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Sentinel-1-based monitoring services at regional scale in Italy: State of the art and main findings

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ABSTRACT

In Italy, three different operational continuous monitoring experiences based on the exploitation of Multi Temporal Synthetic Aperture Radar data (MTInSAR) Sentinel-1 data are here depicted, and the results obtained in one year have been analysed. Tuscany region (Central Italy) has been the first region to implement such service, followed by Valle d'Aosta and Veneto regions (North-West and North-East Italy, respectively). In detail, the services benefit from regularly updated deformation maps (every 12 days) to promptly detect anomalies of deformation, i.e., trend variations in the time series of displacement. In this work, anomalies detected between September 2019 and September 2020 are thus correlated with several types of factors, either related to the environment, intrinsic of the data or derived from ancillary data. A statistical analysis has been performed on the three regions, and are discretized into five macro-areas, namely: i) spatial and temporal statistics, related to the geographic setting and the temporal distribution of the anomalies; ii) parametric, i.e., related to the interferometric processing; iii) triggering factors; iv) environmental and geological factors; v) urban setting. The results derived from the analysis of this work show the obvious differences between the three regions, highlighting distinct distributions of the anomalies according to the different settings of each study area. Furthermore, results were analyzed, to provide a summary of the main findings obtained, giving a first evaluation of the services and hypothesizing future further improvements and applications.

1. Introduction

Spaceborne-based monitoring represents nowadays a consolidated practice for a wide range of natural and anthropogenic phenomena occurring on the Earth's surface. For instance, ground motion is constantly observed by satellites equipped with different sensors. Since the early '90s, Synthetic Aperture Radar (SAR) sensors are widely implemented by several generations of satellites becoming a preeminent ground monitoring system. The recent flourishing of SAR sensor is strongly connected to the development of Interferometric and Differential Interferometric techniques (InSAR and DInSAR) and MTInSAR (Multi Temporal Interferometry SAR) (Crosetto et al., 2016). The early studies, conducted with data belonging to the first generation of satellites, *e.g.*, European Space Agency (ESA) ERS 1/2 and ENVISAT, or Radarsat 1/2 constellations, repeatedly proved the effectiveness of interferometry for ground motion monitoring (Crosetto et al., 2016; Solari et al., 2020). Such constellations were also exploited for national ground motion services, such as the Italian Not-Ordinary Remote Sensing Plan (Costantini et al., 2017; Di Martire et al., 2017).

The launch of the Sentinel-1 mission by the European Space Agency (ESA) represented a turning point for the Earth Observation scenario, providing an unprecedented operational capability for intensive radar mapping of the Earth surface (Lanari et al., 2020). The enhanced revisiting time (now reduced to 6 days, thanks to the dual constellation), the free and open policy, the global coverage, and the rapid product delivery make Sentinel-1 a fundamental tool for mapping and monitoring unstable areas. The significant developments of the MTInSAR techniques made possible to have high increase of number of Measurement Points (MPs) thanks to the development of homogeneous distributed scatterers algorithms and computational capacity (*e.g.*, parallel or cloud computing, virtual machines, etc.) both in terms of spatial and time performance.

Most of the MTInSAR applications with Sentinel-1 data so far have regarded the mapping of unstable areas, at a various scale of analysis,

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such as continental (Crosetto et al., 2020; Lanari et al., 2020), nation-wide (Kalia et al., 2017; Novellino et al., 2017; Dehls et al., 2019; Papoutsis et al., 2020) or regional (Delgado Blasco et al., 2019; Aslan et al., 2020; Bonì et al., 2020). Continental-scale initiatives, such as the European Ground Motion Service (EGMS, https://land.copernicus.eu/pan-european/european-ground-motion-service), will provide ground deformation products with a one year-update plan, thus representing an unprecedented amount of freely accessible data that are, however, insufficient for near-real-time monitoring.

Up to now, applications oriented towards the near real-time monitoring of deformation phenomena at a large scale of analysis are not fully exploited.

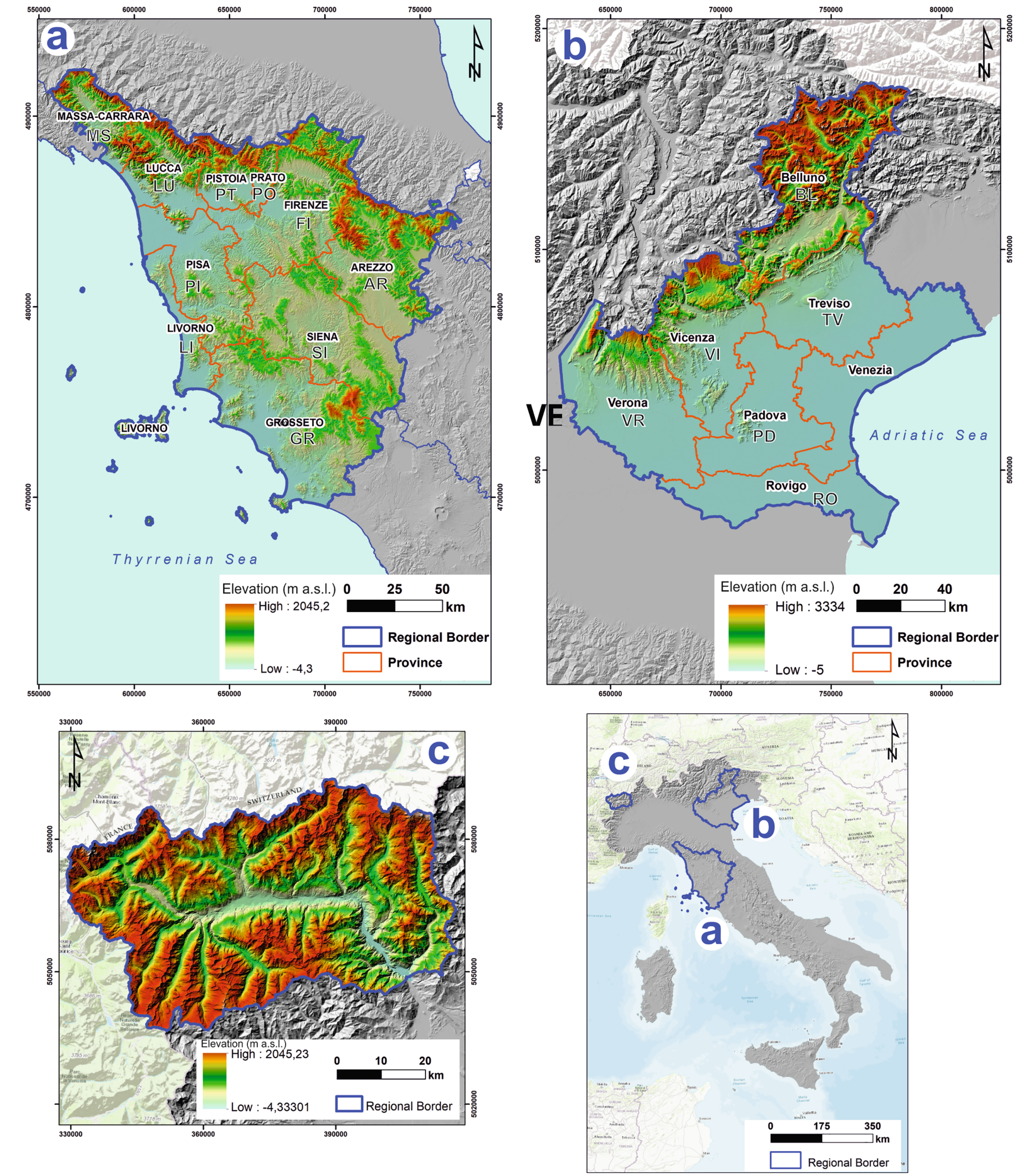


Fig. 1. Setting of the study area: a) Tuscany, b) Veneto, c) Valle d'Aosta. In the bottom right, Italy with the three abovementioned regions. For each province, its acronym was reported.

Italy is at the forefront for what concerns the exploitation of continuous monitoring techniques. Indeed, three experiences that exploit the concept of continuous monitoring are operational and reported here. Such system relies on screening and surveillance activities conducted over large areas with an update frequency sufficient to monitor the evolution of ground deformational phenomena. In Tuscany Region (Central Italy), the first operational continuous monitoring service based on the use of Sentinel-1 interferometric data at a regional scale has been implemented since 2016 (Raspini et al., 2018). Following this example, the Valle d'Aosta and Veneto Regions started in April 2018 and July 2019, respectively, to monitor their territory adopting an approach similar to Tuscany.

The services benefit from regularly updated deformation maps (every 12 days) to promptly detect anomalies of deformation, i.e., trend variations in the time series of displacement. Areas with persistent and significant anomalies are reported and notified to Regional authorities for the definition of further analysis and risk mitigation strategies.

