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Deliverable DE3.3 – DE3.4: Upgraded geohazard activity maps over the two test sites of the project

A deliverable of

Task E: Geohazard impact assessment

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Dissemination Level		
PU	Public	X
PP	Restricted to other programme participants (including the Commission Services)	
RE	Restricted to a group specified by the Consortium (including the Commission Services)	
CO	Confidential, only for members of the Consortium (including the Commission Services)	
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EXECUTIVE SUMMARY

SAFETY is a two-year research project funded under the ECHO (European Commission's Humanitarian aid and Civil Protection department) call “Prevention and preparedness projects in Civil Protection and marine pollution”, which started the 1st January 2016. The mission of the project is to improve the efforts in detecting and mapping geohazards (i.e. landslides and subsidence), by assessing their activity and evaluating their impact on built-up areas and infrastructures’ networks. SAFETY will enhance ground deformation risk prevention and mitigation efforts in highly vulnerable geographic and geologic regions. The outcomes of the project will provide Civil Protection Authorities (CPA) with the capability of periodically evaluating and assessing the potential impact of geohazards on the selected sites.

The Geohazard activity maps are one of the four deliverables foreseen in Task E “Geohazard impact assessment”. This deliverable represents the first complete integration between the available geohazard inventories and the InSAR-derived active deformation areas (HotSpots). These maps show where active and significant ground surface areas intersect the available geohazard inventories, detecting the present activity (stabilization, reactivation or constant movement) of already known phenomena. The final goal is to provide an operable methodology, a protocol, which can be integrated into the Civil Protection prevention activities.

REFERENCE DOCUMENTS

N°	Title
RD1	DoW, Part B
RD2	D.D1: Test site selection
RD3	D.B1: User Requirements
RD4	D.C2.1 Deformation activity maps

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INTRODUCTION

The Geohazard activity maps are one of the four deliverables foreseen in Task E “Geohazard impact assessment”. This deliverable, which will be updated three times throughout the project, aims at developing and testing a methodology capable of generating geohazard activity maps. These maps will detect active and significant ground surface areas, identifying their plausible cause. The final goal is to provide an operable methodology, a protocol, which can be integrated into Civil Protection prevention activities.

In this second version of the Geohazard activity map deliverable the integration between the available geohazard inventories and the InSAR-derived active deformation areas (HotSpots) is presented. In the subsequent update at month 20, the geohazard activity maps will be updated.

1 METHODOLOGY

1.1 State of the art

Differential Synthetic Aperture Radar Interferometry (DInSAR) is a microwave remote sensing technique that enables the measurement of surface displacement with a centimeter to millimeter accuracy and with a large spatial coverage capability (Rosen et al., 2000). It exploits the phase difference between two SAR images acquired over the same area in different epochs providing measurements of the ground displacement component along the radar line of sight (LOS). Advanced DInSAR techniques or multi-temporal interferometric techniques, compute displacement time series from multi-image analysis, typically few tens of SAR images. A comprehensive review of these techniques and their application to monitor geohazards can be found in Crosetto et al. (2016) and Tomás et al. (2015).

Previous works revealed limitations related to the acquisition geometry of the satellite systems or the land use cover (Notti et al. 2010), being evident when an integrated multi-sensor approach is considered (Herrera et al. 2013). Notti et al. (2014, 2015) presented a review on how to consider these issues for an adequate interpretation of InSAR-based ground surface displacements. Therefore, on the basis of the methodology proposed by Bianchini et al. (2013), Herrera et al. (2013) and Notti et al. (2014), which was funded by FP7 DORIS project, we present an adapted methodology to generate Geohazard activity maps based on Sentinel InSAR deformation activity maps with the target of Civil Protection prevention services.

1.2 Description of the methodology

In this section, we describe the methodology to generate the Geohazard activity map based on the deformation activity maps derived by Sentinel-1 InSAR (Figure 1). The methodology consists in three main steps: identification of “hotspots” of active deformation (Step 1), definition of a quality index for the HotSpot areas (Step 2), integration of the hotspots with the pre-existent geohazard inventories (Step 3).

The identification of HotSpot (Step 1) is based on the procedure proposed in the deliverables C2.3 and C2.4, “Upgraded deformation activity maps over the two test sites (V1)”. This procedure is summarized as follows: firstly, the PSs with absolute velocity higher than a stability threshold, representing the general noise of data, are selected; then, from this subset of points, only those areas with at least 5 PSs within a fixed radius are considered as Hotspots representative of a significant active deformation.

The definition of a quality index for the HotSpot areas (Step 2) will be implemented in the proposed methodology with the next and final deliverable of the Geohazard activity maps. The methodology, already defined, will be based on the definition of a quality index for each HotSpot based on the statistical definition of the differences between the time series of deformation of each PS composing each HotSpot.

The integration of the hotspots with the pre-existent geohazard information (Step 3) consists in the intersection of both layers in order to represent the “present” state of a certain geohazard. For example, in the case that a landslide inventory is available this method allows to update the state of activity of a previously known landslide, changing from “dormant” to “active” and conversely.

