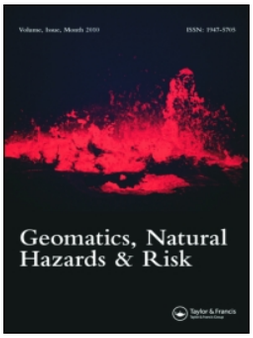

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Application of field surveys and multitemporal in-SAR interferometry analysis in the recognition of deep-seated gravitational slope deformation of an urban area of Southern Italy

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ABSTRACT
The analysis of 4 year In-SAR Interferometry images and a detailed geomorphological survey have been carried out to detect a large Deep-Seated Gravitational Slopes (DSGSD) affecting the urban area of the Episcopia village, in Southern Italy. The DSGSD largely develops within phyllites of the Liguride Units and, in the upper slope, within Pleistocene sand and conglomerate deposits of the Sant'Arcangelo Basin. Field survey has shown trenches at the top and an evident bulge at the base of the DSGSD, corresponding to the Talweg of the Sinni River. Geological and geomorphological field surveys allowed us to hypothesize a listric geometry of the DSGSD subsurface plane reaching about 700 m of depth. Furthermore, the multi-temporal In-SAR Interferometry analysis collected from November 2014 to May 2017 revealed that a ground deformation of ±30 mm was occurred, and the process is still active in the whole area.

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Deep-Seated Gravitational Slope Deformations; Geomorphology; In-SAR Interferometry analysis; urban area; Southern Italy

1. Introduction

A world-wide scientific literature is deals with the Deep-Seated Gravitational Slope Deformations, treating many local case studies characterized by a great variety of geological and geomorphological settings (Agliardi et al. 2001; Panek and Limes 2016 and references therein; Frattini et al. 2018). DSGSD is an acronym of the Deep-Seated Gravitational Slope Deformation referring to gravity-induced slope mass movements that affect high relief mountain slopes over long periods of time and at low rates (Engelen 1963; Goguel 1978; Dramis 1984; Sorriso-Valvo 1984; Cavallin et al. 1987; Agliardi et al. 2001; Pasuto and Soldati 2013). It is classified between landslides and a faulting process that affects the slopes and displaces rock mass

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downward for several kilometres squares and up to 100 m depth, and the detailed processes responsible for their genesis are not well understood yet (Agliardi et al. 2001, 2009a, 2009b). The typical DSGSD features are double ridges, trenches, tension cracks, uphill facing scarps (counter scarps or antislope scarps), downthrown blocks, buckling folds, toe bulging, and secondary mass movements (Agliardi et al. 2001; Panek and Limes 2016). The DSGSDs are world-wide recognized (Panek and Limes 2016) and are peculiar phenomenon of the Italian Alp and Apennine chains (Cavallin et al. 1987; Agliardi et al. 2001, 2009a, 2009b; Forcella and Orombelli 1984; Berardino et al. 2003; Guerricchio 2005; Di Martire et al. 2016; Frattini et al. 2018). All over the world there are a lot of experiences of satellite images classification in the field of geology (Pascale et al. 2013, 2014; Sarma et al. 2015; Nath et al. 2015; Partheepan et al. 2016). The aim of the study is to investigate the Episcopia DSGSD, already recognized by Bentivenga et al. (2009, 2017), using a multidisciplinary approach that consists on both the geological and geomorphological field surveys, integrated by aerial photogrammetry and thematic map interpretations, and a multitemporal image analysis by means of the In-SAR Interferometry technique.

This technology has developed in recent years thanks to the availability of images with increasing resolution and short repetition times (Rosen et al. 2000; Zebker and Goldstein 1986; Dumitru and Datcu 2013). The accuracy of these techniques depends on many parameters including the morphological characteristics of the study area (Moran et al. 1998), hooting geometry and weather conditions. A threshold of the In-SAR analysis for the detection of DSGDS is due to the presence of externalities that modify results such as strong earthquakes (Massonnet et al. 1993), volcanic eruptions, human activities and heavy rainfall events (Faccini et al. 2012), among others.

The DSGSDs area that affects the whole Episcopia urban settlement is characterized of many landslides and is bounded by the Monaco and Confine Streams on the left and the right, respectively. Aerial photogrammetry interpretation confirmed by field surveys have revealed the typical morphological features of DSGSD that involves the whole slope until to the Sinni River valley and the urban settlement of Episcopia producing severe damage buildings.

2. Geological and geomorphological settings

The southern Apennines chain (Figure 1), a Miocene to Pleistocene fold-and-thrust belt, is composed of east-verging tectonic units (Pescatore et al. 1999 and references therein) overlapping on the Apulian Platform and is characterized by large duplex geometries (Patacca and Scandone 2007 and references therein). The study area is located in the eastern sector of the south-Appennine chain and is formed by the Mesozoic to Cenozoic Apennines Unit successions overlapped by Pliocene to Pleistocene clastic deposits (Figure 1). The Apennines units are represented by the Liguride Unit (Amodio Morelli et al. 1976) composed of different tectonic units named Frido, Crete Nere, Saraceno and Albidona fms (Vezzani 1969; Bonardi et al. 1988; Monaco et al. 1991; Cavalcante et al. 2012). The Frido Fm is the highest tectonic unit; it is divided in two tectonic subunits, Cretaceous to Oligocene in age (Monaco and Tortorici 1995; Schiattarella 1996), and is composed of polydeformed

