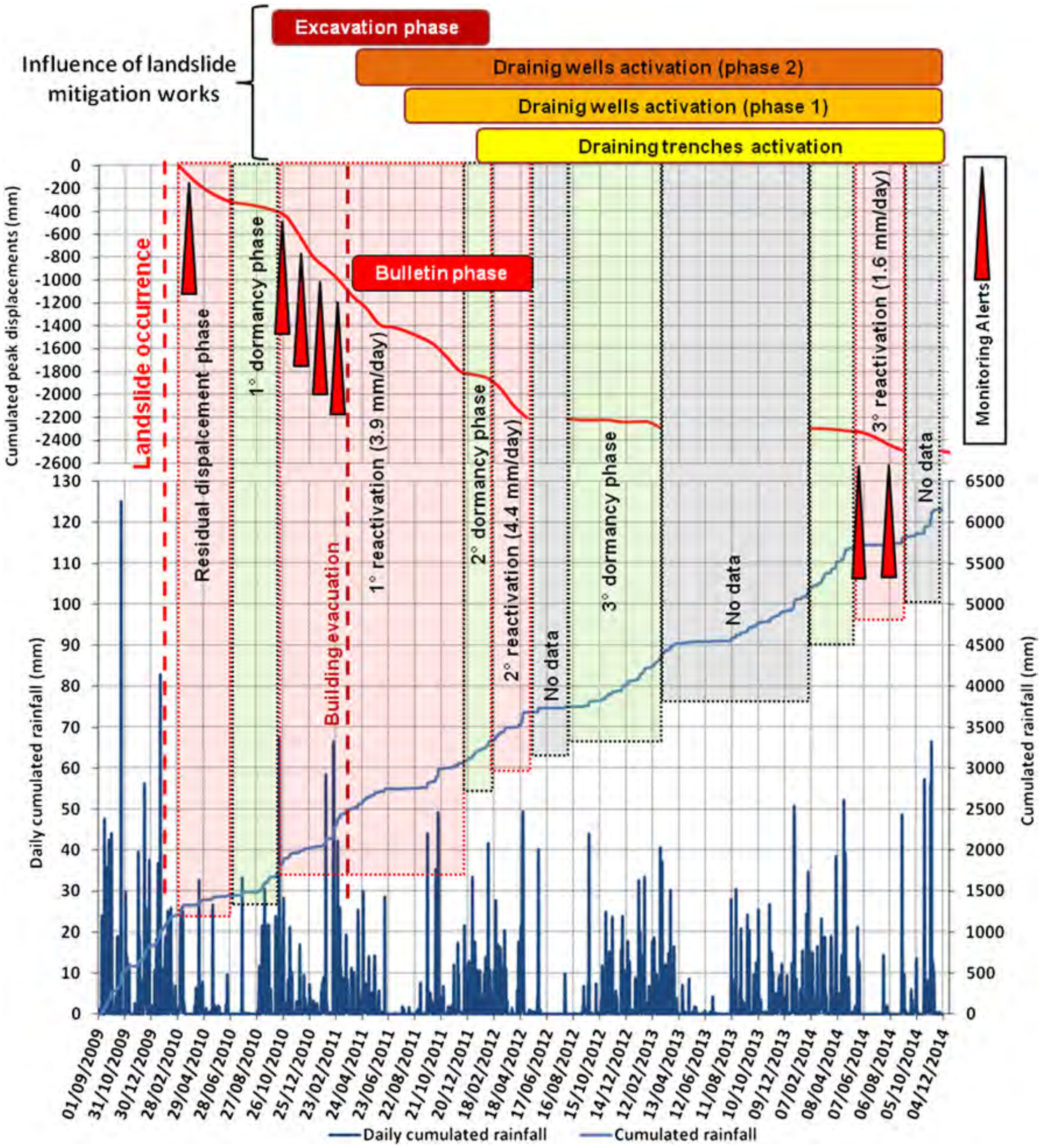

Fig. 13 Timeline of the monitoring campaign, explained through the use of cumulated peak displacements compared with rainfall data, recorded in the San Fratello area between September 2009 and December 2014 (courtesy of S.I.A.S. Sicilian Agro-meteorological Informative System)