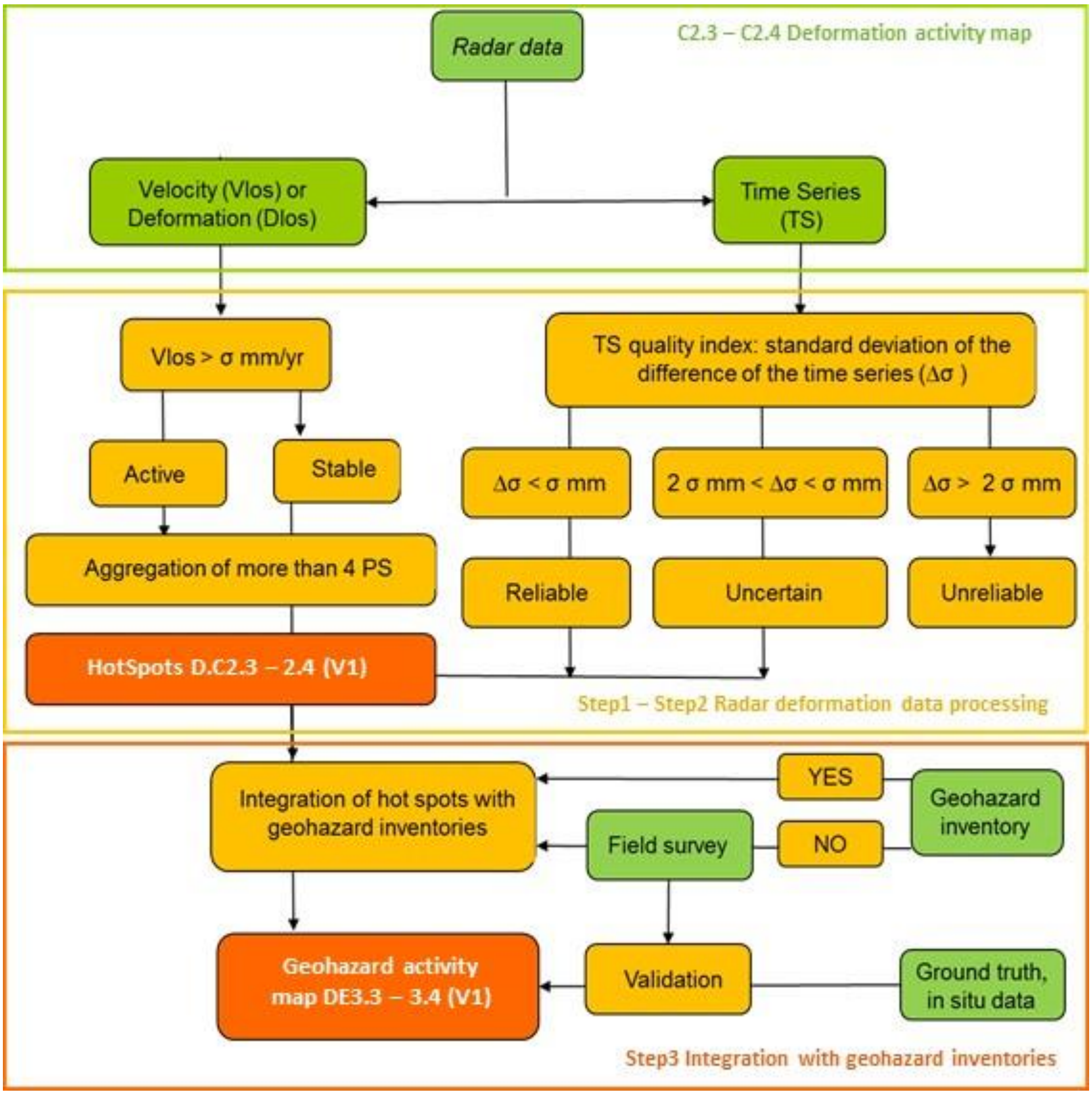

Figure 1 - Flow chart of the methodology to improve geohazards PSI analysis. Green cells represent necessary input data. Light orange is procedure steps and dark orange the output of the methodology.

2 GEOHAZARD ACTIVITY MAP

2.1 Volterra test site

2.1.1 Input data: HotSpot map and geohazard inventory

The HotSpot map for the Volterra test site is highly dependent from the analysis chosen for the SAR images processing. In fact, the product obtained from the second data processing (deliverable C2.4 – "Southern Tuscany, Volterra area, deformation activity map V1) was more robust and reliable than the previous one but at the price of losing sampling density. Moreover, in these second iteration of the SAR images processing, both orbits where acquired.

The total number of HotSpots obtained is 7: 5 hotspots are in descending orbit with mean velocity values ranging from -5.7 to -4.7 mm/yr in line of sight (LOS) and 2 hotspots are in ascending orbit with mean velocity values ranging from 4.8 to 5.7 mm/yr in LOS. All the active deformation areas are located in the south-south western portion of the city of Volterra, outside the walls that delimitate the historical city centre.

The geohazard inventory for the Volterra test site is made of a Landslide Inventory Map (LIM) layer containing 1040 landslides that have been mapped relying on two landslide inventories provided by the Tuscan region and by the GEOPROGETTI company (Figure 2). The first geodatabase is recorded at a regional scale and represent an evolution of the previous IFFI (Inventario dei Fenomeni Franosi in Italia) database, improved with ERS 1/2 an Envisat PSInSAR information (DIANA project, Dati Interferometrici per l'ANalisi Ambientale). The second one is referred to a detailed survey performed only in the 20 km^2 covered by the Volterra city (GEOPROGETTI, 2010). The results of the two inventories were merged in order to provide a database, which shows the extension of the phenomena and their state of activity.