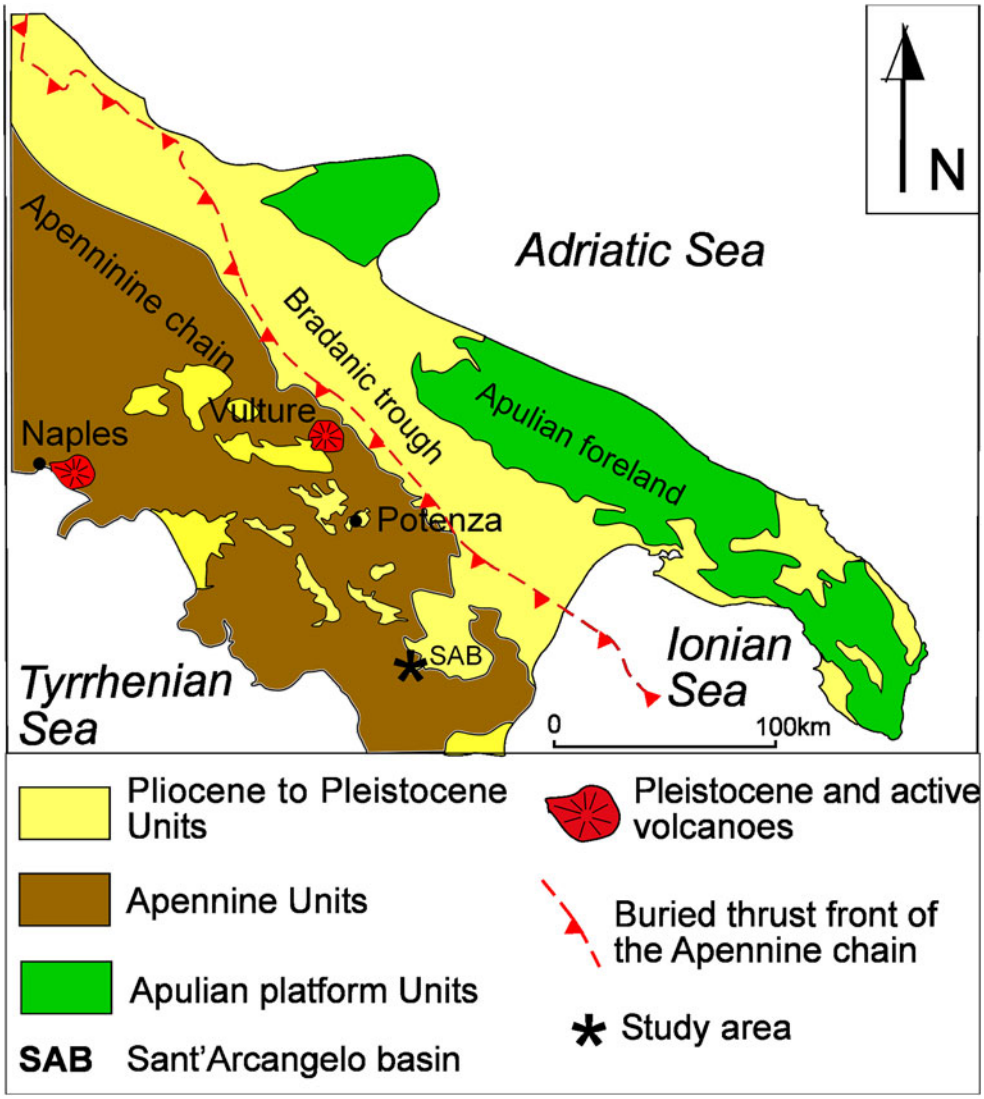

Figure 1. Geological sketch map of southern Italy (Bentivenga et al. 2004a, modified).

metamorphic rocks with associated blocks of ophiolite-bearing and continental-type rocks (Figures 2 and 3). The ophiolitic rocks are mainly represented by serpentinized peridotite and metabasite (Vezzani 1967, 1969). The Crete Nere, Saraceno and Albidona fms are the tectonic units underlying the Frido one. The Crete Nere Fm (Knott 1987; Bonardi et al. 1988) is a deep-sea water succession, Cretaceous to Eocene in age, formed by quartzarenites and arenaceous limestones interbedded to black shales (Figures 2 and 3). It is stratigraphically covered by the Saraceno Fm that is composed of calcareous turbidites mainly formed by thin layers of limestones, marls and clay. Finally, an angular unconformity divides the Saraceno Fm, at bottom, and the Albidona Fm to the top. This latter is formed by turbidite facies that vary

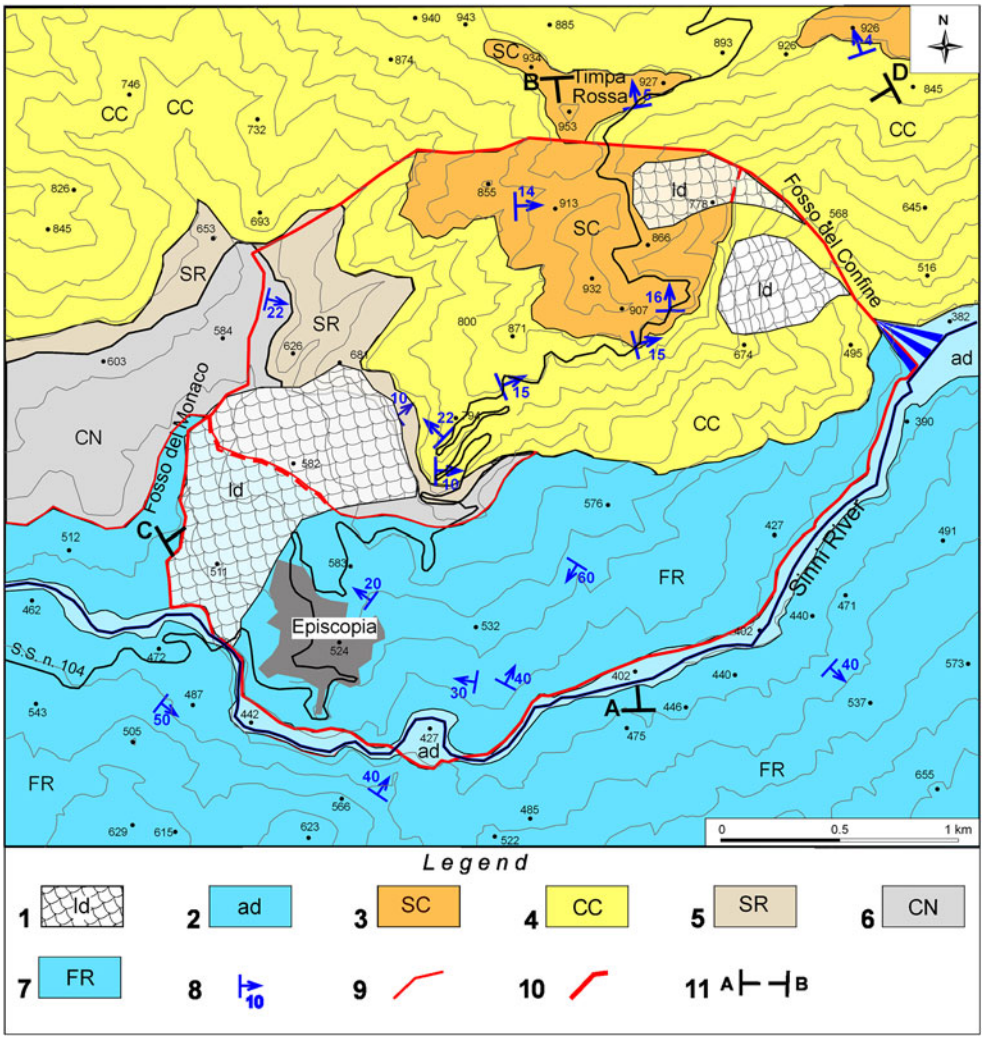

Figure 2. Geological sketch map of the study area. Legend: 1: landslide deposits; 2: alluvial deposits; 3: Serra Corneta Fm (Middle Pleistocene); 4: Castronuovo Fm (Late Pliocene to Early Pleistocene); 5: Saraceno Fm (Late Oligocene to Early Miocene); 6: Crete Nere Fm (Cretaceous to Middle Eocene); 7: Frido Fm (Oligocene); 8: Bed attitude; 9: Tectonic boundary; 10: DSGSD boundary; 11: Trace of geological cross-sections in Figure 3.