(the geomorphological landslide map and the slope fracture mapping carried out within the urban area; Fig. 12), it can be noticed how the main landside scarps delimitate areas affected by intense residual displacements in the town's southern areas (sectors F and G; Figs. 6a and 12a). On the contrary, the majority of the mapped ground fractures are located within the town's urban centre (sectors B and E), where minor cumulated ground deformations were measured by the radar-monitoring system (Fig. 12a). In the context of field-mapping activities, the deformational pattern of the 2010 landslide is also confirmed by the spatial distribution of the building damage (Ciampalini et al. 2014; Fig. 12b). The building inspection also revealed the presence of several damaged buildings located in the town's north-western sector. This area cannot be monitored, because it is located along the town's western slope, and so is not visible the GB-InSAR system. The recognized building damage was partly developed after the 2010 landslide, suggesting that the area corresponding to the 1922 landslide crown (town north-eastern sector) was partly reactivated by this latest landslide event (Ciampalini et al. 2014; Bianchini et al. 2015).

The most severe and widespread damaged town sectors were primarily area B and area E, while localised partial and total building collapse takes place in area F and area G (Fig. 12b). All the previous considerations suggest that the displacements recorded by the radar system are connected to intermittent activations of minor surface landslides (Figs. 8 and 11); this is particularly evident by analysing the residual reactivation and frequency maps (Fig. 10). On the contrary, it can be inferred how the slope deformations connected to the 2010 landslide event were initially severe in the slope's northern and uppermost sectors (sectors A, B, and D; Fig. 12). The latter deformations were mainly exhausted before the implementation of the monitoring system (Figs. 6a, 7, and 8). Continuous residual displacements have been recorded primarily in the slope's southern sectors, fortunately in mainly uninhabited areas.

Management of landslide residual hazard

The landslide kinematics was analysed by comparing the incremental cumulated peak displacements with the rainfall data of the S.I.A.S. (Sicilian Agro-meteorological Informative System) rain gauge network (Fig. 13). According to this analysis, the 2010 landslide trigger appears to be related to intense rainfall (the involved slope cover was mainly saturated due to a shallow water table; Bardi et al. 2014; DRPC 2010). Furthermore, following an initial phase of landslide residual displacements, lasting until the end of June 2010, three dormancy periods and three reactivation phases were detected (Fig. 13). A rainfall-induced displacement trend of the landslide is confirmed regarding the first reactivation, spanning from November 2010 to December 2011. This reactivation was the most severe in the monitored period, as testified by four occurred alerts and the planning of a monthly monitoring bulletin phase (Figs. 5 and 13). In this context, persistent and widespread accelerations were detected from March 4, 2011 within the San Benedetto quarter (area F). Field inspections were promptly carried out in the detected area by the DRPC personnel revealing the increase of the crack and fissure pattern in correspondence of a few buildings. Therefore, on March 17, 2011, the latter buildings were evacuated as a precautionary measure (Fig. 13). The initial rainfall-induced landslide kinematics was also confirmed by the time series of the selected measuring points (Fig. 7; Table 2), by the MCD maps and the quarter displacement analysis (Figs. 8 and 9), which all highlight as dormancy phases occur in dry periods, whereas reactivation phases usually take place during wet winter-fall months.

Following the second reactivation phase (February–April 2012, showing a 4.4-mm/day average velocity), a progressive reduction in slope deformation is observed, both in terms of area extension and displacement rate, whereas regarding the subsequent minor reactivations, the increase of displacement trend does not appear to be related to rainfall. In fact, starting from 2012, no accelerations were detected in correspondence of the main rainfall events (see for example the third dormancy phase in Fig. 13). This suggests the efficiency of the landslide mitigation works, since the full activation of draining trenches and wells starts from February 2012 (Figs. 7 and 13).