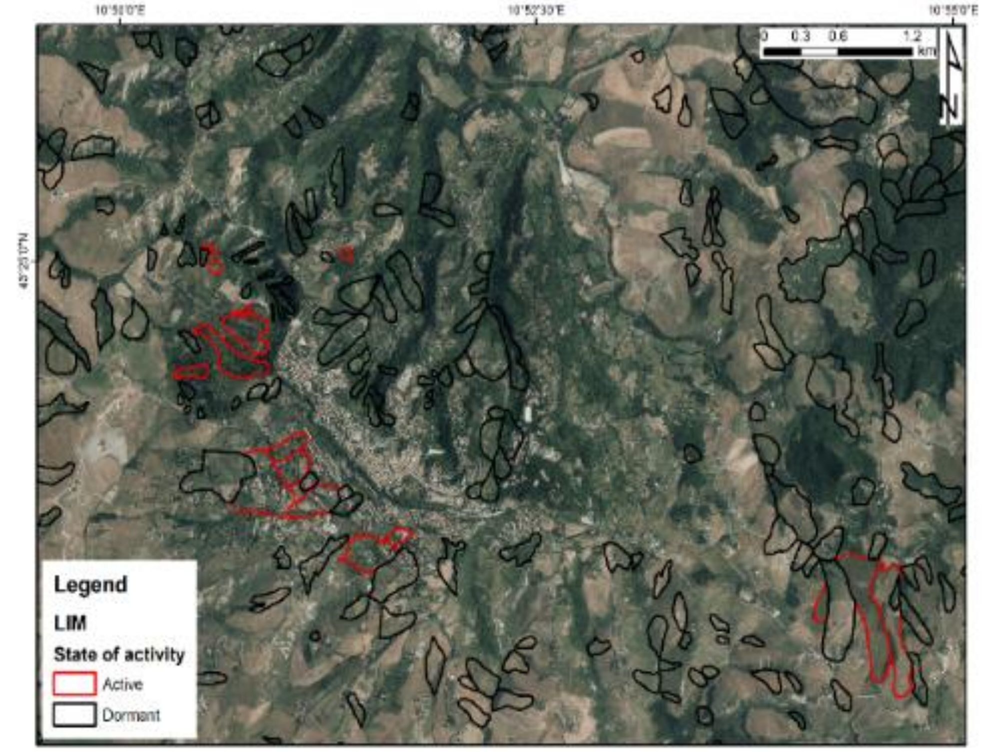

Figure 2 – Landslide Inventory Map around the city of Volterra. A 2013 digital orthophoto is used as background image.

2.1.2 *Geohazard activity map*

The landslide inventory map (LIM) has been intersected with the PS radar benchmarks and with the HotSpot map, considering both ascending and descending orbits.

Within the spatial distribution of PSI LOS velocities, the stability threshold is fixed at ±3 mm/year for distinguishing stable targets (displayed in a green color) from moving ones. PSI-based displacement data depend on the combination of the sensor acquisition geometry (orbit and incidence angle) with the local topography (aspect and slope of the area) and with the real direction of movement, and generally, radar data collected in ascending orbit are suitable for detecting E-facing slope movements, while descending geometry is more appropriate for W-facing slope movements. Given the west-facing orientation of the Volterra southwestern area, movements measured by the SENTINEL-1 satellite in ascending geometry consistently record a movement towards the satellite (positive) and potentially underestimate the downslope motion, as they are minimized by the combination of slope topography and LOS. Conversely, movements recorded in descending orbit are a good approximation of the real displacements, as ground motion direction is nearly parallel to LOS direction and the measured velocities are negative (away from the satellite).

The 5 HotSpots obtained from the descending dataset (Figure 3) fall into the boundaries of mapped landslides in the Le Colombaie-Il Cipresso and in the Fontecorrenti site on the south-western sector of Volterra city. In particular, 4 hotspots are located on active slides, while one Hotspot is located on a mapped dormant slide (Figure 3). The 2 hotspots on the active slide on Il Cipresso site include PS benchmarks with mean negative annual LOS (Line Of Sight) velocities ranging from -2.5 up to -7.6 mm/yr. The 2 hotspots on the active slide on Fontecorrenti site include PS benchmarks with mean negative LOS velocities ranging from -3.6 up to -6.6 mm/yr; similarly, the hotspot located on the dormant slide in Fontecorrenti site is characterized by PS LOS mean yearly velocities of -3.2 mm/yr up to -6.8 mm/yr (Figure 3).