from arenaceous to pelite in the bottom to conglomerate-arenaceous toward the top (Figures 2 and 3). This succession represents the infill of the Miocene thrust-top/foredeep basins developed in the frontal sector of the southern Apennines accretionary wedge. Starting from the Eocene the area was affected by four tectonic events that were developed at several crustal levels and with different metamorphic grade (Knott 1987; Monaco and Tortorici 1995; Schiattarella 1996). The lower Miocene tectonic event generated NE-verging fold-and-thrusts involving both the Ophiolite and siliciclastic units. Differently, during the middle Pleistocene it was active a NW-SE

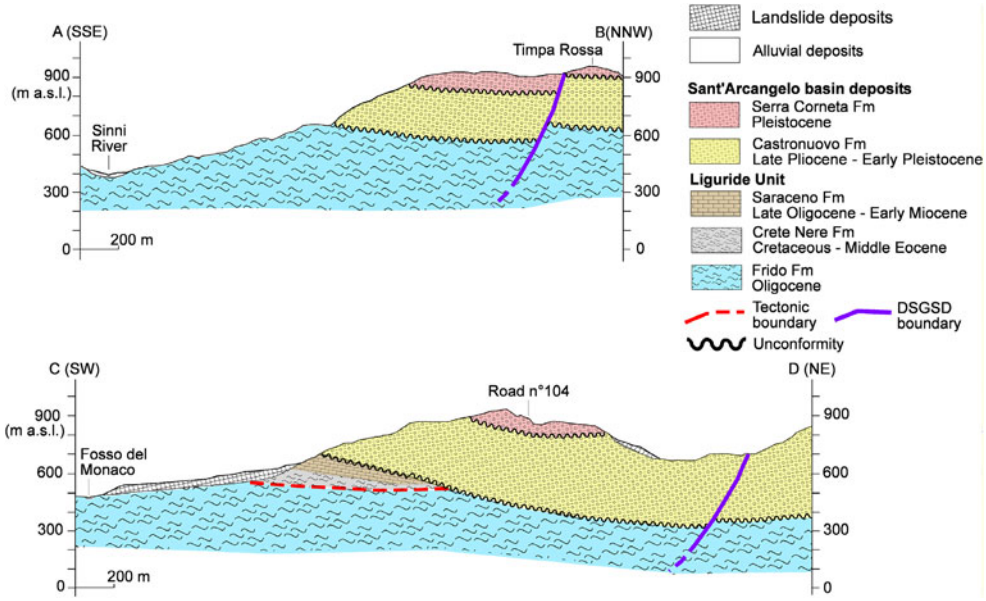

Figure 3. Geological cross-sections of the study area. Geological profile traces are reported on Figure 2.

oriented normal faulting that partially re-activate the older structures. The Liguride unit successions are lying by the marine to continental clastic deposits of the Sant'Arcangelo basin "*Auctt.*", a Pliocene to Pleistocene basin filled by up to 2500 m thick deposits (Vezzani 1967; Hippolyte et al. 1994; Pieri et al. 1994). The sedimentary succession in the study area is formed from bottom to top by Late Pliocene to Early Pleistocene polygenetic conglomerate with yellow sandy matrix that constitutes the Castronuovo Fm. This latter is overlapped by the fluvial conglomerates and sands with red sand matrix of the Middle Pleistocene Serra Corneta Fm (Vezzani 1967).

The landscape of southern Apennine chain is formed of a shape that change from planar coastal plain areas bounding the Tyrrhenian, Adriatic and Ionian seas to the high-relief peaks of the axial zone of the chain, through a hill-side area differently extended. Considering that, it can be roughly divided into three morphological zones (inner, axial and outer belts) parallel to its NW-SE-elongation axis (Figure 1). The inner belt corresponds to the Tyrrhenian side of the Sele coastal Plain and the Cilento Promontory, with a maximum elevation reached at Cervati Mt. (1900 m a.s.l.). Transverse incised fluvial valleys drive westward the main rivers toward the Tyrrhenian Sea, locally producing narrow gorges of one hundred metres deep. The axial belt corresponds to the highest mountains peaks that are up to 2000 m a.s.l. and includes the remnants of the Pliocene to Pleistocene erosion land surfaces uplifted and dismembered by Quaternary faults (Schiattarella et al. 2013; Giano 2016). Block-faulted mountains bounded by high-angle fault scarps retreated by slope replacement processes (Giano and Schiattarella 2014; Giano et al. 2018) are also present. They are alternated with tectonically controlled basins filled by fluvial to lacustrine deposits (Di Leo et al. 2009; Giano 2011; Aucelli et al. 2014; Giano et al. 2014). The fluvial

Table 1. Dataset used for the interferometric analysis.

Dataset	Sentinel 1A/B
Format	SLC
Polarization	VV
Pass direction	Ascending
Incidence angle	~41°
Radar frequency	5.405 MHz

network follows the regional dip of the chain and often transversally cut the bedrock to flow into the Tyrrhenian, Adriatic, or Ionian seas. The outer belt of the chain is characterized by a general passive north-eastward tilting as a consequence of the uplift of the axial zone of the chain (Giano and Giannandrea 2014; Bentivenga and Piccarreta 2016; Bentivenga et al. 2014). This is also supported by the drainage network that often flows perpendicularly to the main tectonic structures, in agreement with the regional slope of the belt (Cinque et al. 1993; Bentivenga et al. 2004a; Scorpio et al. 2015) toward to both the Adriatic and Ionian seas. The outer belt displays a landscape with a lower elevation than the axial belt and does not exceed 1100 m a.s.l.; the fluvial valleys are oriented from NE-SW in the northern sector to E-W in the southern sector and transversally cut the plain bending of the chain.