The objective of this work is to statistically analyze the anomalies obtained in one year of continuous monitoring in the three above-mentioned regions. In detail, such analysis has been conducted by coupling the anomalies with several types of factors, either intrinsic of the data or external, related to the environment and derived from ancillary data. Nevertheless, most of the factors used for the statistical analysis are used as ancillary data to correctly interpret the anomalies generated by the algorithm. The statistics are discretized into five macro-areas: i) spatial and temporal statistics, related to the geographic setting and the temporal distribution of the anomalies; ii) parametric, i.e. related to the interferometric processing; iii) triggering factors; iv) environmental and geological factors; v) urban setting. The outcomes of the study show the obvious difference between the three regions, highlighting distinct distributions of the anomalies related to the different settings of each study area. Nonetheless, such kind of work is intended to show a first summary of the results obtained in the framework of the operational services, analyzing the distribution and the impact of the anomalies in the operational chain.

2. Regional settings of Tuscany, Valle d'Aosta and Veneto

Tuscany, Valle d'Aosta (VdA) and Veneto regions are placed in different areas of the Italian peninsula, and, accordingly, are characterized by different geological and geomorphological features, each one characterized by peculiar landscapes. Here, short outlines are reported for each regional geological and geomorphological setting.

2.1. Tuscany

Tuscany region, located in central Italy, along the Tyrrhenian and Ligurian seas coastline, is one of the largest and most populated Italian regions (Fig. 1a). It extends for more than 23,000 km^2 and it is administratively divided into 10 provinces, among which Firenze is the most important and the regional capital. From a physiographic point of view, Tuscany is a variegated territory characterized by wide plains, both fluvial and coastal, gentle hilly slopes, and mountainous ridges belonging to the Northern Apennines. The Tuscany region includes the Tuscan Archipelago formed by 7 islands, among them Elba and Giglio islands are the largest. The Northern Apennine consist of a NE-oriented fold-and-thrust belt, originated during the Cretaceous (Boccaletti and Guazzone, 1974). Main geological formation cropping out in Tuscany are made by remains of the oceanic crust and their sedimentary cover, consisting of a thick sedimentary sequence of carbonate and siliciclastic deposits. Other main geological formations are the metamorphites of the Apuan Alps (in the northwestern sector) and the volcanic rocks of the Mt. Amiata at south; the internal part of the Tuscany region is characterized mostly by the Apennine flysch ridges, alternating with NW-SE trending intermontane basins filled with lacustrine and fluvial deposits. The actual geomorphological setting of Tuscany is strongly dependent on geological-tectonic processes.

Ground deformational phenomena are frequent in Tuscany, among which landslides result to be the most recurrent ones (Segoni et al., 2015; Tofani et al., 2017). Recent estimations include approximatively 91,000 dormant and active landslides (Rosi et al., 2017). Tuscany is characterized also by several subsidence areas, mostly spread in the coastal plains (Grosseto and Pisa plains) (Bianchini et al., 2019) and some internal basins, such as the Florence-Prato-Pistoia and Chiana plains (Del Soldato et al., 2018; Ezquerro et al., 2020), mostly due to water over-exploitation, and the Larderello geothermal site (Solari et al., 2018).

2.2. Valle d'Aosta

VdA is the smallest Italian region, covering only about 3,000 km^2. There is not any subdivision in provinces and Aosta city is the regional capital (Fig. 1c). The VdA physiographic setting is mainly mountainous, with the highest elevations over 4,000 m a.s.l. (Mont Blanc, 4,808 m high, is the highest peak of the Alps). The VdA territory is crossed by one east–west longitudinal valley following the course of the Dora Baltea, the main watercourse of VdA, and by five North-South-oriented tributary valleys. The main lithologies cropping out in the area reflect the tectonic activity within the area, with metamorphic sequences, from eclogitic to low-grade metamorphism facies (Frey et al., 1999). After the last glaciation, the VdA landscape was severely modeled by the ice action, shaping the valleys, and forming glacio-fluvial deposits. This kind of setting influences the slope dynamics (Carraro and Giardino, 2004), and, according to the last inventory, 2,052 landslides have been mapped, including also DSGSDs (Deep-Seated Gravitational Slope Deformation), which occupies approximatively 76% of the total unstable area (Solari et al., 2019). Among the mass movements, a typical Alpine landform such as rock glaciers are scattered in VdA. Morra Di Cella et al. (2011) identified and mapped 837 rock glaciers, equal to 2% of the entire territory.

2.3. Veneto

Veneto is one of the largest Italian regions, with seven provinces and Venezia as regional capital (Fig. 1b). It is located in the northeastern part of Italy, and it is characterized by various natural landscapes. The coastal sector overlooks the Northernmost part of the Adriatic Sea, while the Southern part of the region is included in the Po plain and delta. Gentle slopes are recognizable in the western portion of the region, including the Colli Euganei and Colli Berici. The hilly morphology is gradually substituted by an Alpine environment in the Northernmost part of the region, where the Dolomites dominate the landscape. Veneto region is included in a complex tectonic system which led to the formation of the Alpine belt, shaped by the continental collision between the African and Adria plate. Geologically, Veneto region is made up of three main sectors, from N to S: i) the Alpine area, mainly constituted by calcareous-dolomitic deposits, Mesozoic in age, and, to a lesser degree, by flysch deposits (Eocene); ii) the piedmont area, made by alluvial and morenic deposits Pleistocene in age; iii) the great plain area, made by Holocene alluvial sediments. The geomorphology of Veneto region reflects the tectonic and glacial events occurred over geological time. Landslides are very diffused in Veneto regions and according to the IFFI (*Inventario dei Fenomeni Franosi in Italia*, landslide inventory in Italy, Trigila et al., 2010) project, updated in 2007, almost 10,000 landslides are reported, distributed especially in Belluno, Verona, Vicenza and Padova provinces. Subsidence is a relevant phenomenon as well, mainly occurring in the coastal area of Venice and the Po delta (Carminati and Martinelli, 2002; Tosi et al., 2007).

3. Data and methods

The regional continuous monitoring services benefit from Sentinel-1 (both A and B) data. A baseline product is derived at the start of the services, acquiring, and processing the available Sentinel-1 stack by means of SqueeSAR technique (Ferretti et al., 2011). Within the framework of the operational services, time series of displacement are generated, and abrupt changes in the trend, i.e., the anomalies, are highlighted and evaluated. This stage is called "PS monitoring phase" and is coupled with another activity, called "PS mapping phase", during which archived Sentinel-1 (S1) data are analyzed and interpreted to map and characterized areas affected by relevant motion, as individuated by the interferometric data. In this stage, clusters of deformation are generated through a specific algorithm and with specific thresholds, to have a periodic picture of the deformational state of the art of each region. The description of the Sentinel-1 datasets adopted, and the mapping activities can be found in the supplementary material.

3.1. Analysis of the time series

Ground deformation maps for all three regions have been elaborated by using the SqueeSAR technique (Ferretti et al., 2011), a second-generation PSInSAR algorithm (Ferretti et al 2001) capable to process long temporal stacks of SAR images, acquired over the same area. Further details on the SqueeSAR technique can be found in the supplementary material.

Once obtained a ground deformation map, the dynamic streaming of displacement data at a regional scale is implemented for the monitoring activity. The time series screening, necessary to identify the anomalies, consists in a procedure based on the addition of two consecutive processed S1 images. Hence, anomalies are delivered every 12 days.

Displacement time series of each measurement point for both ascending and descending geometries are automatically analysed to identify, in the last 150 days of the time series, any change in the deformation pattern. The 150-days window has been selected after a "tuning period" carried out on Tuscany region and it has been adopted also in the other two territories, after an agreement with regional authorities. When a change is identified, a breaking point (Tb) is automatically set, comparing different polynomial models before and after the temporal threshold assigned. The average deformation rates before and after the breaking point are recalculated; when their difference $|\Delta V|$ is higher than 10 mm/yr, the point is highlighted as anomalous (Fig. 2). A more detailed description of the anomalies detection algorithm is found in Raspini et al. 2018. The final stage of the operational service is the interpretation of the anomalies. In this stage, it is determined that an effective displacement is occurring, and it is classified according to the interpretation, supported by ancillary data, such as DEMs, slope and aspect, orthophotos, etc.

3.2. Ancillary data

For the computation of the statistics, anomalies have been coupled with ancillary data derived from several sources. Here, a shortlist of the used products and their origin is provided:

- Land Cover maps belong to the CORINE Land Cover (CLC) project (https://land.copernicus.eu/pan-european/corine-land-cover/clc2018). The map dated back to 2018 and it has been used for comparing the anomalies location to the third level (the most detailed) of land cover.
- Slope, aspect and altitude derive from Digital Elevation Models (DEMs) of the three regions. The DEMs have been downloaded from each regional cartographic service and their resolution is 20 m.
- Landslide inventories derive from the IFFI database, integrated and updated with Basin Authorities and other sources data. For Tuscany, the latest dataset date back to 2014, VdA and Veneto IFFI database were updated in 2007.
- Geo-lithological maps derived from the regional cartographic services. Such maps have been generated from different sources, such as geological maps, scientific and professional studies.
- Structures and infrastructures catalogues derived from the Technical Regional Cartography of each region.

4. Results

The results obtained through the cross-correlation between anomalies in the time series and different types of factor obtained, are here depicted. In detail, figures obtained have been categorized in five macro-areas, classified as follows: i) spatial and temporal statistics; ii) parametric, i.e., statistics related to the DInSAR processing; iii) main triggering factors and typology of anomaly; iv) environmental and geological factors; v) urban setting. A general map of the anomalies classified according to the type (cfr. Paragraph 4.3), is reported in Fig. 3.