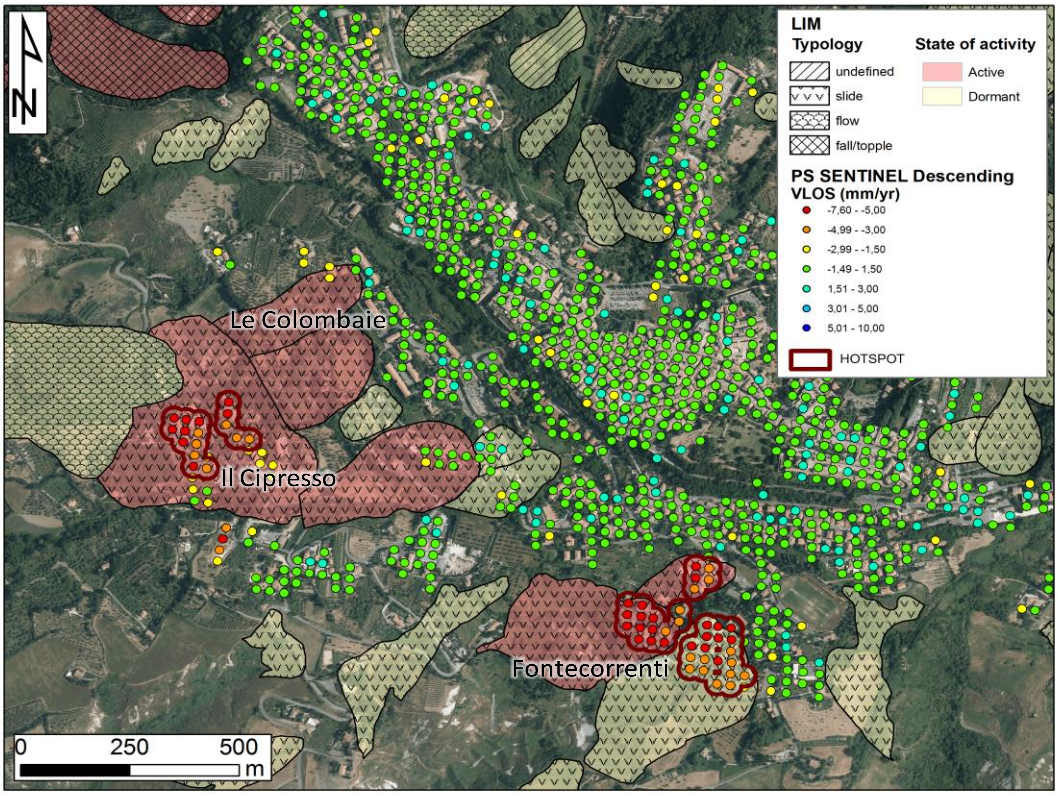

Figure 3 - PS SENTINEL in Descending geometry and related HotSpots, overlapped on LIM in the SW sector of the Volterra city. A 2013 digital orthophoto is used as background layer.

Likewise, the 2 HotSpots obtained from the ascending dataset (Figure 4) fall into the boundaries of the same mapped slides, the active one in Le Colombaie-Il Cipresso site and the dormant one in Fontecorrenti site on the south-western sector of Volterra city.

The HotSpot on the active slide on Il Cipresso site includes PS benchmarks with mean positive annual LOS velocities ranging from 3.4 up to 10.1 mm/yr. The HotSpot on the dormant slide on Fontecorrenti site is characterized by PS LOS mean yearly velocities of 2.3 mm/yr up to 7.5 mm/yr (Figure 4).

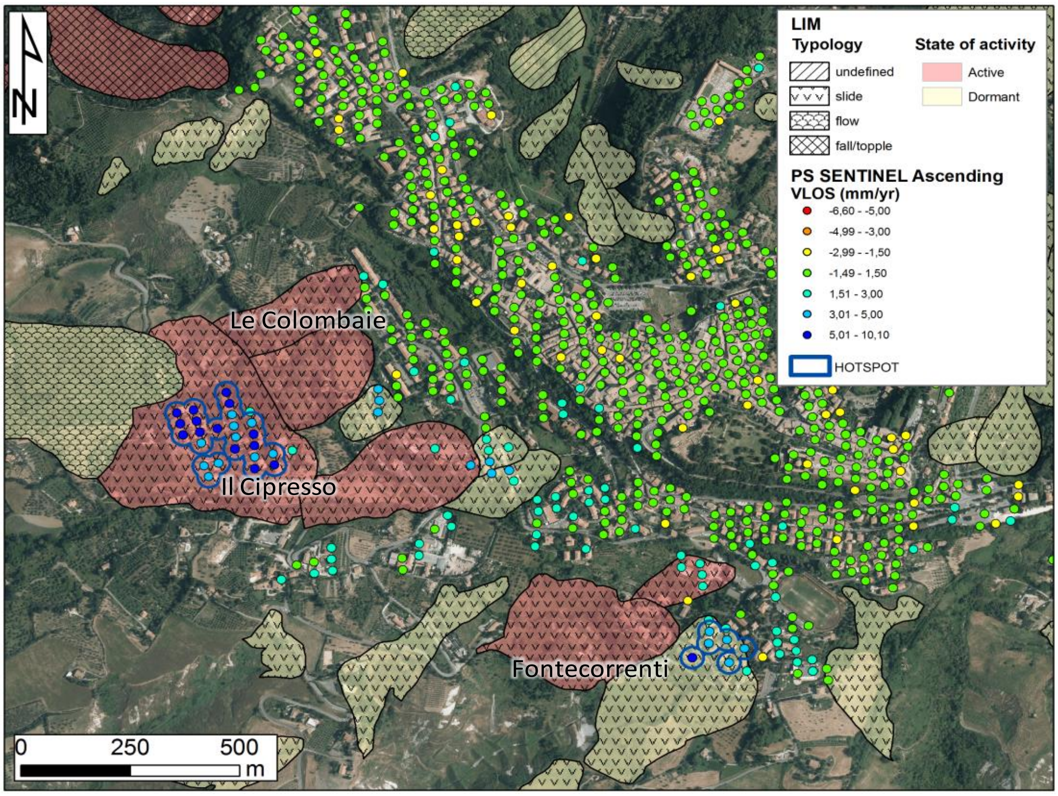

Figure 4 - PS SENTINEL in Ascending geometry and related HotSpots, overlapped on LIM in the SW sector of the Volterra city. A 2013 digital orthophoto is used as background layer.