3. Materials and methods

The use of a multidisciplinary approach is needed for the Episcopia area considering a variety of instability processes that occurs in the whole area. To this aims, topographic contour maps at 1:5.000 scale were used to produce both the detailed geological and geomorphological maps. In addition, aerial photos at 1:33000 scale were analysed to integrate the field survey. The geological field survey of the Episcopia area has revealed large slope deformations not only attributable to landslides, but rather than to a deeper mass movement. Furthermore, a detailed geomorphological survey furnished a wide distribution of the features associated to the mass movements. With the aim to investigate the kinematic of slope mass movements and the morphological evolution of the area, a multitemporal analysis by means of I.G.M.I. aerial photos relative to the 1954/55, 1992/93, and 2003 years has been carried out.

DSGDS phenomena can also be analyzed through technologies based on interferometry based on satellite images using Synthetic Aperture RADAR (SAR) technology (Rosen et al. 2000; Small and Schubert 2008). The most used methodology is the Din-SAR which calculates the phase difference between two images acquired at different times before and after the event (Lanari et al. 2007; Massonnet and Feigl 1998; Mora et al. 2003). The phase difference calculated between the two acquisitions makes it possible to obtain indications of the change in the earth's surface. The measurement of the phase is affected by high de-correlation attributed to conditions of the surface investigated, to different weather conditions and to a large spatial baseline. DSGDS phenomena, being very slow movements, require very long period of observations, analysis that can be carried out using the permanent scatteres (PS) (Ferretti et al. n.d.) technique that exceeds the limits of D-inSAR. This technique aims to identify stable points called persistent scatters and monitor them in the analyzed time frame.

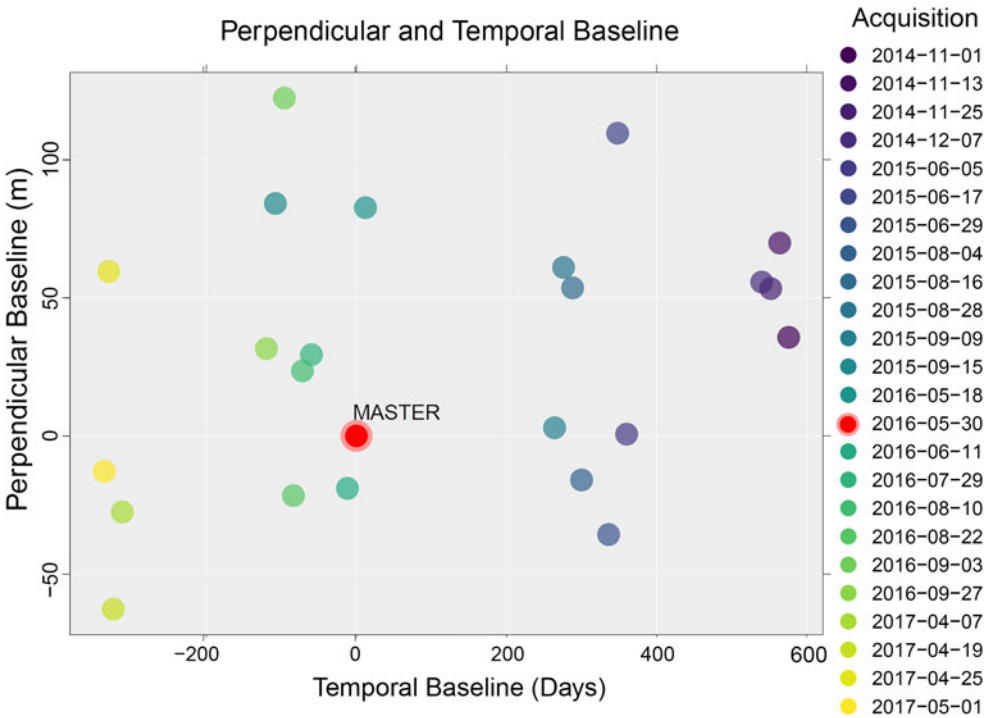

Figure 4. Optimal In-SAR master selection showing the choice of the best image.

For this purpose, we used 24 images of single look complex (SLC) downloaded free of charge from the Copernicus site (Copernicus https://scihub.copernicus.eu/dhus/#/home, 2017). We used the TOP-SAR images captured by sentinel satellites 1 A and B that produced 23 interferograms. We chose to use images in ascending mode because the study area is hilly and facing south. On the contrary, the acquisition in descending mode would not have given any contribution to the analysis (De Zan and Monti Guarnieri 2006; Gernhardt et al. 2009; Goldstein and Werner 1998).

The dataset of the Interferometry stack (time of acquisition, sensor, mode and data of the spatial baseline) allowed to select the master image so to minimize the temporal and perpendicular baseline dispersion (Table 1). The choice of the best Image as reported in the Figure 4 allowed us a better interpretation of the Interferograms improving their quality. The Interferogram images have been produced as follows: (a) Co-registration of both master and slave pair images, coming from the same sub swath, using the orbit of the two images and a DEM; (b) Creation of the Interferogram (Prati et al. 1990; Gabriel et al. 1989); (c) Removal of the topographic phase thus to remove the DEM from the Interferogram; (d) Phase of filtering to improve the accuracy of the phase unwrapping (Zebker and Goldstein 1986); (e) phase of unwrapping to resolve the correlation between the Interferometric and topographic phases (Small and Schubert 2008; Derauw and Orban 2004); (f) unwrapped phase in vertical displacement has been transformed (Ferretti et al. 2007).