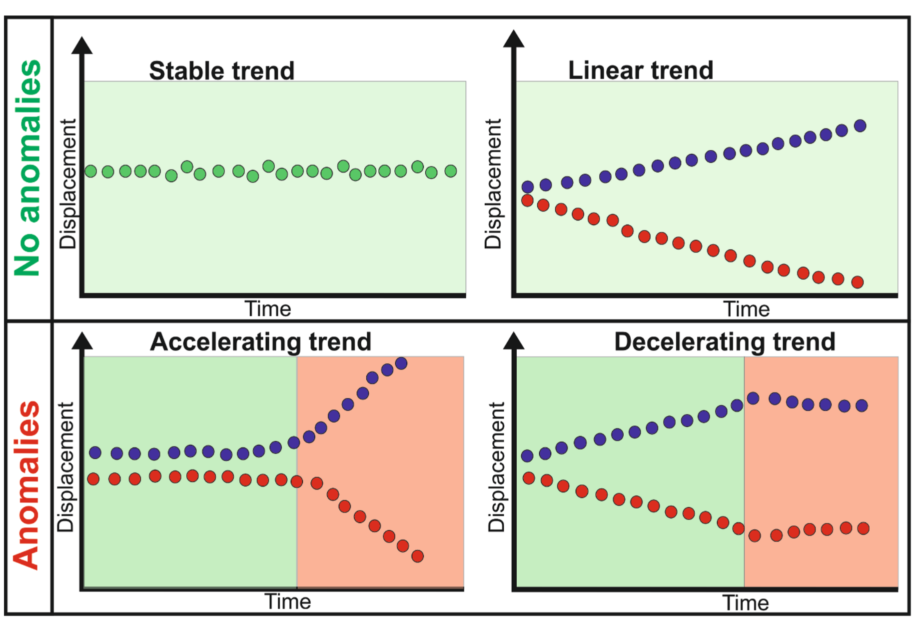


Fig. 2. Schematization of trend changes generating anomalies of movement.

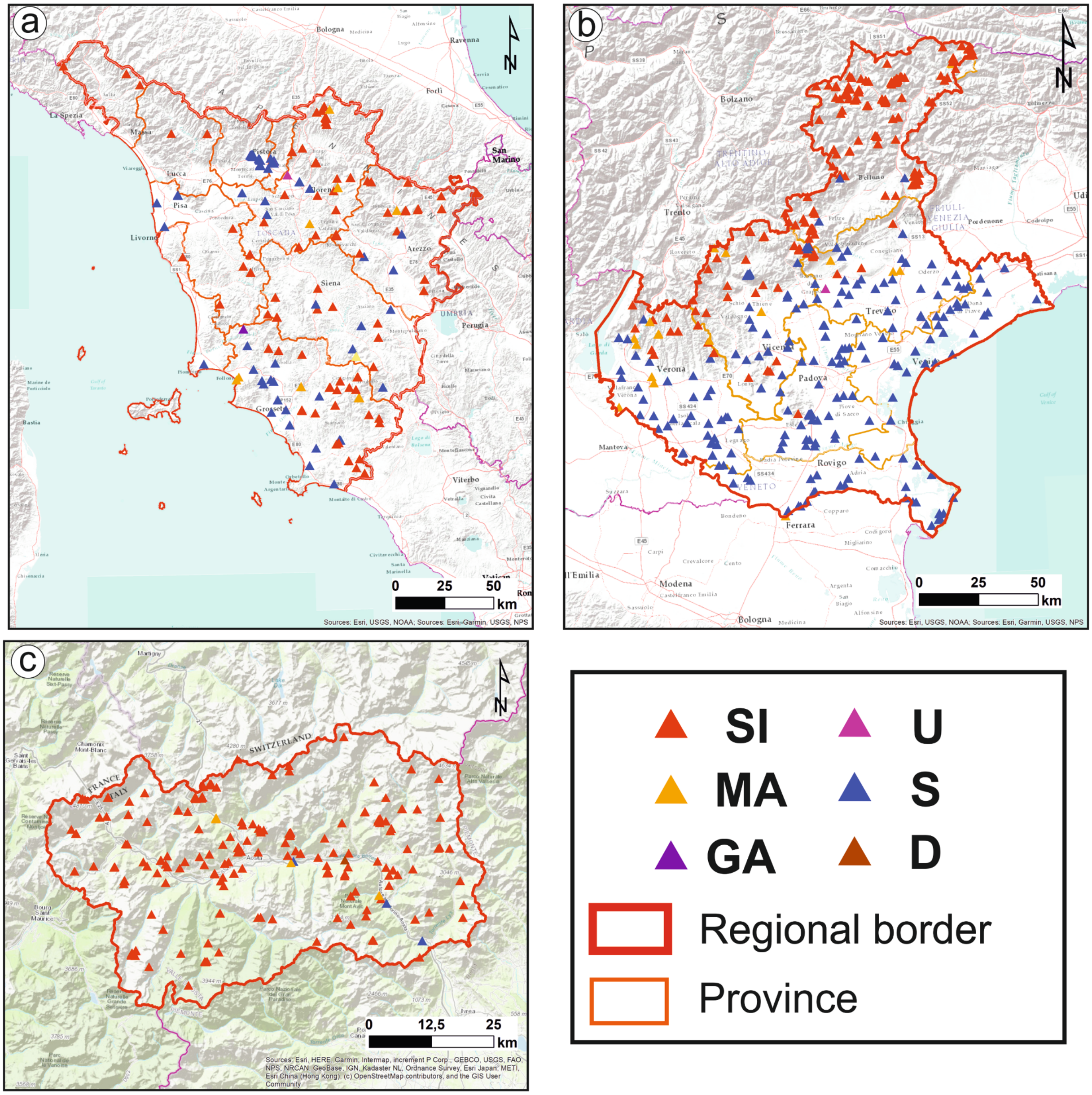


Fig. 3. Anomalies spatial distribution, classified for their type, for a) Tuscany, b) VdA, c) Veneto. SI stands for Slope Instability; U for Uplift; MA for Mining Activity; S for Subsidence; GA for Geothermal Activity; D for Dump site.

4.1. Spatial and temporal statistics

In this section, all the relationships between anomalies, the geographical setting of each region and the temporal factors have been analyzed. In detail, the number of anomalies has been determined for each province of the three regions (Fig. 4, excluding the VdA, composed only by the Aosta province), as well as the number of anomalies for each month and season (Fig. 5).

In Tuscany the Firenze and Arezzo provinces experienced the highest number of anomalies consistent with an effective ground displacement, followed by Grosseto, Pistoia, Prato, Siena and Pisa. Finally, Massa Carrara, Lucca and Livorno provinces summed up had a total of fewer than 50 anomalies (Fig. 4a). It is worth mentioning also that about 70% of the municipalities did not show any anomaly in the timespan considered, and the value of density of anomaly is 0.08 anomalies/km^2. As for the months, the highest number of anomalies was registered in September 2019, whereas March, April and May showed the lowest number. Autumn and Winter 2019 were characterized by more than 500 anomalies, whereas summer 2020 recorded less than 250 anomalies (Fig. 5).

In VdA 598 interpreted anomalies were detected. Almost 80% of the VdA municipalities showed at least one anomaly. September 2019 recorded the highest number of anomalies, followed by August 2020, whereas just 18 anomalies were detected in December 2020; accordingly, 205 anomalies were found during autumn 19 and 78 during winter 19/20 (Fig. 5).

Among the seven provinces of Veneto, Belluno province showed the highest number of anomalies (1563), followed by Padova and Vicenza (672 and 551, respectively), while Venezia and Rovigo had the lowest number of anomalies (193 and 205, respectively) (Fig. 4b). In total, 24% of the municipalities showed at least one anomaly. As for the monthly distribution, the highest number of anomalies was recorded in August 2020, followed by July and March (379, 372 and 360 respectively), as well as during summer 2020 (1064) the highest seasonal number is registered (Fig. 5).

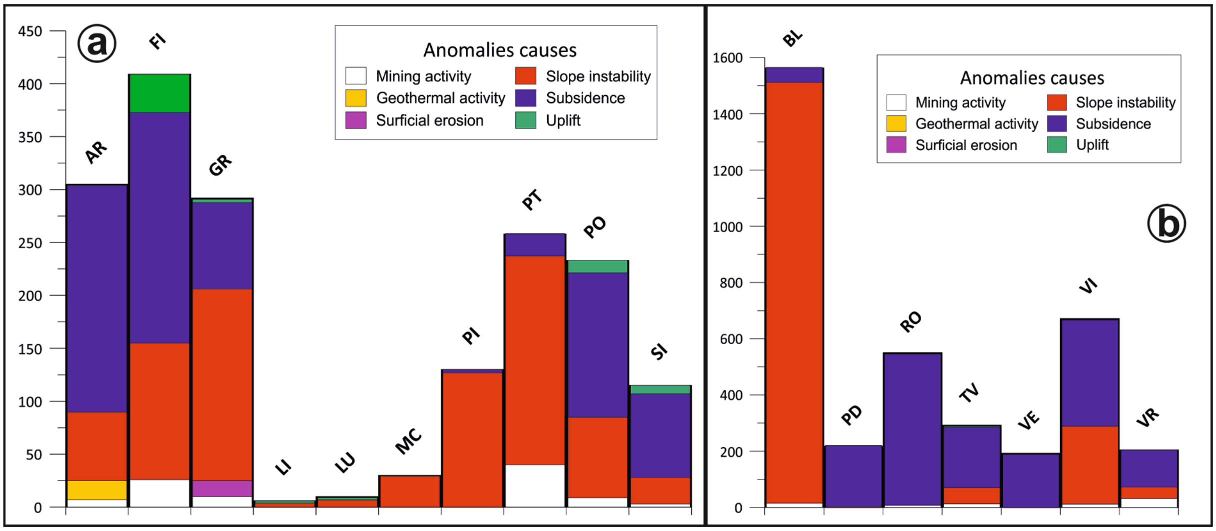


Fig. 4. Provincial distribution of Tuscany (a) and Veneto (b) anomalies classified according to their type. For the acronym definition, see Fig. 1.