The PS LOS velocities (VLOS) in ascending and descending orbits were projected along the local steepest slope, for obtaining VSLOPE values, according to Notti et al. (2014).

The estimation of VSLOPE velocities is related to the scaling factor used for the downslope projection, which depends on the local topography (slope and aspect derived from DEM with 10 m cell resolution) and on the angle between the steepest slope and the LOS direction. Following Bianchini et al. (2013) and Nolesini et al. (2016), for this angle we set the absolute maximum value of 72° as threshold, which corresponds to the condition number of 15 for the inversion matrix solving the algebraic system in the projection process, consequently making the VSLOPE be no higher than 3.33 times the VLOS.

This procedure allows a more reliable data interpretation, since ground motions are mostly localized on W-facing slopes and LOS measurements, especially the ascending ones, would not have been very representative of real movements as they are minimized by the combination of acquisition geometry and local topography.

The spatial distribution of VSLOPE velocities shows that the city center appears to be almost stable within the acquisition period, while the highest ground motion rates are recorded on the

SW slope of the Volterra hilltop, likewise the VLOS data, with velocities ranging 5 mm/yr up to 20 mm/yr. These areas of maximum VSLOPE overlap with the HotSpot areas within the dormant and active landslides in the Le Colombaie-Il Cipresso and Fonteccorrenti districts.

It is worth to highlight that within this PS post-processing elaboration, the positive and negative PS velocities were merged and the absolute values were taken into account, since after the downslope projection the negative/positive signs depend on the VLOS/C ratio (where C is the correction factor, Bianchini et al., 2013) and all the PS VSLOPE data are referred to the maximum steepest slope (assumed to be the most probable direction of movement because the landslides are translational slides). In Figure 5 the PS VSLOPE are displayed as arrows, whose colour is referred to the VSLOPE absolute value and direction derives from the DEM-derived aspect layer.

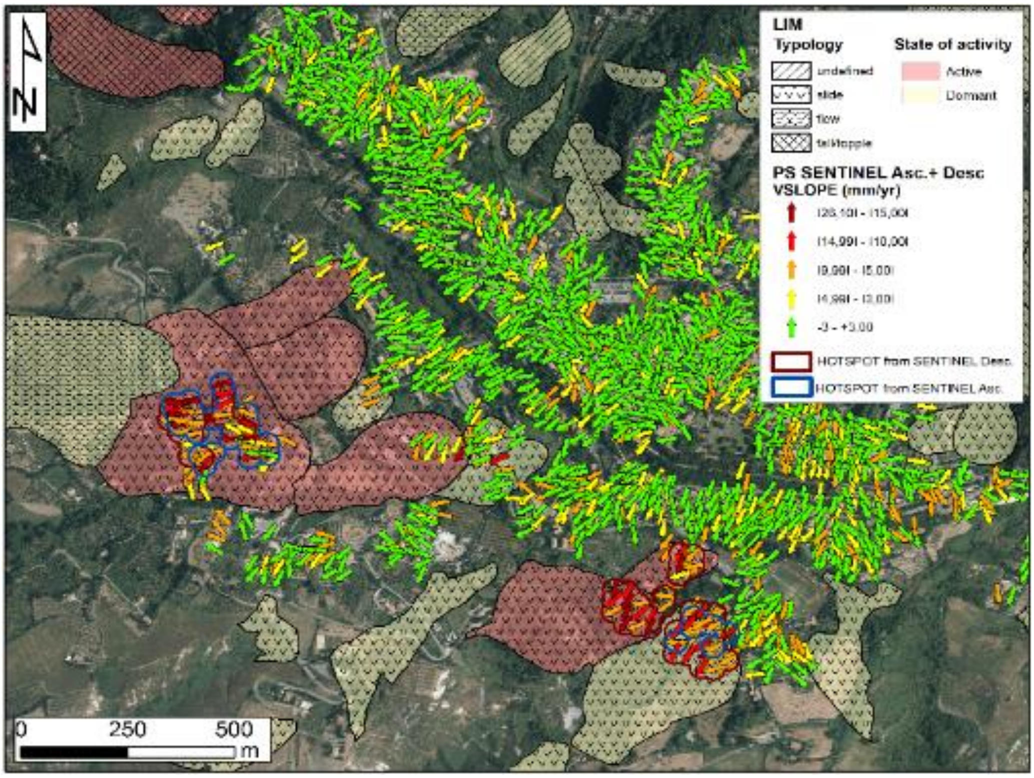

Figure 5 - Spatial distribution of PS data classified by absolute values of VSLOPE velocity, by merging descending and ascending geometries, related Hotspots and LIM on the SW sector of the Volterra city.

2.2 Canary Island test site

2.2.1 Input data: HotSpot map and geohazard inventory

For the Canary Islands test site, the geohazard information available for three islands of the Canarian archipelago (Gran Canaria, La Gomera, Tenerife) includes a landslide inventory with rockfall records and a volcanic susceptibility map in the Island of Tenerife. The rockfall inventory cannot be integrated with the HotSpot map due to the velocity of this type of landslide that cannot be detected with Sentinel 1 radar measurements. Other landslide types such as slides or slow earth flows that could be monitored with radar satellites, have not been map in the islands.