These interferometric pairs are combined to improve the Signal to Noise Ratio SNR (Costantini 1998) represented by the ratio of power signal and power noise. Finally, for displacements analysis, we use the Coherent Pixels Technique (CPT)

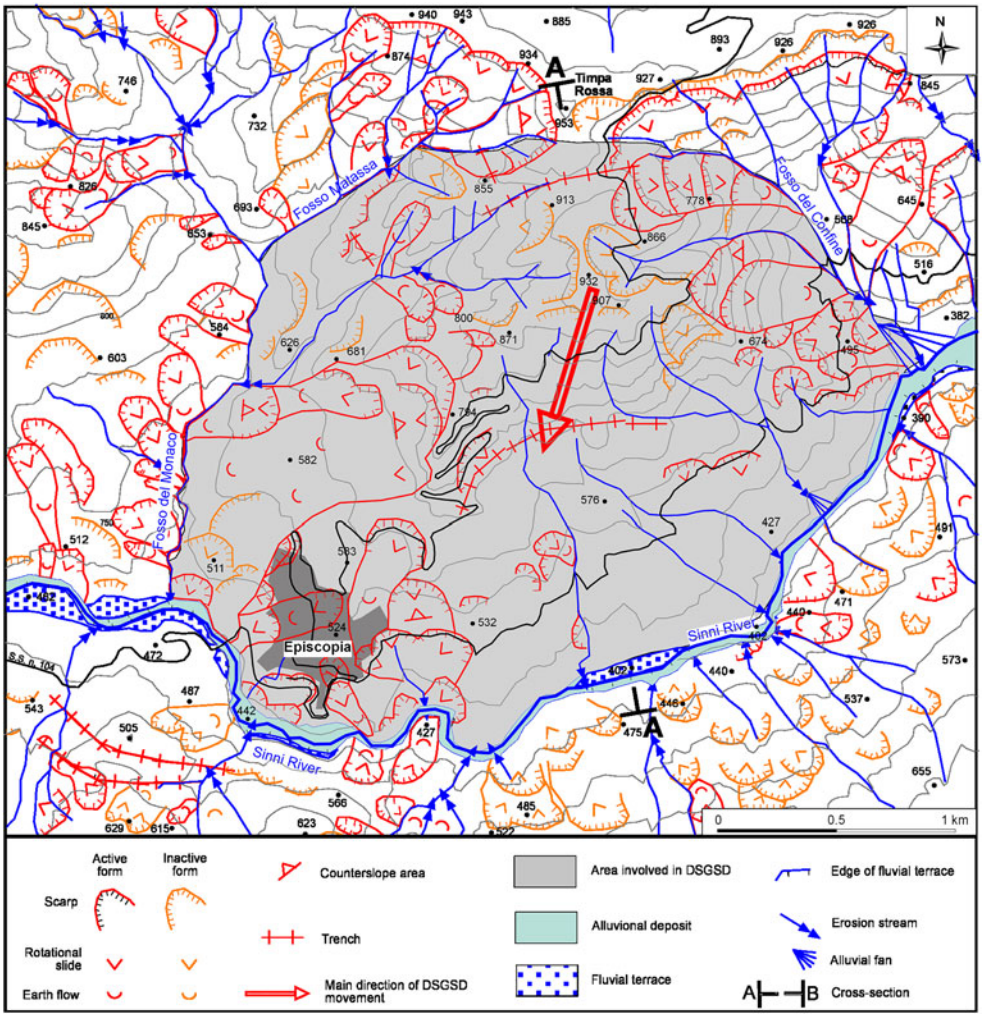

Figure 5. Geomorphological map of the Episcopia area.

(Mora et al. 2003; Blanco-Sànchez et al. 2008). This method is based on the coherence estimation, in fact the displacement analysis is realized on high coherent pixels that show a time-stable electromagnetic reaction. The CPT method allows to extract a list of differential interferograms regarding on the deformation affecting wide areas and large time intervals (Di Martire et al. 2016; Frattini et al. 2018).

4. Results

4.1. Geomorphological analysis

A wide slope of about XX° of slope angle and located in the left side of the upstream Sinni River is the study area. It is bounded by the Sinni River in the downside and

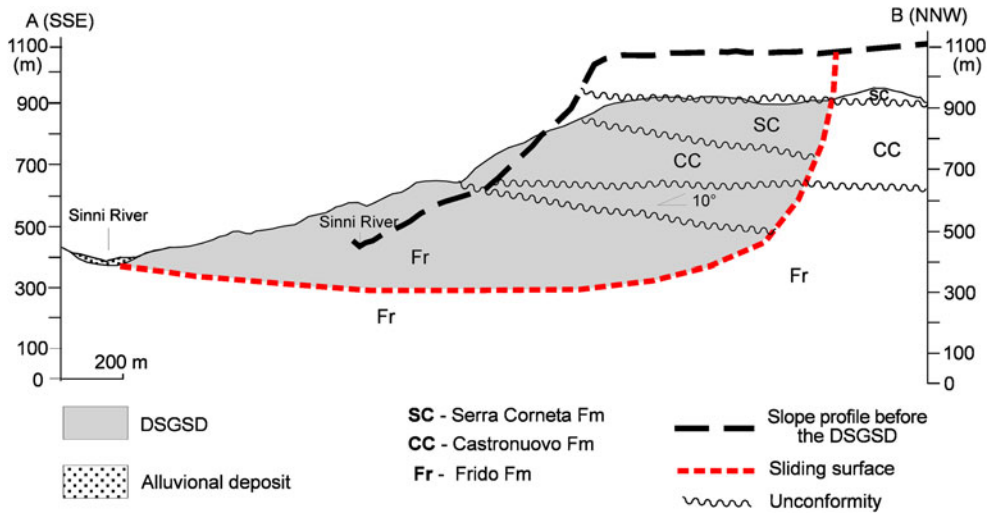

Figure 6. Slope profile showing the sliding plane of the DSGDS and the counter-slope tilting of about 10° that affected the Quaternary clastic successions of both the Castronuovo and Serra Corneta fms.

by flat top surfaces in the upside. The small village of Episcopia is placed on the left side of the Sinni River, where many landslides of different wideness and width are located (Figure 5). Different types of landslides such as rotational slides and earth flows cover almost the whole study area thus to mask the main and widest mass movement. The geomorphological analysis of the southern area of the Timpa Rossa site allowed us the recognition of some trenches laterally jointing to stream channels and other trenches placed at the base of the main slopes (Figures 5 and 6). The wider landslides are found on the left side of the Monaco Stream and their main scarps have affected in the movement the Pleistocene conglomerates and sands deposits of the Sant'Arcangelo basin. Smaller secondary scarps also involved deposits of the Liguride units. In the right side of Fosso del Confine Stream, the main landslide scarps involved only conglomerates and sand of both the Serra Corneta and Castronuovo formations. On the slope near to the Episcopia village, some head of landslides show slope deposits arranged on a convex downward slope profile. The wider landslides of the study area have been interpreted as rotational slide because of the occurrence of backward tilting terraces, and also as complex landslides formed by rotational slide in the head and by earth flow in the toe (*sensu* Varnes 1978; Carrara et al. 1985; Bentivenga et al. 2012). The smaller landslides affecting the urban area of the Episcopia village and surroundings, the south-east sector and the whole base slope of the Sinni River, on its right side. In this latter case, only the deposits of the Liguride Unit are involved in the movement. The landslides of the study area shown in Figure 5 specify the type of movement and the state of activity. This latter parameter came from both the field morphological surveys and the built damages evaluation. The active landslides are mainly located along the valley-side of the Monaco and Confine streams, in the urban area of the Episcopia Village and at the base slope of the right side of the Sinni River (Figure 5 for details). The fluvial pattern of the Episcopia slope is dendritic in the upper reach and radial in the middle to lower one.