4.2. Parametric statistics

Dvel (Differential velocity) and persistency are the most important parameters of the anomalies as generated by the abovementioned algorithm. The first one quantifies the magnitude of change in the deformation rate. The persistency indicates the recurrence in time and space of the points with the same trend variation for each consecutive update. Therefore, anomalies repeated over consecutive updates in the same area can be defined as persistent (Raspini et al., 2018; Del Soldato et al., 2019). In detail, anomalies detected and interpreted have been classified according to the value of Dvel and to the value of persistency. Moreover, the temporal persistency of the interpreted anomalies is analyzed. Finally, anomalies have been compared and intersected with the clusters derived from the mapping activity that every year is accomplished in the three regions.

In Tuscany, ~70 % of the anomalies are characterized by a Dvel value comprised in the range between 10 and 20 mm/yr, and the frequency decreases with the increase of the value of Dvel, reaching the minimum with the highest class of Dvel (>80 mm/yr), with only 9 anomalies. The situation in VdA is very similar, with 75% of the anomalies having Dvel between 10 and 20 mm/yr and with a decreasing trend, where only 4 anomalies have a value >80 mm/yr. Finally, Veneto region shows a similar trend as well, with 60% of anomalies with Dvel between 10 and 20 mm/yr, and a decreasing trend, until the last class (>80 mm/yr), counting 40 anomalies. A summary of the distribution of anomalies vs. DVel is in Fig. 6.

As for the persistency, the graph in Fig. 7 shows for the Tuscany region 4 peaks related to 4 different periods with the highest number of persistent anomalies after three updates. A similar trend is recorded analyzing the anomalies with persistency after 5 updates. These peaks (up to 45 anomalies) are distributed in the whole year, with a seasonal-like behavior, one peak for every season, while the highest number of anomalies is obtained in the first update (September 2020). VdA is characterized by a high number of anomalies in the first (3rd and 4th update, October 2019) and in the final period of analysis (the 30th and 31st update, August 2020), as well as the number of persistent anomalies (both after 3 and 5 updates), showing a fluctuating distribution trend, with an exception represented by the minimum in the summer 2020 period (Fig. 7). Finally, Veneto region shows a generally high number of anomalies in the overall period of analysis, except for the period between the 10th and 12th update (across November and December 2019), where a lower number is registered. The persistency of the Veneto anomalies has a very similar trend, with a high number of persistent anomalies starting from the 17th update (with few oscillations between 90 and 35 anomalies, at the 18th and the 27th update), while the minimum is registered between the 9th and the 15th update (Fig. 7).

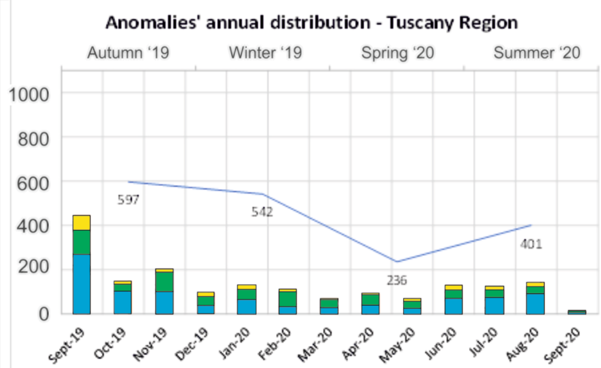
Finally, the anomalies detected have been compared to the cluster derived from the ongoing mapping activities. For mapping is intended the clustering of PS data showing common deformation patterns. For Tuscany region, 508 anomalies fall within clusters of deformation derived from mapping activities, 313 of which are within clusters related to slope instability (Montalti et al., 2019); VdA shows 274 anomalies falling within clusters of movement (derived from mapping activies, Solari et al., 2019), while for Veneto, 455 anomalies are recorded within clusters mapped in September 2020 (clustering activity was not subject of publication).

4.3. Type of anomaly and main triggering factors

Anomalies generated are analysed to decide whether they are consistent with real ground dynamics and to assign, reliably, a link with a driving force. Taking advantage of the available thematic information, all the anomalies are interpreted and classified according to their driving forces, distinguishing 8 categories. The other/remaining 2 classes correspond to anomalies whose trigger cannot be determined (ND), or with noisy time-series (R). Six classes can be reconducted to effective movements, as recognized during the interpretation stage, namely: (i) Mining Activity (MA), (ii) Geothermal Activity (GA), (iii) Dump site (D), (iv) Slope Instability (SI), (v) Subsidence (S) and (vi) Uplift (U).

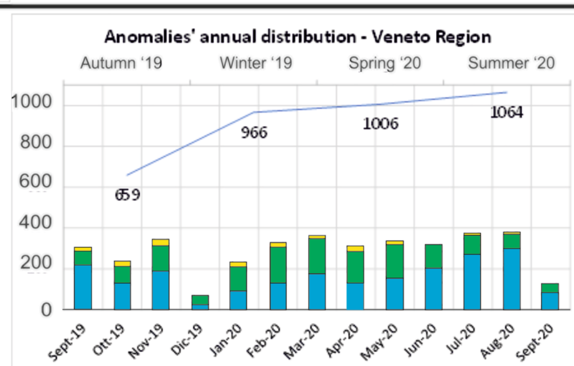
Tuscany region is characterized by different types of deformational phenomena. Most of the anomalies which can be interpreted (1,788 in total) corresponds to Slope Instability (almost 50%), followed by Subsidence, while the number of anomalies falling into the other classes is much lower (less than 10% of the total). The anomalies are spread in the whole Tuscan territory (Fig. 4). The spatial distribution of each typology of anomaly is influenced by the different physiography of each province. For instance, Pistoia, Firenze, Grosseto and Pisa provinces showed a majority of SI anomalies, mostly located over the hills and the reliefs bounding the major cities; S anomalies are predominant in Arezzo, Prato and Siena provinces, mostly due to local subsidence phenomena linked to the overexploitation of the underground resources, mainly water and secondarily geothermal fluids. Livorno, Lucca, Massa and Carrara exhibit the lowest number of anomalies (Fig. 4a). The sum of ND and R for Tuscany is 3470 anomalies (2861 ND and 609 R).

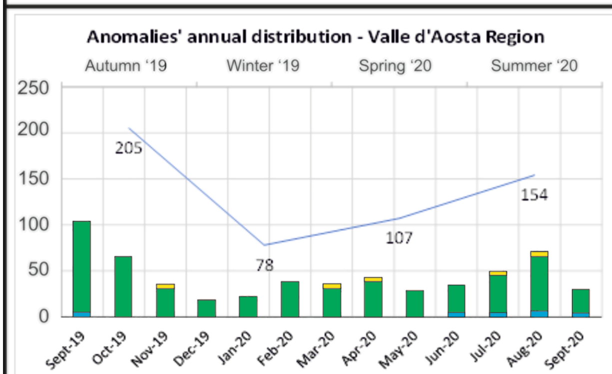
In VdA, a total of 3,324 anomalies have been identified and analyzed in the timespan considered. Being the VdA located in an Alpine setting, the great majority of the anomalies were classified as SI (more than 95%), while a few of them were attributed to S or MA (Fig. 8). As for the



Investigated months	Number of anomalies
September 2019	447
October 2019	150
November 2019	204
December 2019	98
January 2020	128
February 2020	112
March 2020	72
April 2020	93
May 2020	71
June 2020	132
July 2020	125
August 2020	144
September 2020	12

Investigated months	Number of anomalies
September 2019	300
October 2019	235
November 2019	341
December 2019	68
January 2020	231
February 2020	326
March 2020	360
April 2020	309
May 2020	337
June 2020	313
July 2020	372
August 2020	379
September 2020	124





Investigated months	Number of anomalies
September 2019	104
October 2019	65
November 2019	36
December 2019	18
January 2020	22
February 2020	38
March 2020	35
April 2020	43
May 2020	29
June 2020	34
July 2020	49
August 2020	71
September 2020	30

Fig. 5. Seasonal (blue line) and monthly (blue bar for subsidence anomalies; green bar for landslide anomalies, yellow bar for other types of anomaly) distribution of the anomalies for each analyzed region. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

ND and R anomalies, the total number is of 2724 (903 ND and 1821 R).