Conclusions

On February 14, 2010, a large landslide affected the San Fratello town urban centre. In the context of the post-event recovery activities, starting from March 8, 2010, a GB-InSAR displacement monitoring campaign was carried, with the aim of assessing the landslide residual risk and analyse its deformation trend. The analysed scenario was subdivided into town quarter areas, where ICD maps recorded slope deformations span from about 0.46 up to 2.52 m. The areas characterized by the most frequent and intense ground deformations are located in the town southern sectors, as confirmed by the analysis of the measuring point trend, MCD maps, and quarter areas average deformations. On the basis of selected displacement thresholds and frequency of activation, nine residual active slope sectors were detected and mapped. The latter sectors are located within shallow active minor landslides, in the main body of the landslide, which were mapped and characterized in pre-existing landslide inventory. The overall landslide kinematics was investigated through the analysis of both displacement time series of selected measuring points and peak displacements within the monitored area, leading to the detection of an initial residual displacement phase, followed by three reactivations and dormancy phases. The main triggering factor for these shallow reactivations is intense rainfall events. After the initial intense residual displacements, following April 2012, a progressive reduction of both the measuring points and cumulated peak displacements occur, suggesting the efficiency of the landslide mitigation works. Based on the surface of the deformation areas and the increasing trends of displacement time series, several alerts were obtained. In this context on March 17, 2011, a few buildings were evacuated in the Riana-San Benedetto quarters by the DPCR personnel. GB-InSAR monitoring also allowed controlling the slope instability during the implementation of the mitigation works, for the safety of the involved workers. The implemented local scale GB-InSAR system provided a clear, user-friendly, and valid scientific support, designed for all the personnel involved in managing the immediate response, for a better understanding of such a critical landslide scenario and an improvement in the decision-making process.

Acknowledgments

The authors would like to thank the National and Sicily Region Departments of Civil Protection for their support during the post-landslide emergency phase; a special mention goes to Alessandro Battaglia and Demetrio Crocco (DRPC). The GB-InSAR apparatus used in this application was designed and produced by Ellegi s.r.l. and based on the proprietary technology GB-InSAR LiSALAB derived from the evolution and improvement of LiSA technology licensed by the Ispra Joint Research Centre of the European Commission. F. Di Traglia is supported by a post-doc fellowship founded by the "Università degli Studi di Firenze – Ente Cassa di Risparmio di Firenze" within the context of the "Bando Giovani Ricercatori Protagonisti" ("Volcano Sentinel" project).

References

AdB (2012) Regione Sicilia PAI – Piano Stralcio di Bacino per l'Assetto Idrogeologico Available at http://www.sitr.regione.sicilia.it/pai

Antonello G, Casagli N, Farina P, Leva D, Nico G, Sieber AJ, Tarchi D (2004) Ground based SAR interferometry for monitoring mass movements. Landslides 1:21–28

Bamler R, Hartl P (1998) Synthetic aperture radar interferometry. Inverse Probl 14:1–54

Bardi F, Frodella W, Ciampalini A, Bianchini S, Del Ventisette C, Gigli G, Fanti R, Moretti S, Basile G, Casagli N (2014) Integration between ground based and satellite SAR data in landslide mapping: the San Fratello case study. Geomorphology 223:45–60

Bardi F, Raspini F, Frodella W, Lombardi L, Nocentini M, Gigli G, Morelli S, Corsini A, Casagli N (2017) Monitoring the rapid-moving reactivation of earth flows by means of GB-InSAR: the April 2013 Capriglio landslide (northern Appennines, Italy). Remote Sens 9(2):165

Bertolaso G, De Bernardinis B, Bosi V, Cardaci C, Ciolli S, Colozza R, Cristiani C, Mangione D, Ricciardi A, Rosi M, Scalzo A, Soddu P (2009) Civil protection preparedness and response to the 2007 eruptive crisis of Stromboli volcano, Italy. J Volcanol Geoth Res 182:269–277