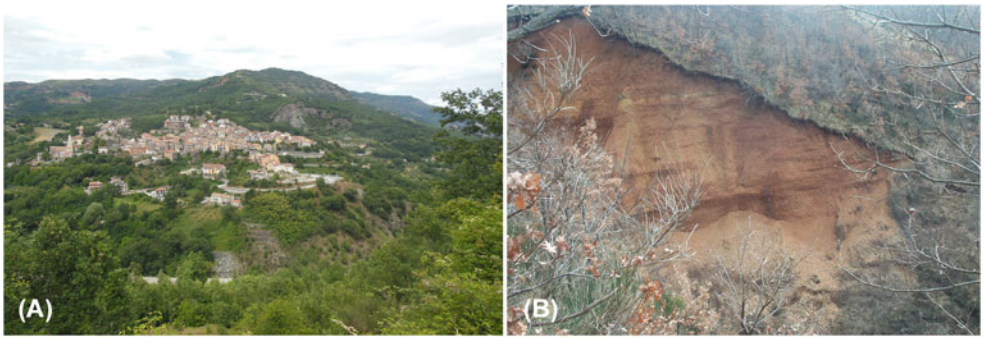

Figure 7. Panoramic view of the DSGDS base-slope, cuts by the Sinni River (A). Detail of the counter-slope tilting of Quaternary deposits (B).

In fact, the western streams are tributary of the Monaco Stream, the eastern streams of the Fosso del Confine Stream, and the southern ones of the Sinni River.

4.2. The deep-seated gravitational slope deformation of the Episcopia village

The detection of the Episcopia DSGSD has been obtained by the joins of geomorphological and geological analyses as well shown in Figures 2 and 5. In order to analyse the geological area, we measured the extent of the rotation suffered by the DSGSD area based on the physical correlation of a stratigraphic horizons guide represented by the unconformity between the Serra Corneta Fm and the Castronuovo Fm (Figures 3 and 6). This stratigraphic boundary is easily to observe and map because the Serra Corneta deposit is reddish in colour whilst the Castronuovo deposit is yellow. This unconformity is sub-horizontal in the whole surrounding area and conversely downward to the main trench it is rotated counter-slope of about 10°. As a consequence, a gravitational subsidence of the upper side and a backward tilting of the entire slope is shown (Figure 6). It has been taken into consideration some important morphological clues as the evident trenches upstream of the slope of Episcopia. In this sector, there are two evident trenches characterized by an arcuate trend with the concavity towards the valley. The first and main trench has an E-W trending direction south to the Timpa Rossa site and curves laterally towards the valley thus to produce a connection with the tributary of the left-side valley of the Sinni River. In particular, the trench joins laterally the streams of the western side to those of the eastern one. The second trench, mapped on the southern side (Figure 5), has a same trend of the previous one and is connected to the west with a left tributary of the Monaco Stream and to the east with the Confine Stream. At the base of the slope flows the Sinni River that is characterized by a curved channel with a convexity toward south, especially in the place at the base of the Episcopia village (Bentivenga et al. 2004b; 2017). In addition, along the curved fluvial reach there are not formed terraces alluvial. This further morphological evidence allowed us to accurately define the area involved by DSGSD that turns out to be equal of about 6 km^2. The upstream bounds of the DSGSD corresponds to the main trench, laterally to both the Matassa and Monaco streams to the east and the Fosso del Confine Stream to the west and to

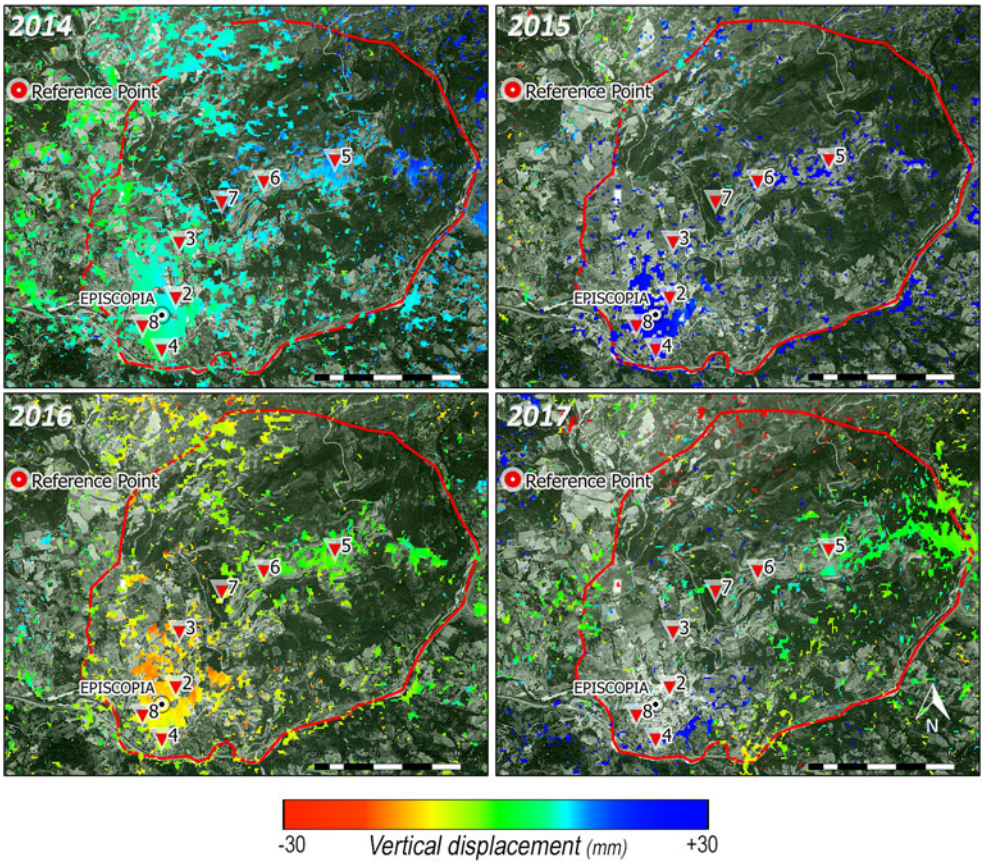

Figure 8. Ground surface displacement map from 2014 to 2017 years of observation. Red line shows the boundary of the study area, whereas red point (on the left of each map) indicate the ground CP related to a stable area. Source: Image from Google Earth