The volcanic susceptibility map is composed of contours that define the spatial probability of hosting a volcanic vent for both mafic and felsic volcanism. This map was derived by Martì and Felpeto, 2010 from available data on volcanic vents and alignments in the last 35 ky (Figure 6).

Due to the absence of the necessary geohazard databases in the Gran Canaria and La Gomera Islands we will consider for this deliverable the HotSpots in the Island of Tenerife. However, in the next update of this deliverable the geohazard activity map from the other two islands will be included.

In the Tenerife Island 220 HotSpots were derived from the second delivery (D.E2.3 – 2.4) of the Deformation activity map (V1). Of these, 191 HotSpots recorded mean negative velocities, ranging from -37 to -4.4 mm/yr, while 29 HotSpots recorded mean positive velocities, ranging from +4.2 to +8.6 mm/yr. The greatest number of HotSpots are located in the SSE sector of the island and within the Cañadas caldera area, especially on the northern flanks of the Teide and Pico-Viejo stratovolcanoes.

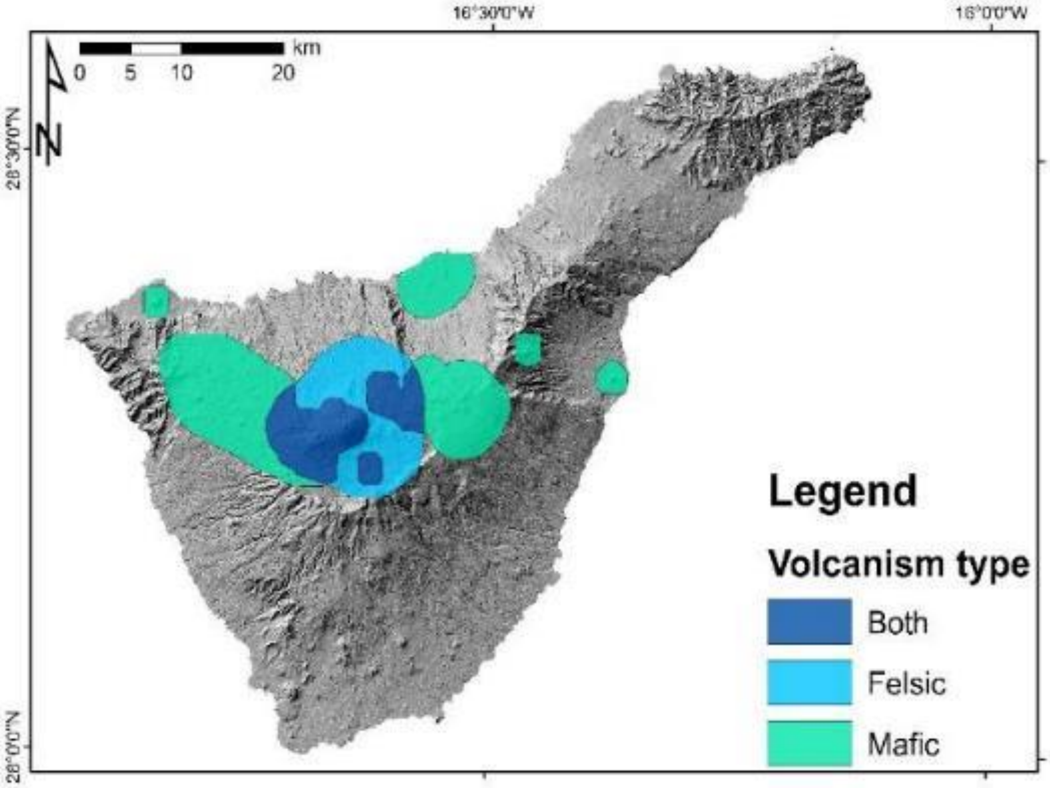

Figure 6 - Volcanic susceptibility contours derived for the Tenerife Island by Martì and Felpeto, 2010. The background image is a 5x5 m DEM.

2.2.2 *Geohazard activity maps*

With the aim of considering not only the volcanic but also the landslide hazard in the Island of Tenerife, we defined a simple qualitative classification of the HotSpots based on a DEM-derived slope map. This classification represents a landslide susceptibility map based only on the slope angle that is considered one of the most important predisposing factors for landslides. For this first approach, only the slope angle is considered as a predisposing factor for landslide occurrence. In the next deliverable, other critical factors (geology, geomorphology, etc.) will be included to define the landslide occurrence potential.

The methodology for deriving the so-called *Landslide Prone Active Areas* is defined as follows:

- Every HotSpot is assigned a value of slope angle (intended as the mean value calculated within the HotSpot area).
- The values of slope angle are then subdivided into 4 classes:
    - 1 (slope angle between 0° and 10°) - Null or low degree landslide-prone area;
    - 2 (slope angle between 10° and 20°) - Medium degree landslide-prone area;
    - 3 (slope angle between 20° and 30°) - High degree landslide-prone area;
    - 4 (slope angle higher than 30°) - Very high degree landslide-prone area;

Class 3 and 4 (high and very high landslide-prone area) represent areas in which the likelihood of occurrence of a landslide phenomenon is the highest.