Bianchini S, Ciampalini A, Raspini F, Bardi F, Di Traglia F, Moretti S, Casagli N (2015) Multi-temporal evaluation of landslide movements and impacts on buildings in San Fratello (Italy) by means of C-band and X-band PSI data. Pure Appl Geophys 172:3043–3065

Bozzano F, Cipriani I, Mazzanti P, Prestininzi A (2011) Displacement patterns of a landslide affected by human activities: insights from ground-based InSAR monitoring. Nat Hazards 59(3):1377–1396

Broussolle J, Kyovtorov V, Basso M, Ferraro Di Silvi E, Castiglione G, Figueiredo Morgado J, Giuliani R, Oliveri F, Sammartino PF, Tarchi D (2014) MELISSA, a new class of ground based InSAR system. An example of application in support to the Costa Concordia. ISPRS J Photogramm Remote Sens 91:50–58

Carlà T, Intrieri E, Di Traglia F, Casagli N (2016a) A statistical-based approach for determining the intensity of unrest phases at Stromboli volcano (Southern Italy) using one-step-ahead forecasts of displacement time series. Nat Hazards 84(1):669–683

Carlà T, Intrieri E, Di Traglia F, Nolesini T, Gigli G, Casagli N (2016b) Guidelines on the use of inverse velocity method as a tool for setting alarm thresholds and forecasting landslides and structure collapses. Landslides:1–18

Casagli N, Catani F, Del Ventisette C, Luzi G (2010) Monitoring, prediction, and early warning using ground-based radar interferometry. Landslides 7(3):291–301

Casagli N, Frodella W, Morelli S, Tofani V, Ciampalini A, Intrieri E, Raspini F, Rossi G, Tanteri L, Lu P (2017) Spaceborne, UAV and ground-based remote sensing techniques for landslide mapping, monitoring and early warning. Geoenv Disasters 4:9. doi:10.1186/s40677-017-0073-1

Ciampalini A, Cigna F, Del Ventisette C, Moretti S, Liguori V, Casagli N (2012) Integrated geomorphological mapping in the north-western sector of Agrigento (Italy). J Maps 8:136–145

Ciampalini A, Bardi F, Bianchini S, Frodella W, Del Ventisette C, Moretti S, Casagli N (2014) Analysis of building deformation in landslide area using multisensor PSInSARTM technique. Int J Appl Earth Observ Geoinfo 33:166–180

Ciampalini A, Raspini F, Bianchini S, Frodella W, Bardi F, Lagomarsino D, Di Traglia F, Moretti S, Proietti C, Pagliara P, Onori R, Corazza A, Duro A, Basile G, Casagli N (2015) Remote sensing as tool for development of landslide databases: the case of the Messina Province (Italy) geodatabase. Geomorphology 249:103–118

Ciampalini A, Raspini F, Lagomarsino D, Catani F, Casagli N (2016b) Landslide susceptibility map refinement using PSInSAR data. Remote Sens Environ 184:302–315

Ciampalini A, Raspini F, Frodella W, Bardi F, Bianchini S, Moretti S (2016a) The effectiveness of high-resolution LiDAR data combined with PSInSAR data. Landslides 13(2):399–410. doi:10.1007/s10346-015-0663-5

Confuorto P, Di Martire D, Centolanza G, Iglesias R, Mallorqui JJ, Novellino A, Plank S, Ramondini M, Thuro K, Calcaterra D (2017) Post-failure evolution analysis of a rainfall-triggered landslide by multi-temporal interferometry SAR approaches integrated with geotechnical analysis. Remote Sens Environ 188:51–72

Cruden DM, Varnes DJ (1996) Landslide types and processes. In: Turner AK, Schuster RL (eds) Landslides: investigation and Mitigation, Sp. Rep. 247, Transportation Research Board, National research Council. National Academy Press, Washington DC, pp 36–75

