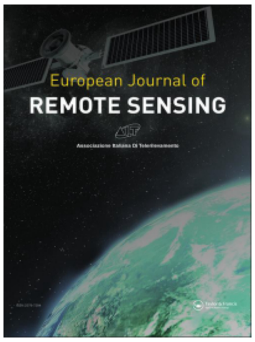

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Active lateral spreads monitoring system in East-Central Sardinia

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ABSTRACT
In Italy, landslides are one of the main geological hazards. Sometimes urban areas are affected by deep-seated gravitational slope deformations (DGSDs) that can lead to a potentially catastrophic failure and trigger a secondary collateral landslide. In these cases, monitoring is important for early warning and risk reduction. In this study, we analyzed DGSDs, in particular, lateral spreads, and landslides in the inhabited areas of Ulassai, in eastern-central Sardinia. Starting from high-resolution geostructural and geomorphological surveys of lateral spread, integrated with high-resolution digital elevation models acquired by UAV (Unmanned Aerial Vehicle), we created geological 3D models of the slope deformations. To better understand the kinematics and temporal evolution of unstable slope deformation, a monitoring system, consisting of Space-borne Interferometric Persistent Scatter Synthetic Aperture Radar (PS-InSAR), GNSS antennas, tiltmeters, and extensometers, was performed. PS-InSAR analysis confirmed by GNSS periodic measurement identified downslope movement of up to 10 mm per year in the lateral spread. Continuous acquisition by extensometers and tiltmeter recorder displacement in large block inclinations and opening and closing of fractures since 2021. Integrated data analysis will be essential to define the threshold for a future 24/7 early-warning system.

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DGSDs; monitoring; InSAR; GNSS; geomorphology; early-warning system

Introduction

Landslides are extremely widespread phenomena in Italy. Each year, they significantly affect the population, urban and rural centers, linear communication infrastructures, and the economic sector. Italy, with over 620,000 landslides recorded in the Landslide Phenomena Inventory of Italy (IFFI) (APAT, 2007), is the most susceptible to landslides country in Europe. In particular, Sardinia (Figure 1), with 22.5% of landslide hazard areas, is one of the regions of Italy with the greatest landslide risk (APAT, 2007; Trigila et al., 2018). Every year much money used for landslide risk mitigation through direct structural geoengineering works to make landslides safe. Sometimes, the landslide volumes are too large to use these methods, and monitoring is the only methodology for risk mitigation (Barbarella et al., 2015; Miccadei et al., 2022; Nikolakopoulos et al., 2017; Travelletti et al., 2012; Wieczorek & Snyder, 2009).

Deep-seated gravitational slope deformation (DGSD, Dramis & Sorriso-Valvo, 1994) is a large-scale complex type of rock slope failure that mostly affects hard rock terrains (Dramis et al., 2002). Lateral spreading DGSD type (Agnesi et al., 2015; Cruden & Varnes, 1996; Devoto et al., 2021; Jahn, 1964; Mateos et al., 2018; Pasuto & Soldati, 1996; Soldati et al., 2019) consisting of rock spreads often evolving in catastrophic collapsed and trigger secondary landslide (Demurtas et al., 2021a). DGSDs are characterized by slow movements that can suddenly accelerate and cause a catastrophic collapse of sections of the deformed slopes (Radbruch-Hall et al., 1976; Agliardi et al., 2022; Crosta & Agliardi, 2003; Nemčok, 1972; Ostermann & Sanders, 2017). Therefore, this phenomenon represents an important geo-hazard in relation to high-magnitude secondary collateral landslides. Monitoring is a fundamental tool for deepening the knowledge of landslides and evaluating deformation trends (Bianchini et al., 2021; Demurtas et al., 2021a; Frigerio et al., 2014; Palis et al., 2017; Sestras et al., 2021; Zhang et al., 2021). The data provided by monitoring techniques also help in the design of slope protection structures and subsequently the assessment of their long-term effectiveness. Monitoring represents a “non-structural” risk mitigation measure that is fundamental to properly handle the territory and activating procedures for alerting the population to safeguard human lives. Monitoring landslides is a complex and dynamic process, which requires continuous technological and managerial adjustments to obtain detailed information about the phenomena temporal evolution. The design of an effective monitoring system is based on technical, logistical and economic evaluations. In areas marked by high landslide risk levels, the installation of stationary, long-term monitoring devices is deemed essential to achieve a successful and effective Early Warning System (EWS) (Intrieri et al., 2012). Several definitions