Figure 7 shows the results of the applied methodology in the Tenerife Island. Starting from the whole HotSpot dataset composed of 220 active deformation areas, we obtained 68 HotSpots (31% of the total) classified as “Null or low degree landslide-prone area”. The 21% of the total (47 HotSpots) are classified as “Medium degree landslide-prone area”, 60 HotSpots (27% of the total) fall into the range of values of the “High degree landslide-prone area” class while the remaining 45 points (21% of the total) are classified as “Very high degree landslide-prone area”.

Figure 8 shows a close-up of the Cañadas caldera area, where the highest density of HotSpots classified in class 3 and 4 (high and very high landslide-prone area) is recorded. The areas in which most of these HotSpots are identified correspond to the northern flanks of the Teide and the Pico Viejo volcanic edifices and to the caldera border. In the first case, the registered deformations are probably related to the presence of steep slopes (maximum slope angle of 65°) composed of loose volcanic deposits where superficial slides can develop. The caldera border, also affected by similar movements, is characterized by sub-vertical slopes; this fact represents a problem for the SAR acquisition, creating a shadow effect.

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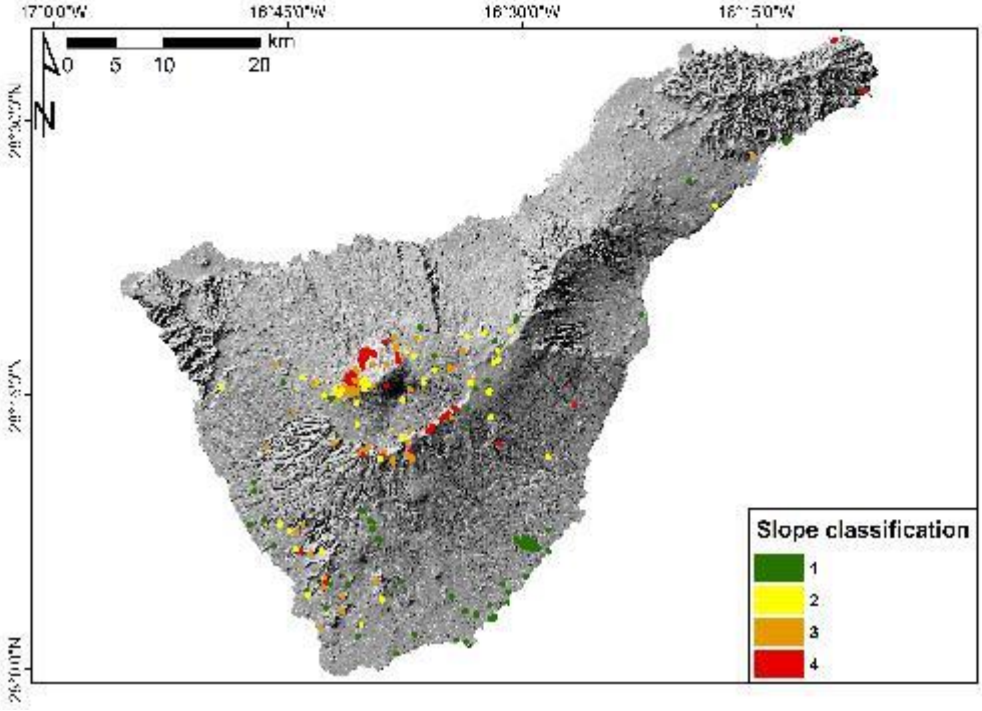

Figure 7 – Landslide Prone Active Areas map derived in the Tenerife Island. The background image is a 5x5 m DEM.

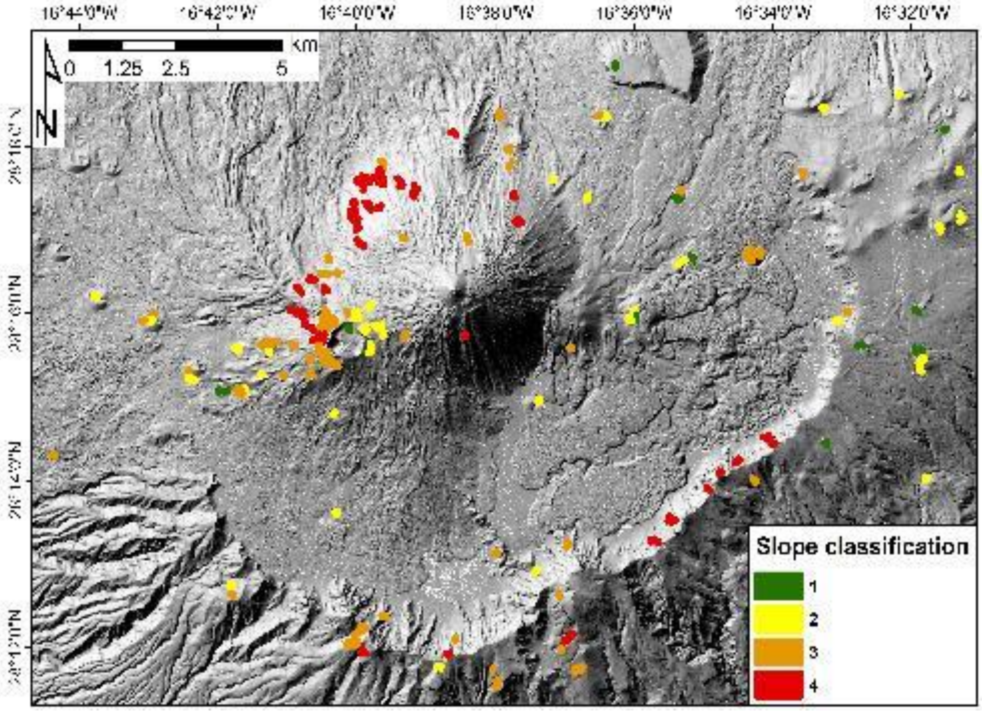

Figure 8 – Close-up of the Landslide Prone Active Areas map in the Cañadas caldera area. The background image is a 5x5 m DEM.