The 31 updates conducted for the Veneto region highlighted 3,695 points that were classified as anomalies indicators of potential movements. Most of the SI anomalies are detected over the alpine belt, making the Belluno province the one with the highest number of anomalies, more than 90% classified as SI. Provinces mainly featured by coastal and/or flat territories such as Rovigo, Padova and Venice, show a predominance of subsidence-related anomalies (Fig. 4b), mostly connected to local overexploitation of groundwaters and in areas where well-known subsidence of the Po delta (Tosi, 2013, Farolfi et al., 2019) is found (however local accelerations might be due to several factors). ND and R anomalies are in total 4418 (1394 ND and 3024 R). A summary of the classified anomalies for all the territories involved in the monitoring service is provided in Fig. 8.

A special focus has been devoted to the SI anomalies since they represent a constant and continuous threat in all three regions (Fig. 9). Firstly, SI anomalies have been intersected with the existing landslide inventories, derived from the IFFI project. In Tuscany, only 231 anomalies (out of 1788 SI anomalies in total) fall within an IFFI landslide. More than 50% of them belong to the ND type, while the remnant part falls within rapid flows and slides. A similar distribution pattern was found in the Veneto region, where only 147 anomalies (8% of the SI anomalies) are included in the IFFI database, of which the majority included in slides and complex landslides. Conversely, VdA has 47% of SI anomalies within the IFFI landslide polygons, mostly crossing falls/topples, slide and complex landslides. It must be also stated that 185 anomalies intersect DSGSDs (Deep-Seated Gravitative Slope Deformations). Furthermore, SI anomalies have been crossed with slope gradient and slope aspect. In detail, Tuscany SI anomalies are mostly distributed in the slope range $< 10^{\circ}$ (almost 70%) and are characterized by a decreasing trend in their number with the increase of the slope. As for the aspect, anomalies are equally distributed over the west and east slopes, with a slight prevalence of the first. Differently, in VdA most of the SI anomalies are distributed between slope values of 20[a] to 40° (about 66%), while just 8% of the anomalies is found in mountain flanks with low slope angle. Western-facing slopes show the highest number of anomalies, while a very high number is on slope exposed to the south (21%). At last, in Veneto, the SI anomalies are fairly distributed in all slope classes, except for the lowest ($<10^{\circ}$), with the highest concentration between 40 and 50°. Landslide-related anomalies are mostly

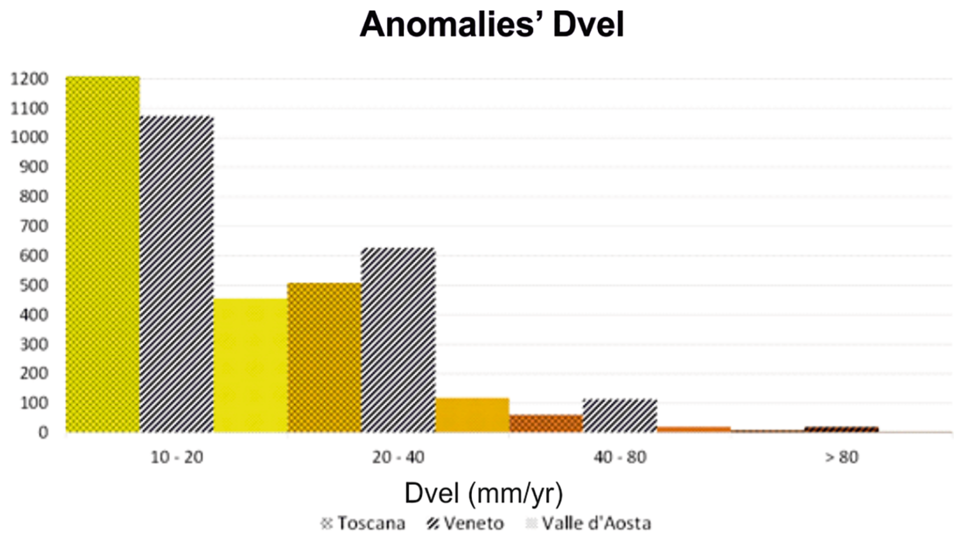


Fig. 6. Distribution of the anomalies according to the DVel class.

distributed on west- (almost 40%) and north-facing slopes (8%).

4.4. Environmental and geological factors

An important environmental factor that has been considered and plays a role both in the anomalies and in the generation of MPs is the altitude (Fig. 10). In Tuscany, 80% of the anomalies are distributed in the altitude range 0–500 m a.s.l., almost 20% between 500 and 1000 m and just 10 anomalies located over 1000 m of altitude. The anomalies distribution is quite different in VdA, with a small percentage of them located between 0 and 1000 m a.s.l. (14%), a higher portion between 1000 and 2000 m (about 40%), and the majority of anomalies (46%) over 2000 m. In Veneto region, the distribution is variegated: a large part of anomalies (45%) is distributed between 0 and 500 m a.s.l., while 35% between 1000 and 2000 m and 11% over 2000 m.

An important environmental factor considered is the land use of the three regions. To do so, anomalies have been compared with the Corine Land Cover, updated in 2018 (Fig. 11). In Tuscany, a major part of anomalies (52%) falls within the "artificial surface" category (1st category of CLC), most of them placed on "industrial and commercial zones" (code 121), "non-continuous urban fabric" and "mining areas", respectively (codes 112 and 123). The 32% of the anomalies are within the category "agricultural areas" (2nd category of CLC), mostly on "agricultural crop" (code 242) and 12% are over "forested and semi-natural areas" (3rd category of CLC). VdA shows different outcomes, since a small part of anomalies corresponds to urban areas (4%), while much greater is the number of anomalies falling over the "forested and semi-natural areas" (82%), mostly due to anomalies over shrubby and sparse vegetation; finally, the remnant part can be found over agricultural areas. Finally, Veneto region shows a similar trend to VdA: urban areas represent a small percentage (5%), while a much greater contribution is given by agricultural and forested areas, with 43 and 50 %, respectively. In these two classes, most of the anomalies are located over crop areas (30% of the total), followed by grazing and rangeland (9%). ND and R anomalies, instead, are mostly located over vineyards, rocks and sparse vegetation.

Another key factor for the generation of deformational events is represented by the local geological conditions that quite often influence the triggering of displacement events.

Thirteen lithological units can be distinguished in Tuscany, among which the highest number of anomalies can be found in the alluvial or detrital deposits, with about 41%, followed by the arenaceous and marl flysch deposits (21%), and clays and clayey deposits (12% ca.). No anomalies were found in rocky units, such as metamorphic or intrusive rocks (Fig. 12a).

In VdA, 10 lithological units are identified, as derived from the geo-lithological map. Most of the anomalies are located over micashists units, estimated to be about 35% of the total; other important amounts of anomalies can be found over calcschists, marbles and quarzites and serpentinites, metagabbros and prasinites (20% and 14% of the total) (Fig. 12b).

In Veneto region 14 lithological units are distinguished. The great majority of the anomalies fall within the limestone and dolomitic formations (equal to 39% of the total), followed by clayey and peat formations (14 and 12%, respectively). The minimum, instead, is registered over argillites and gypsum units and conglomerates deposits (Fig. 12c).

The number of anomalies for each lithological unit was also normalized according to the number of PSs and the areal extent of each unit. In this case, the analysis has revealed slightly different results. In Tuscany, the higher influence in the generation of the anomalies is given by the marl-arenaceous flysch, with 40.46%, followed by alluvial and detrital deposits, mudstones and the pelitic flysch, with 13.64%, 11.51% and 10.29%, respectively. The other lithological units weigh less than 10%. In VdA, the higher "weight" is given by the mica shists (34.02%), followed by calcshists and granodiorites, with 17.52% and 15.85%, respectively. As for Veneto, the lithology with higher normalized percentage of anomalies is still the limestone and dolomite, with 46.86%, followed by the peat deposits, with 16.22%; clays and clayey limestones "weigh" 7.38% and 6.33%, respectively.

4.5. Urban-related factors

In this class, the interaction between anomalies and the urban and built environment is summarized. In detail, both structures and infrastructures are considered, coupled with the detected anomalies.

In detail, a buffer of 50 m has been applied to either road and railways and buildings.

In Tuscany, 8 anomalies (0.4%) are in correspondence of railways, 262 (15%) intersect main roads, while 107 are located close or over the building (about 6%). Among the buildings, 6 anomalies are over schools, as classified by the Regional Technical Cartography.

In VdA, 4 anomalies intersect regional roads, and 15 anomalies are in correspondence of local roads. No information on building usage was available.

Finally, in Veneto 244 anomalies are over or around buildings, 17 of which are over strategic buildings (i.e., hospitals, schools, public edifices), while 427 anomalies are located in correspondence of railways (11%) and streets (382, 10% of the total).