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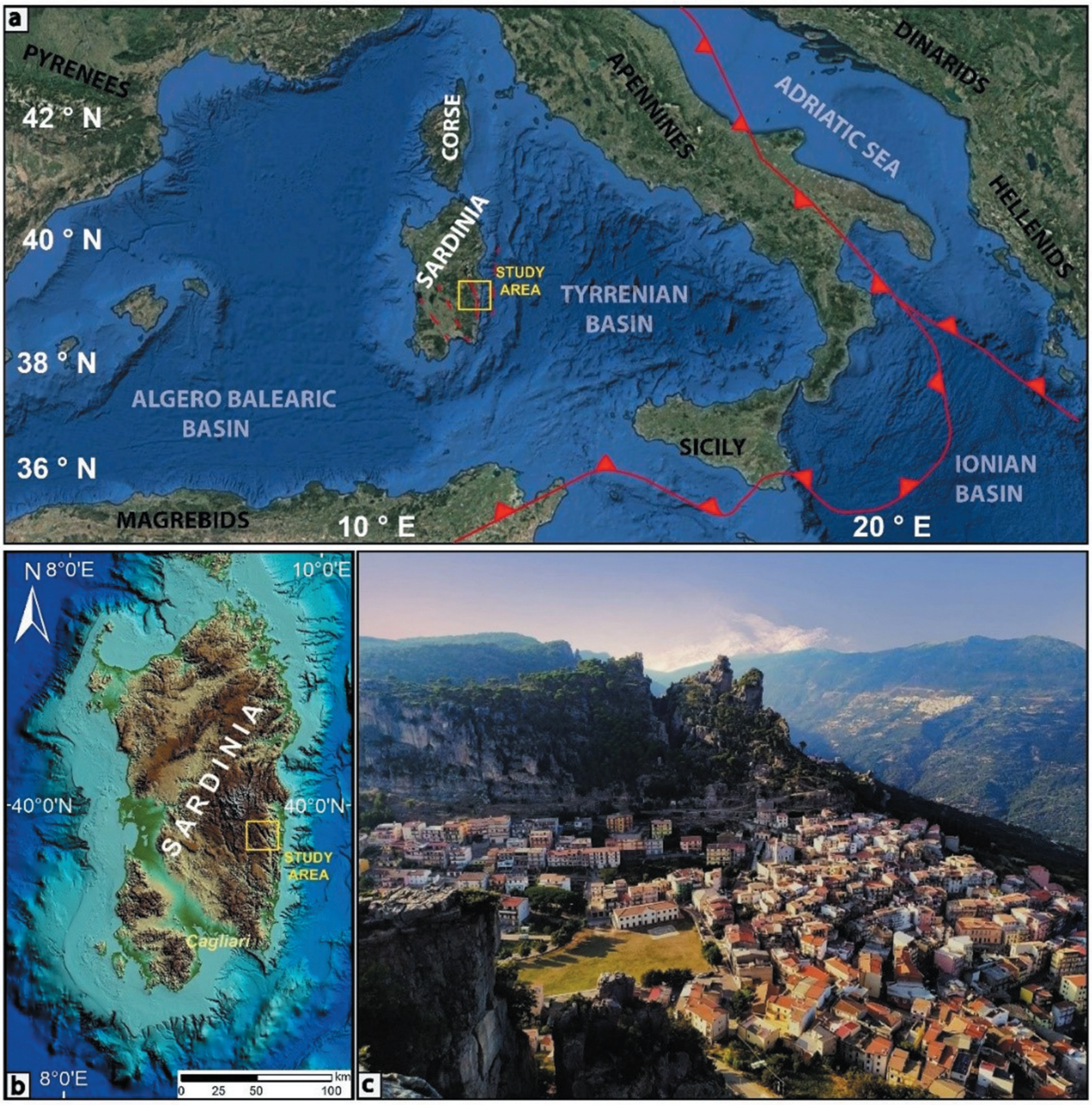


Figure 1. a) Geographical location and structural features of the study area. b) Digital terrain model of Sardinia bloc comprising continental and marine area. c) Ulassai village under plateau edges.

of EWS can be found in the literature. Medina-Cetina and Nadim (2008) define them as "monitoring devices designed to avoid, or at least to minimize the impact imposed by a threat on humans, damage to property, the environment, or/and more basic elements like livelihoods". According to the United Nations International Strategy for Disaster Reduction (UNISDR, 2009) they are "the set of capacities needed to generate and disseminate timely and meaningful warning information to enable individuals, communities and organizations threatened by a hazard to prepare and to act appropriately and insufficient time to reduce the possibility of harm or loss". Even after an event, landslides are always characterized by significant residual instability related to the possible reactivation of the entire landslide or, more frequently, parts of it.

In this paper, we present the study case of the lateral spread near Ulassai village (East Sardinia) (Figure 1(b, c)). The village is located under carbonate plateau wall edges and is affected by different gravitational processes that need to be mapped, characterized, and monitored in order to design an early-warning system (Demurtas et al., 2021a, 2021b, 2021c). The problem in this context is linked to extremely rapid collateral landslides with possible catastrophic scenarios. Monitoring system for early warning or alert purposes is aimed at identifying the speed variation and real-time landslide dynamics. These peculiarities of monitoring systems in Sardinia are less widespread.

In this paper, we would understand the kinematics and temporal behavior of lateral spread and landslides in this sector of Sardinia.