Di Traglia F, Intrieri E, Nolesini T, Bardi F, Del Ventisette C, Ferrigno F, Frangioni S, Frodella W, Gigli G, Lotti A, Tacconi Stefanelli C, Tanteri L, Leva D, Casagli N (2014a) The ground-based InSAR monitoring system at Stromboli volcano: linking changes in displacement rate and intensity of persistent volcanic activity. B Volcanol 76(2):786

Di Traglia F, Nolesini T, Intrieri E, Mugnai F, Leva D, Rosi M, Casagli N (2014b) Review of ten years of volcano deformations recorded by the ground-based InSAR monitoring system at Stromboli volcano: a tool to mitigate volcano flank dynamics and intense volcanic activity. Earth-Sci Rev 139:317–335

Di Traglia F, Battaglia M, Nolesini T, Lagomarsino D, Casagli N (2015) Shifts in the eruptive styles at Stromboli in 2010–2014 revealed by ground-based InSAR data. Sci Rep 5:13569

DRPC (Dipartimento Regione Protezione Civile sicilia) (2010) La frana di San Fratello. Rapporto di sintesi sulle indagini geognostiche. Servizio Rischi Idrogeologici e Ambientali. Internal report

Fanti R, Gigli G, Lombardi L, Tapete D, Canuti P (2013) Terrestrial laser scanning for rockfall stability in the cultural heritage site of Pitigliano (Italy). Landslides 10(4):409–420

Frodella W, Morelli S, Fidolini F, Pazzi V, Fanti R (2014) Geomorphology of the Rotolon landslide (Veneto region, Italy). J Maps 10(3):394–401

Frodella W, Fidolini F, Morelli S, Pazzi F (2015) Application of infrared thermography for landslide mapping: the Rotolon DSGDS case study. Rend Online Soc Geol It 35:144–147

Frodella W, Ciampalini A, Gigli G, Lombardi L, Raspini F, Nocentini M, Scardigli C, Casagli N (2016) Synergic use of satellite and ground based remote sensing methods for monitoring the San Leo rock cliff (northern Italy). Geomorphology 264:80–94

Gigli G, Intrieri E, Lombardi L, Nocentini M, Frodella W, Balducci M, Venanti LD, Casagli N (2014b) Event scenario analysis for the design of rockslide countermeasures. J Mt Sci 11(6):1521–1530

Gigli G, Frodella W, Garfagnoli F, Mugnai F, Morelli S, Menna F, Casagli N (2014a) 3-D geomechanical rock mass characterization for the evaluation of rockslide susceptibility scenarios. Landslides 11(1):131–140

Guzzetti F, Mondini AC, Cardinali M, Fiorucci M, Santangelo M, Chang KT (2012) Landslide inventory maps: new tools for an old problem. Earth Sci Rev 112:1–25

Lavecchia G, Ferrarini F, De Nardis R, Visini F, Barbano MS (2007) Active thrusting as possible seismogenic source in Sicily (Southern Italy): some insights from integrated structural kinematic and seismological data. Tectonophysics 445:145–167

Lentini F, Carbone S, Catalano S, Grasso M, Monaco C (1990) Principali elementi strutturali del thrust belt appenninico-maghrebide in Sicilia centro-orientale. Mem Soc Geol Ital 45:495–502

Lentini F, Catalano S, Carbone S (2000) Carta geologica della Provincia di Messina, scala 1: 50000, Provincia Regionale di Messina, Assessorato al Territorio. Servizio Geologico. Soc Elaborazioni Cartogr, Firenze, p 70

Lombardi L, Nocentini M, Frodella W, Nolesini T, Bardi F, Intrieri E, Carlà T, Solari L, Dotta G, Ferrigno F, Casagli N (2016) The Calatabiano landslide (southern Italy): preliminary GB-InSAR monitoring data and remote 3D mapping. Landslides 14(2):685–696

Luzi G, Pieraccini M, Mecatti D, Noferini L, Guidi G, Moia F, Atzeni C (2004) Ground-based radar interferometry for landslides monitoring: atmospheric and instrumental decorrelation sources on experimental data. IEEE Trans Geosci Remote Sens 42(11):2454–2466