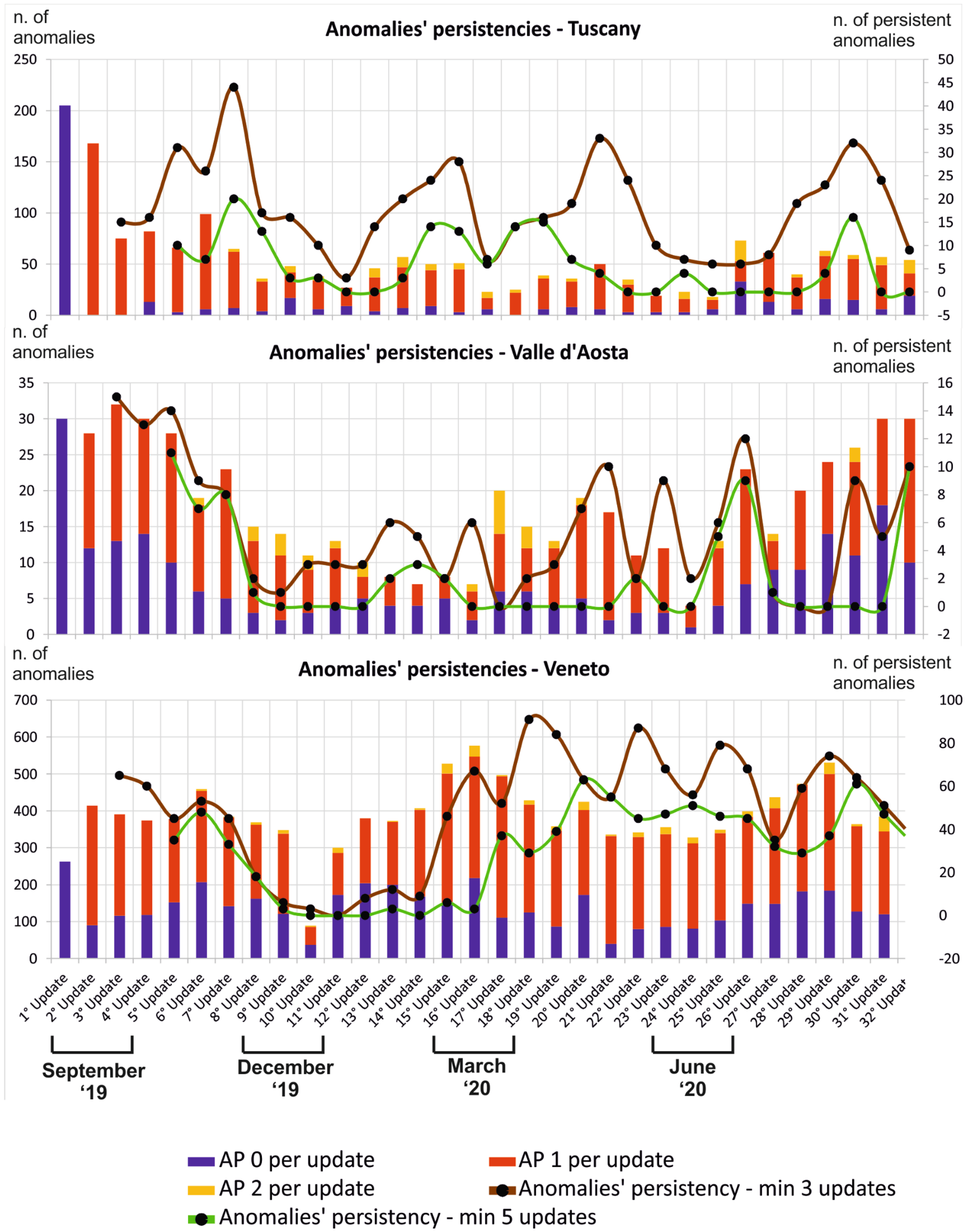


Fig. 7. Anomalies distribution after each update, along with number of persistent anomalies after each update. AP0 stands for non-persistent anomalies, AP1 for anomalies with persistence of one update, AP2 for anomalies with persistence of 2 updates.

5. Discussion

All the latest innovations in the field of Earth Observation have led to a new phase for the exploitation of DInSAR data. From the static view of the territories, at different scales, it is nowadays possible to obtain a constant and up-to-date near-real-time monitoring of wide areas, enhancing the use of SAR data for long-term operational services. Regional authorities, such as Tuscany, VdA and Veneto Regions benefit from continuous SAR-derived information, having the possibility of identifying location and time of activation of acceleration or deceleration of displacements, i.e., anomalies of movement. The generation of the anomalies can be due to several factors, of geological, geomorphological, or environmental nature, and may affect in different measure the territory and the life of people.

This paper summarizes the monitoring results obtained for the three operational ground motion services active over Tuscany, VdA and Veneto. Here, anomalies have been analyzed and categorized into 5 different classes, each one determined according to its own peculiarity.

In the first class, all the anomalies detected have been correlated to their geographical distribution, highlighting a massive presence of changing trends in time series of displacement in areas affected by well-known deformation, such as Pistoia for the Tuscany Region, as

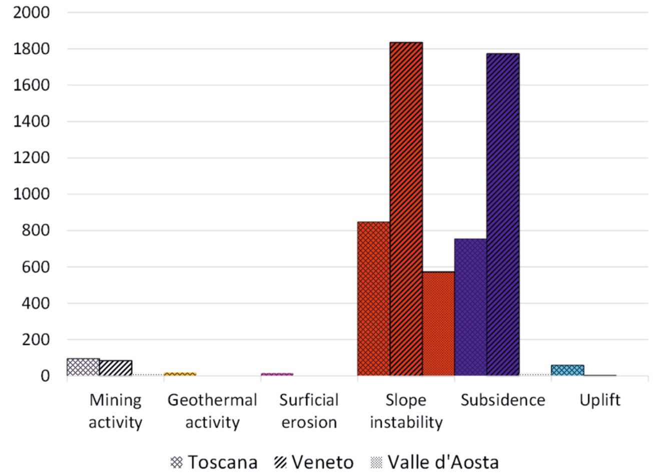


Fig. 8. Anomalies classified according to their cause, in all the three regions analyzed.

documented by Del Soldato et al. (2018) and Ezquerro et al. (2020), Ayas Valley for VdA (Salvatici et al., 2018; Solari et al., 2019) and Monselice for Veneto (Strozzi and Wegmuller, 1999). The number and spatial consistency of anomalies of motion confirm the need for constant surveillance of the territory. In addition, the seasonal trends have shown how, according to the type of phenomenon, the number of anomalies detected can vary: in autumn and winter an increase in SI anomalies is recognized, as well as in summer S anomalies are much more than in the rest of the year. This is a well-known trend, related to the triggering factors (*e.g.,* rainfalls), that is confirmed by the results obtained in one year of monitoring.

The results of the second class, correlating anomalies detected with "DInSAR" parameters, show how often the acceleration of the displacements is not necessarily very high (more than 60% of the anomalies show a Dvel between 10 and 20 mm/yr), indicates that the algorithm can provide information on the early stage of an acceleration, when such information is extremely useful for local authorities to plan proper remedial actions considering that the phenomenon is still under control. Moreover, the estimation of the anomalies' persistence is a clear proxy of the long duration of some events, mostly having a seasonal behavior, as for instance slow-moving landslides reactivations triggered by rainfalls or subsidence events accelerating for long groundwater withdrawal during the summer period (or uplift for aquifer recharge during the rainy season). Finally, it has been shown how significant are, for each region, the mapping activities, with a high number of anomalies falling within known clusters of deformation. This result implies that either mapping and monitoring activities based on S1 data are necessary to fully characterize the deformation scenarios in specific and at times well-known areas. Moreover, the presence of anomalies within clustered areas may help regional authorities to prioritize specific phenomena with respect to others (*e.g.*, first intervention, in situ surveys, fund allocations).

The prevalence of anomalies connected to a certain triggering cause with respect to another is a clear reflection of the physiography and environmental/anthropogenic context of each region. In Tuscany and Veneto, a balance between SI and S is reported, due to the complexity of their territories, with either hills and mountains and extensive plains, while in VdA the almost totality of the anomalies is due to SI since its territory results mostly mountainous. The intersection with landslide inventories, instead, has highlighted a very minor percentage of the SI anomalies falling within IFFI polygons (generally below 30%, with Veneto < 10% and VdA about 55%). Given the current availability of SAR images and considering the high accuracy reached by the technique, the complete update of the Italian landslide inventory is a goal to achieve. Finally, SI anomalies have been analyzed by correlating them with the slope and the aspect map. Tuscany show SI anomalies mostly recognizable in lower slope classes, while VdA is characterized by a majority of anomalies over steeper slopes; Veneto exhibits SI anomalies distributed in all slope classes, being characterized by both steep slopes, in the Alpine belt, and by gentler slopes, as for instance in the Colli Euganei area.

The comparison with the CLC has highlighted that in Tuscany a major part of the anomalies is detected over urban areas, while in Veneto and VdA over agricultural and barely vegetated areas. This highlights a certain difference in the land use in the three regions, where Tuscany has more urban areas affected by deformation than the others, where many instability phenomena are not directly involving an urban area.