For the definition of the possible relations between volcanic geohazard and registered active movements we created the so-called *Volcanic Susceptibility Areas with Deformation* map that is the simple overlapping between the volcanic susceptibility contours and HotSpot map.

The map derived in this way represents a preliminary information for Civil Protection Autorities, constituting a useful information for knowing a-priori the presence of active movements in areas in which a potential volcanic activity can develop. The estimation of the existence or not of a real correlation between the movements and the volcanic activity is not within the aims of this deliverable, not having enough information for this type of analysis.

Using this approach, we obtained 110 HotSpots falling within the volcanic susceptibility contours (Figure 9). The 68% of the HotSpots (68% of the total) fall into the contours defined for the probability of occurrence of a volcanic event both mafic or felsic; 19 HotSpots (17% of the total) fall into the felsic source contours and 16 HotSpots (15% of the total) are classified as "mafic".

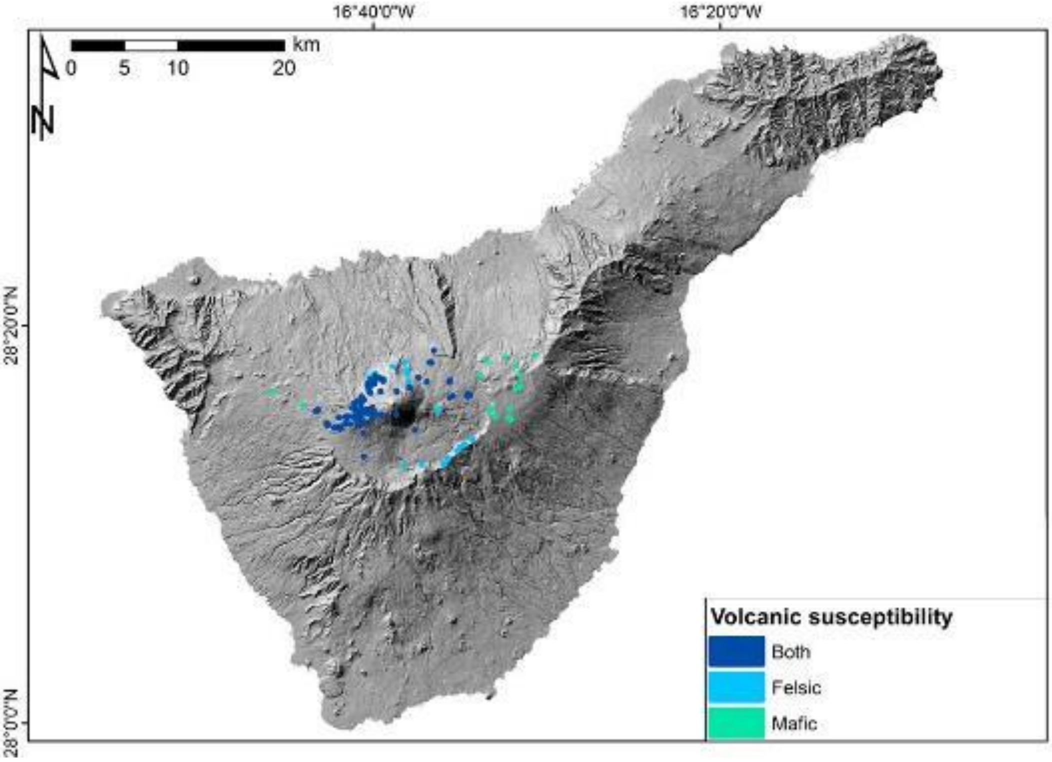

Figure 9 – Volcanic Susceptibility Areas with Deformation map for the Tenerife Island.

3 CONCLUSIONS

This deliverable represents the first complete integration between the available geohazard inventories and the InSAR-derived active deformation areas (HotSpots).

In the Volterra test site, exploiting the LIM and the HotSpot map, a landslide activity map for the urban area of Volterra was derived. This map show where active and significant ground surface areas intersect the available landslide inventory, detecting the present state of activity (stabilization, reactivation or constant movement) of already known phenomena.

In the Canary Islands test site, an inventory of landslides detectable with InSAR is not available. Considering that, we propose the definition of a Landslide Prone Active Areas map based on the classification of the mean slope angle within the area of each HotSpot. Moreover, the volcanic hazard in the Tenerife Island was considered exploiting the Volcanic Susceptibility Areas with Deformation map, which represent the overlapping between the volcanic susceptibility contours and HotSpot map.

In the next and final deliverable, field information, especially for the Canary Islands will be collected to improve the proposed approaches. Moreover, the quality index for the HotSpot will be introduced to have a robust statistical evaluation of each HotSpot. Moreover, the geohazard inventories will be improved with new data or field checks were needed.

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