Luzi G (2010) Ground based SAR interferometry: a novel tool for Geoscience. P. Imperatore, D. Riccio (Eds.), Geoscience and Remote Sensing. New Achievements, InTech, pp 1–26

Monserrat O, Crosetto M, Luzi G (2014) A review of ground-based SAR interferometry for deformation measurement. ISPRS J Photogramm Remote Sens 93:40–48

Nigro F, Sulli A (1995) Plio-Pleistocene extensional tectonics in the Western Peloritani area and its offshore (northeastern Sicily). Tectonophysics 252:295–305

Nolesini T, Frodella W, Bianchini S, Casagli N (2016) Detecting slope and urban potential unstable areas by means of multi-platform remote sensing techniques: the Volterra (Italy) case study. Remote Sens 8(9):746

Oppikofer T, Jaboyedoff M, Blikra L, Derron MH, Metzer R (2009) Characterization and monitoring of the Åknes rockslide using terrestrial laser scanning. Nat Hazards Earth Syst Sci 9:1003–1019

P.A.I. (Piano Stralcio di Bacino per l'assetto Idrogeologico) (2004) Carta della Pericolosità e del Rischio Geomorfologico n° 03; Bacino Idrografico del Torrente Inganno e area territoriale tra il bacino del F. Rosmarino e il bacino del T.te Inganno. Regione Sicilia, Assessorato Territorio e Ambiente, Dipartimento Territorio e ambiente, Servizio 4 "Assetto del Territorio e Difesa del suolo"

Pagliara P, Basile G, Cara P, Corazza A, Duro A, Manfrè B, Onori R, Proietti C, Sansone V (2014) Integration of earth observation and ground-based HR data in the civil protection emergency cycle: the case of the DORIS project. In: Pardo-Igúzquiza E, Guardiola-Albert C, Heredia J, Moreno-Merino L, Durán JJ, Vargas-Guzmán JA (eds) Mathematics of planet earth, lecture notes in earth system sciences. Springer, Berlin Heidelberg, pp 263–266

Raspini F, Ciampalini A, Bianchini S, Bardi F, Di Traglia F, Basile G, Moretti S (2015) Updated landslide inventory of the area between the Furiano and Rosmarino creeks (Sicily, Italy). J Maps 12(5):1010–1019

Rudolf H, Leva D, Tarchi D, Sieber AJ (1999) A mobile and versatile SAR system. Proc IGARSS 1:592–594

Salvatici T, Morelli S, Pazzi V, Frodella W, Fanti R (2017) Debris flow hazard assessment by means of numerical simulations: implications for the Rotolon Creek Valley (Northern Italy). J Mount Sci. doi:10.1007/s11629-016-4197-7

Sturzenegger M, Stead D (2009) Quantifying discontinuity orientation and persistence on high mountain rock slopes and large landslides using terrestrial remote sensing techniques. Nat Hazards Earth Syst Sci 9:267–287

Tarchi D, Ohlmer E, Sieber AJ (1997) Monitoring of structural changes by radar interferometry. Res Nondestruct Eval 9:213–225

Tarchi D, Casagli N, Fanti R, Leva D, Luzi G, Pasuto A, Pieraccini M, Silvano S (2003) Landslide monitoring by using ground-based SAR interferometry: an example of application to the Tessina landslide in Italy. Eng Geol 68:15–30

Zhang Z, Zheng S, Zhan Z (2004) Digital terrestrial photogrammetry with photo total station. International Archives of Photogrammetry and Remote Sensing, Istanbul, pp 232–236

W. Frodella (✉) · **A. Ciampalini** · **F. Bardi** · **T. Salvatici** · **F. Di Traglia** · **N. Casagli**
Earth Sciences Department,
University of Firenze,
Via La Pira 4, 50121, Florence, Italy
e-mail: william.frodella@unifi.it

G. Basile
Civil Protection Department – Sicily Region, Hydrogeological and Environmental Hazards Services,
Via Abela 5, 90141, Palermo, Italy