the Sinni River to the south. The size of the deep gravitational movement that involved the slope of Episcopia corresponds to an average width of 2.5 km and an average length of about 2.4 km. The depth of the DSGSD has been derived from geometric reconstructions involving the whole mass movement and corresponds to about 700 m of thickness (Figure 7). The geometry of the sliding surface, connecting the upstream trench to the most advanced portion of the foot in the valley floor has been hypothesized as a listric surface (Bentivenga et al. 2004b). The geological evidence of the deformation is linked to the counter-slope movement of the geological boundary between the Serra Corneta Fm and the underlying Castronuovo Fm. Moreover, the well-preserved morphological evidence such as the upstream trenches, the incision streams, the absence of fluvial terraces along the Sinni River and its right-side lateral planation are field evidence of the activity of the gravitative movement. Further, the distribution of active landslides that are placed along the stream sides and in the urban area of the Episcopia village supports the above-mentioned field evidence (Figure 5).

Table 2. Pin displacement (mm) of each CP.

	pin 2	pin 3	pin 4	pin 5	pin 6	pin 7	pin 8
2014	2,578	2,210	1,538	7,050	5,712	5,761	0,737
2015	11,618	9,821	15,103	26,660	13,842	22,693	15,539
2016	−12,627	−12,414	−7,371	−1,209	−3,097	−4,489	−10,130
2017	12,881	−11,273	17,144	−2,442	27,076	−2,532	5,002

4.3. In-SAR interferometry analysis

The first step of In-SAR interferometry analysis concerned individually the years 2014, 2015, 2016, and 2017, in a second one all the time span from November 2014 to May 2017 was analyzed, thus to compute the mean ground displacement occurring in the analyzed time span. The choice of the best coherent pixels was obtained applying a mask to the mean coherence thus to exclude all coherent pixel values lower than 0.40 (Mora et al. 2003). In fact, coherent pixel values lower than 0.40 indicate ground areas that changes more frequently and correspond mostly to woody and cultivated areas, whilst those with values higher than 0.40 are typical of no-frequently change areas such as a road, rocky areas or roof of buildings. The reference point, considered as a stable ground point with regard to the analyzed time span, is chosen out of the red perimeter that bound the study area (Figure 8) which is considered stable by previous geomorphological studies. Note that the relative value of ground displacement obtained by the fixed external reference point are quite the same if we change the spatial position of the reference point. Figure 8 shows the ground displacement maps from 2014 to 2017 and the location of Control Points (CP) used for monitoring of the Episcopia DSGSD. Displacements of the different spatial values related to each CP are reported in Table 2 and their trend is illustrated in Figure 9. A growth of the ground displacement is observed in 2015 that get 26.66 mm in the CP 5 (Figure 9), located in the upper side of the study area. A trend inversion on the CP points is shown between the 2015 and 2016, changing from a positive to a negative trend that could be interpreted as a horizontal translation of the ground surface. Figure 9 shows a deviation of the pins in 2015 from the average trend. To understand the different trend, the dataset concerning the water cumulations for each month from November 2014 to May 2017 has been analyzed, shown in Figure 10 where for each month the water cumulation in millimetre has been reported. In October 2015, the largest accumulation of rain was recorded with a value of 279.2 mm. The data were acquired by the monitoring unit (lat 40° 4’10.00 "N long 16° 6’23.00 "E) of the Basilicata functional center of the Civil Protection. This peak of rain in the year 2015 helps us to explain the reversal of the trend of displacement in the same period.

The general trend of the pin displacement shows a positive linear increase (Figure 9). This means that there has been a slow increase in the ground movement in the last 4 years, corresponding to a range of −30 and +30 mm. If we observe the figure showing the cumulative years of the ground displacement, it is possible to recognize small negative values in both the urban area and the south-western sector of the Episcopia village that in some case are quite close to zero values, corresponding to the absence of ground movement. Conversely, more consistent positive values are found in the central and northern sector of the study area (Figure 11).

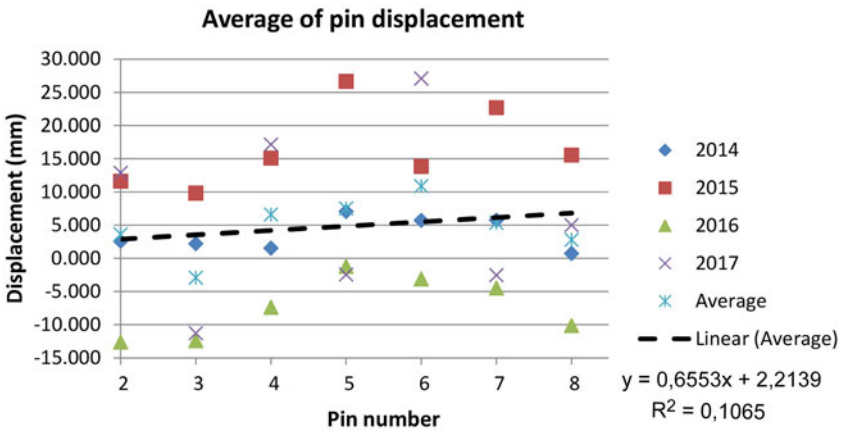

Figure 9. Regression line of the Pin displacement.

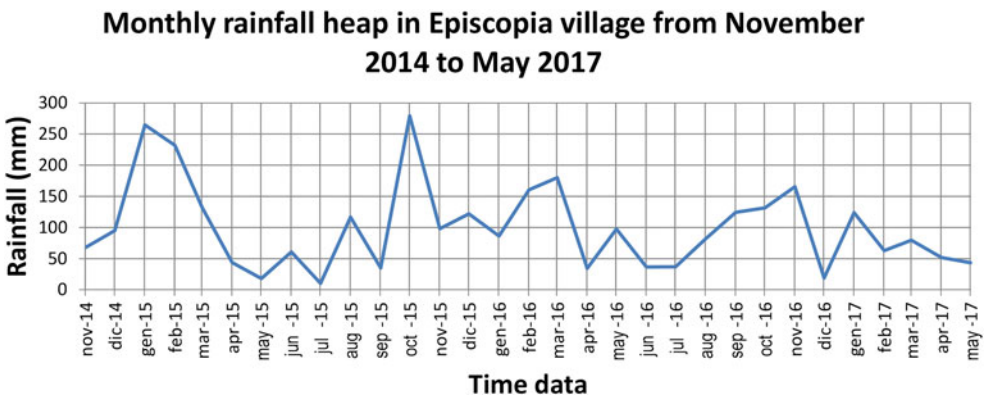

Figure 10. Diagram showing the distribution of the rainfall (mm) at the Episcopia village from November 2014 to May 2017.