The number of ND and R anomalies detected over sparsely vegetated areas or coniferous areas points out that obviously, SAR signal is less reliable, however, the conspicuous number of MPs over less coherent areas underline the sensible improvements brought by the SqueeSAR technique, capable of increasing the density of targets in an area. Nonetheless, a certain number of false positives is always expected, since the anomalies are automatously generated, as testified by the elevated

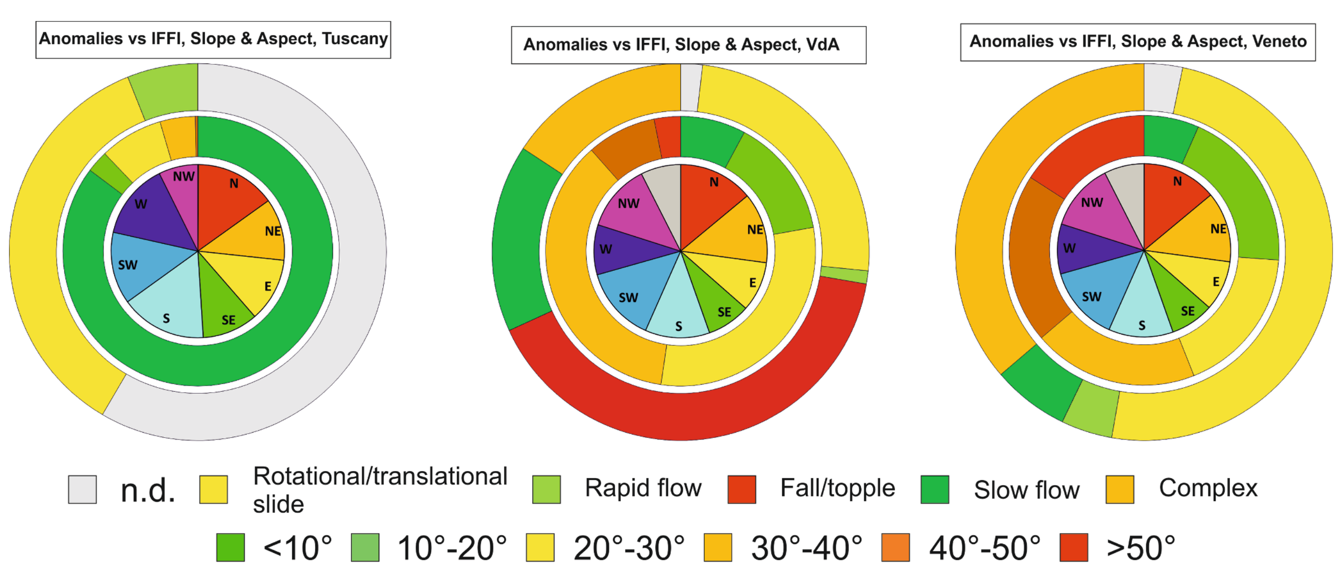


Fig. 9. Pie and donut charts for each analyzed region (from the left to the right Tuscany, VdA and Veneto). From the outside to the inside: Anomalies vs. Type of landslide; anomalies vs. Slope gradient; anomalies vs. Aspect. Only the anomalies related to slope movements are considered (SI class).

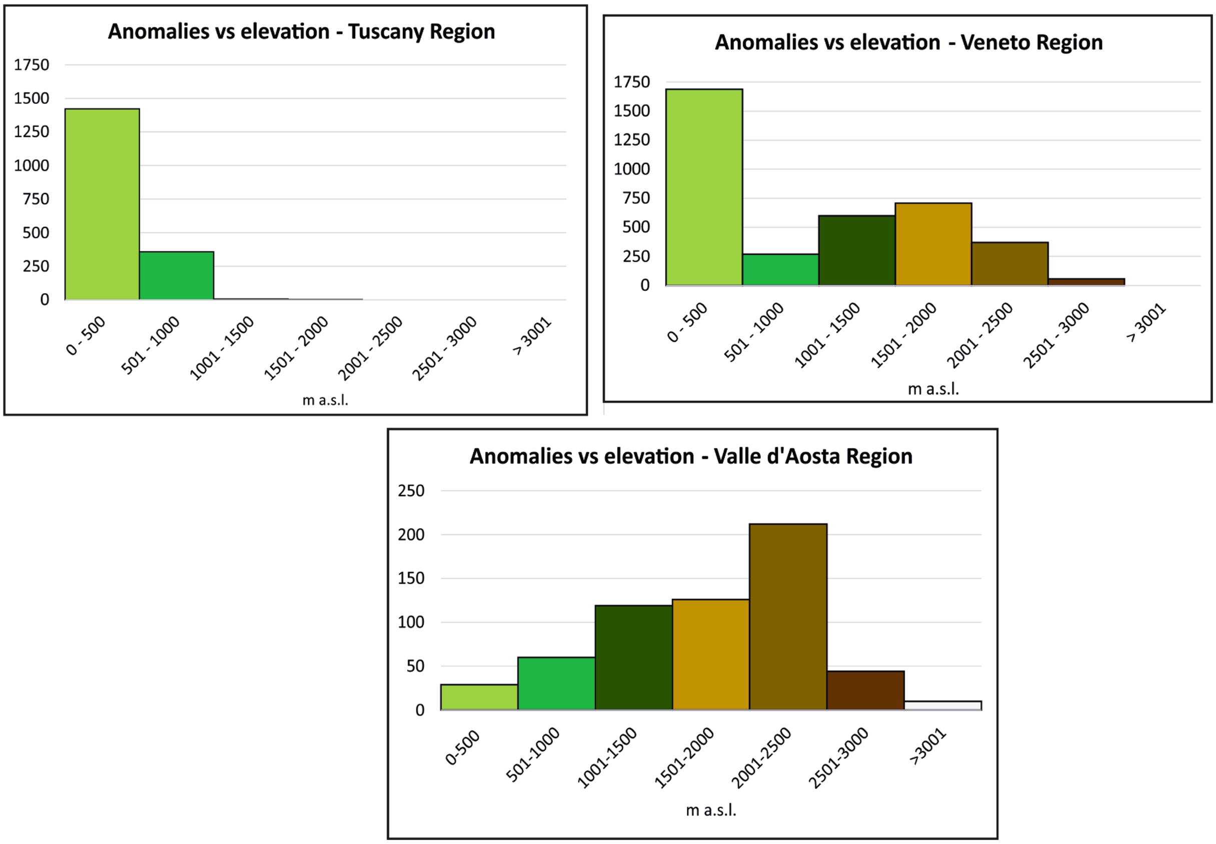


Fig. 10. Anomalies distribution according to each elevation class.

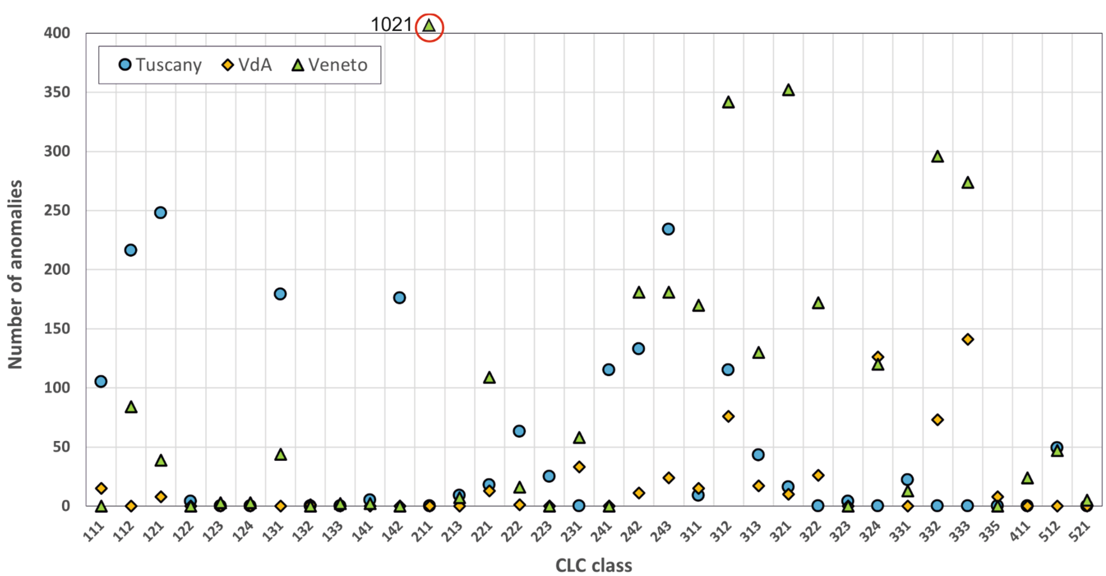


Fig. 11. Anomalies distribution in each CLC class for all the three regions. In the red circle, class 211 for Veneto region (1021 anomalies); for graphical reasons, the graph was not adapted to its numerical value. CLC codes can be found at https://land.copernicus.eu/user-corner/technical-library/corine-land-cover-nomenclature-guidelines/html. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

number of anomalies found in Veneto over the class 1021 (non-irrigated arable land). This is a constraint which must be addressed in the next future. In the timespan considered, more than 55% of the anomalies are detected as ND and R; in this sense, the human-supervised interpretation stage is fundamental to correctly address and categorize every signal detected, however, a reduction of the false positive can fasten up the interpretation process.

By the geological point of view, the spatial distribution of anomalies is comparable for the three regions, with a high number of anomalies in soft terrains such as alluvial deposits or flysch and clay terrains, except for the micashists, extensively present in VdA and limestone and dolomitic formations in Veneto (which mantle most of the Veneto reliefs). Also normalizing the number of anomalies for the number of PSs and the areal extent of each lithology, flysch terrains and alluvial deposits are

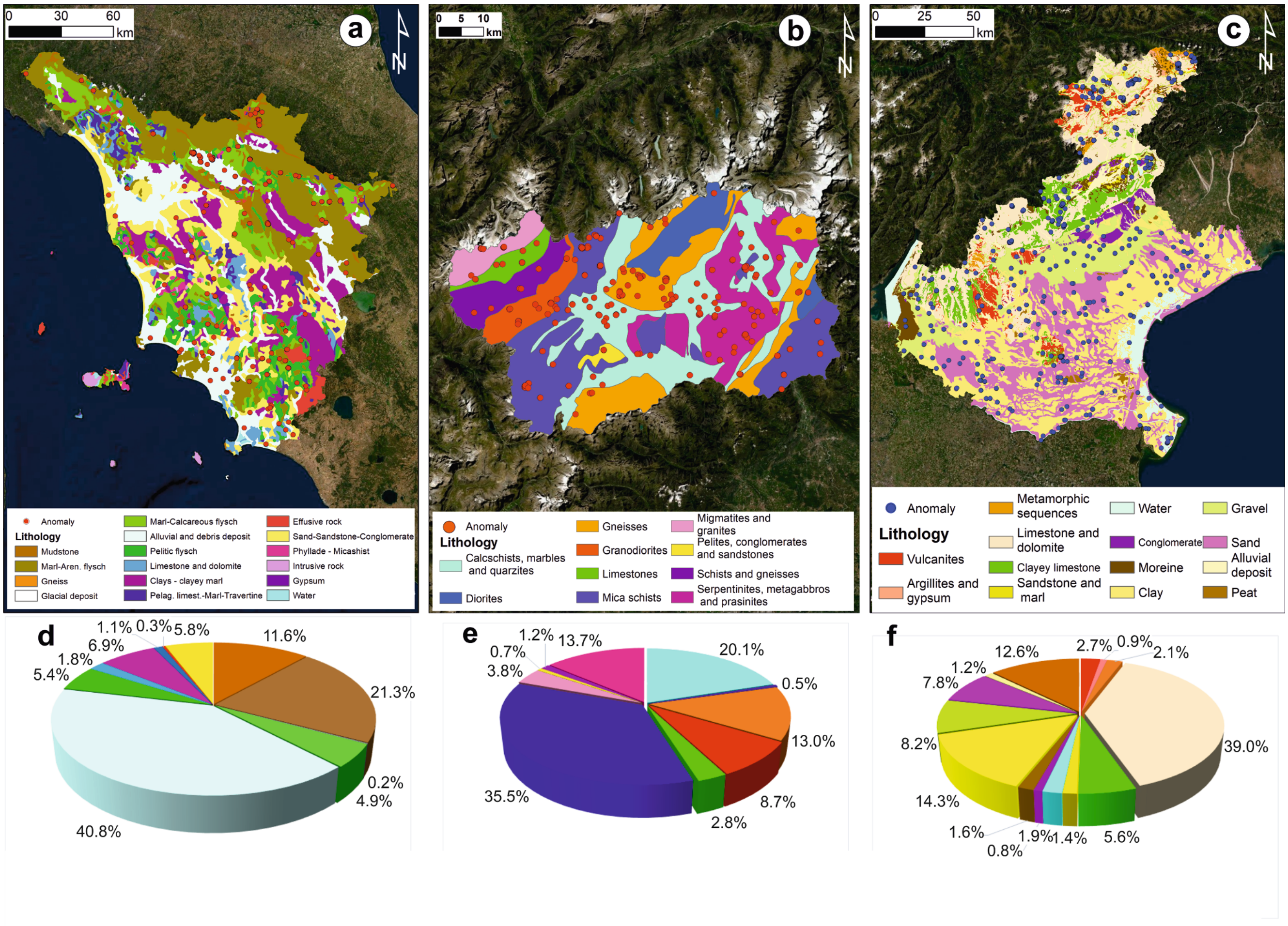


Fig. 12. Geolithological map of a) Tuscany, b) VdA, c) Veneto. Below, d), e) and f) show the distribution of the anomalies in each lithological class, in Tuscany, VdA and Veneto, respectively. For the colors of the pie chart, refer to the legend in the maps.

more likely to have anomalies, except for VdA.

The combination between anomalies and urban areas, show how many anomalies are found over buildings and infrastructures, thus highlighting the significance of such methodologies for the constant monitoring of structures and infrastructures, as also proved by many recent works (*e.g.,* Infante et al., 2019; Reyes-Carmona et al., 2020). This last aspect is of capital importance, in order to promptly detect any movement on the Earth's surface which may endanger people and objects, thus supporting CP activities. Regional and local authorities are warned through different procedures. On one hand, Tuscany region is alerted through regular bulletins, updated every 14 days. In detail, Del Soldato et al. (2019), in collaboration with civil protection and risk management regional authorities, developed a procedure based on the anomaly interpretation, bulletin release and potential field survey finalized at the preliminary risk assessment. On the other hand, Veneto region relies on warnings on specific events detected after the interpretation stage. In detail, persistent and relevant areas affected by displacement are signaled to regional authorities through an *ad hoc* report; VdA is creating a protocol of usage of anomalies data on three levels, knowledge, control and emergency.

In the year of analysis (September 2019–2020) no warnings have been delivered to Tuscany region, while in VdA and Veneto 2 and 3 warnings (2 slope instability anomalies in VdA, 2 of landslides in Belluno province and one related to subsidence in Padova province), respectively, have been indicated to the regional authorities. After that, field surveys and further investigations have been implemented to define the best actions to reduce ongoing risks. A relevant example of warnings delivered in the past to Tuscany authorities is included in Del Soldato et al. (2019), where subsidence induced by groundwater withdrawal in the municipality of Montemurlo (Prato province) was recorded. After that, water pumping was reduced, and simultaneously a decrease in the subsidence rates was registered.

As seen in the three Italian regions, the anomalies distribution clearly reflects the different physiographic and geomorphological settings, thus demonstrating the versatility of satellite-based monitoring systems. Nonetheless, further improvements can still be made. These can be achieved, by, for instance, enhancing the processing chain in order to reduce the number of false positive, automatizing the classification of the anomalies, assessing the territories most likely to have anomalies, implementing the services also with X-Band imagery on targeted systems such as infrastructures, etc. For this last peculiar aspect, however, a new experimentation would be needed to set the proper parameters (velocity threshold and time interval).

6. Conclusions

The worldwide coverage and the shortest revisit time of the orbit of Sentinel-1, compared to the other spaceborne SAR missions, enhanced the establishment of a continuous operational monitoring service.

Three Italian Regions, Tuscany (Central Italy), Valle d'Aosta (NW Italy) and Veneto (NE Italy), deployed satellite-based monitoring systems that fully exploit the abovementioned features of the Sentinel-1 constellation. The systems are based on the identification, through a data-mining algorithm, of the so-called anomalies of movement, i.e., measurement points with a changing deformation trend. The anomalies, once interpreted, are reported to regional authorities in different forms, for making them aware of potential ongoing geohazards.

In this work, a summary of the results of one year (September 2019 – September 2020) of operational service is provided, by coupling the anomalies with several kinds of factors, either intrinsic of the data and the kind of setting they are interacting with. In detail, five classes resume the statistical analysis conducted on the three regions. The results of the statistical analysis have shown that the spreading of the anomalies is strongly dependent on seasonal variation, as for their temporal distribution, and on physiographic and geological factors, as for their spatial distribution. Moreover, clear differences have emerged among the three regions, where large and geomorphologically variegated regions as Tuscany and Veneto have different anomalies distribution with respect to the mostly alpine setting of Valle d'Aosta, as, for instance, in terms of slope angle, altitude, besides the typology, as assigned after the interpretation stage. Furthermore, the presence of anomalies over urban areas, structures and infrastructures highlights the use of such a system for Civil Protection activities. Besides interferometric information, ancillary data and the interpreter expertise are fundamental to correctly analyze the automatic highlighted anomalies. Therefore, the correlation between MTInSAR-derived anomalies of movement and ancillary data may represent a further step towards the comprehension of changing trends in the deformation and may be used to identify the driving forces that lead to the abovementioned changes. In the next future, such analysis may be applied to estimate the occurrence probability of MTInSAR anomalies of movement and to identify which areas are the most prone to such anomalies, thus contributing to enhanced geohazards prevention.

CRediT authorship contribution statement

Pierluigi Confuorto: Conceptualization, Methodology, Investigation, Formal analysis, Writing – original draft, Visualization. **Matteo Del Soldato:** Methodology, Software, Investigation, Visualization. **Lorenzo Solari:** Methodology, Investigation, Visualization. **Davide Festa:** Investigation, Software. **Silvia Bianchini:** Validation, Writing - review & editing. **Federico Raspini:** Validation, Writing - review & editing. **Nicola Casagli:** Supervision, Project administration.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jag.2021.102448.

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