5. Discussion and conclusions

The Episcopia area is located in the axial zone of the southern Apennines and has been affected by a strong regional uplift starting from Middle Pleistocene that was responsible for the high relief of the area (Amato et al. 2003; Schiattarella et al. 2003, 2013; Giano and Giannandrea 2014). As a consequence, a deep fluvial vertical incision and large landslides were activated in the whole site, and in the occurrence of the high uplift rate the Episcopia slope was affected by the DSGSD movement. The downward movement of the DSGSD modified the slope producing an upslope trench and, in the downslope, a clear deviation of about 800 m toward the south of the Sinni River channel (Figure 6). As a result, the Sinni River valley become transversally asymmetric, the right-side valley is steeper than the left one and is affected by many landslides focused in front of the Episcopia village. A clear field evidence of the downward movement of the DSGSD is also the break of the Sinni fluvial terraces arrangement (Bentivenga et al. 2004a). Moreover, two streams bound the DSGSD, both left tributaries of the Sinni River, the Fosso del Monaco Stream on the west-side and the Fosso del Confine on the east-side are deeply entrenched. Their valley-sides

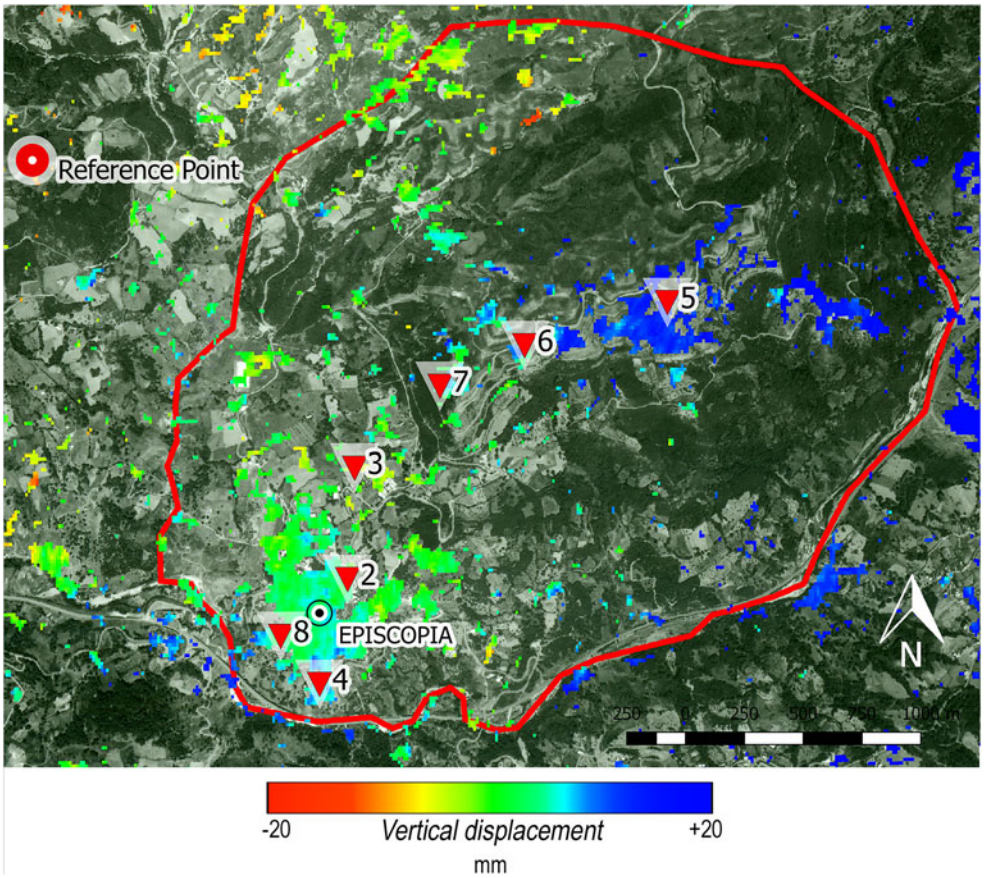

Figure 11. Mean vertical displacement. Source: (Image from Google Earth)

are affected by many active landslides, such as that in the Fosso del Monaco Stream affecting the north-eastern area of the Episcopia village. An older movement of the DSGSD involved the whole Episcopia slope from NNE to SSW, whereas a younger one partially affecting the slope from NW to SE thus to form the Fosso Lomea trench. These movements are also highlighted by the displacement and the rotation of about 10° toward the SW of the stratigraphic horizon between the Serra Corneta and Castronuovo Fms. Based on these information, we have reconstructed the displacement plane of the DSGSD by means of geological sections that allowed to measure at about 700 m of depth its thickness. The vertical displacement in the upslope area and the horizontal translation on its downside are the morphological features that allowed us to suppose a listric geometry of the subsurface plane (Hutchinson 1988). Furthermore, the recent surveying has shown the occurrence of many active landslides with seasonal activity in the south-eastern sector of the DSGSD. They are mainly placed along the valley sides of the Fosso del Monaco and Fosso del confine streams and represent a strong field evidence that led us to consider still active the DSGSD of the Episcopia area (Bentivenga et al. 2004b). The interferometric analysis

is a preliminary result that shows the consistency with geological field surveys, i.e., the stability of the north area and a movement of the south-west area that includes the urban zone. In the case of the Episcopia DSGSD, it would be wise to expand the observation dataset and use more accuracy methodologies for Persistent Scatters choice and analysis of the low coherence pixel (Press et al. 1992). The paper has shown that combining both the field survey and the In-SAR interferometry technique analysis a more detail could be obtained in the study of active processes that affect the landscape such as the DSGSD. Furthermore, these data together with a multitemporal analysis of aerial photo are relevant for the recognition of landscape modification, overall in the last decades.

Disclosure statement

No potential conflict of interest was reported by the authors.

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