The main aims of this paper can be summarized as follows:

- Present a study case about an active lateral spread in an urban contest;

- Highlight the link between the evolution of the lateral spread and secondary collateral landslides;
- Propose a multi-scale and multi-source monitoring system of surface movements;
- Support for territorial planning (urban planning tools) and for the preparation of civil protection plans;
- Support the design of monitoring Early warning system for alert purposes.

Materials

Study area

The study area is located in the center of the Mediterranean Sea, in the eastern sector of Sardinia (Figure 1). This area is particularly susceptible to landslides because it is characterized by steep slopes (Demurtas et al., 2021a; Marini & Ulzega, 1977; Maxia et al., 1973). In this area, DGSDs, rockfalls, rock avalanches and giant toppling represent a high geological risk inserted in this urban context. As is well known, different inhabited centers are continually threatened by disasters (Demurtas et al., 2021b). Different types of interventions were carried out to protect inhabited centers and infrastructures, but they were carried out without a global study of the problem and, therefore, without real knowledge of the evolutionary modalities of the slopes and the real gravitational dynamics (Demurtas et al., 2021b).

Geological setting

Lithological setting

East-central Sardinia (Italy) is characterized by widespread Jurassic dolomitic plateaus (*Tacchi*) overlying a metamorphic Palaeozoic basement, primarily comprising metasandstone, quartzites, and phyllites (Carmignani et al., 2016; Demurtas et al., 2021a; Pertusati et al., 2002) (Figure 2(a,b)). Hydrographic setting is represented by the Pardu River Valley in the east and the Barigau River Valley in the southwest; the central and north-western sectors include an extensive dolomitic plateau called Tacco of Ulassai. The geological basement comprises Palaeozoic metamorphites affected by complex plicative structures and regional low-grade metamorphism (Carmignani et al., 1994, 2001; Elter et al., 2004, 2010). The major Palaeozoic units are the Filladi Grigie del Gennargentu Formation constituted by metarenites, quartzites, and shales (Figure 2(c)) (Middle Cambrian – Middle Ordovician) (Meloni et al., 2017; Pertusati et al., 2002; Vai & Cocozza, 1974). The metamorphic basement summit suffered chemical alterations associated with a warm humid climate during the Permian and Triassic periods (Costamagna & Barca, 2004; Marini, 1984). An angular unconformity of Mesozoic sedimentary succession rests on the metamorphic basement. Basal layers are primarily fluvial sediments of the Genna Selole Formation (Middle Jurassic) (Figure 2(d)), which are overlain by dolomitic limestones of the Dorgali Formation (Figure 2(e)) (Middle-Upper Jurassic) (Costamagna & Barca, 2004; Costamagna et al., 2018; Pertusati et al., 2002). These Mesozoic deposits are extensive and decipherable from their plateau morphology. The Genna Selole Formation (Costamagna, 2015; Dieni et al., 1983) represents a mixed succession of siliciclastic to siliciclastic – carbonate deposits. The Dorgali Formation is represented by dolomitic sequences with thicknesses up to tens of meters. The lower part, with a thickness of approximately 30 m, is affected by marl intercalations, whereas the upper part is typically massive. Mesozoic units are sub-horizontal strata with an attitude of approximately N90/0–5°, and the plateau edges can reach a dip amount of up to 40° and a direction parallel to the slope owing to the DGSD (Demurtas et al., 2021a, 2021b). This particular stratigraphic setting drives the formation of steep slopes in the Jurassic sequence and lower slopes of about 20–40° in the metamorphic basement.

Quaternary covers are primarily landslide deposits, including rockfalls, toppling, and collapsed DGSDs at the Tacch foot slope. The rockfalls and toppling landslides have been characterized by different sedimentological features based on age. Three orders of landslide deposits were identified, namely cemented, quiescent, and active (Figure 2(f-h)). These deposits are associated with rockfalls affecting the plateau edge wall and the collapse of some parts of the DGSDs and lateral spread. We focused on the Bruncu Pranedda Lateral spread (Figure 3(a,c,d)) and the “Torre dei venti” (Figure 3(b)), as they are an important geological hazard in the urban area.

Seismotectonic setting

The geodynamic setting is associated with the collisional dynamics between the African and European plates. The structural setting is associated with the Alpine cycle, which first appeared with a strike-slip fault in the Oligo – Miocene and in the Pliocene and Quaternary with an extensional component (Carmignani et al., 2001, 2016; Carminati & Doglioni, 2005; Cherchi & Montadert, 1982; Gattacceca et al., 2007; Gueguen et al., 1997; Oggiano et al., 2009; Ulzega et al., 2002). Based on preliminary geodetic data from the Peri-Tyrrhenian Geodetic Array network, Ferranti (2008) revealed the presence of low internal deformation in Sardinia. In Sardinia, seismicity is typically scattered and sporadic, except for the dozens of tremors detected following the ML4.7 earthquake of 7 July 2011 in the Corsican Sea, which primarily characterizes the edges of the continental lithosphere block. Different events, even with

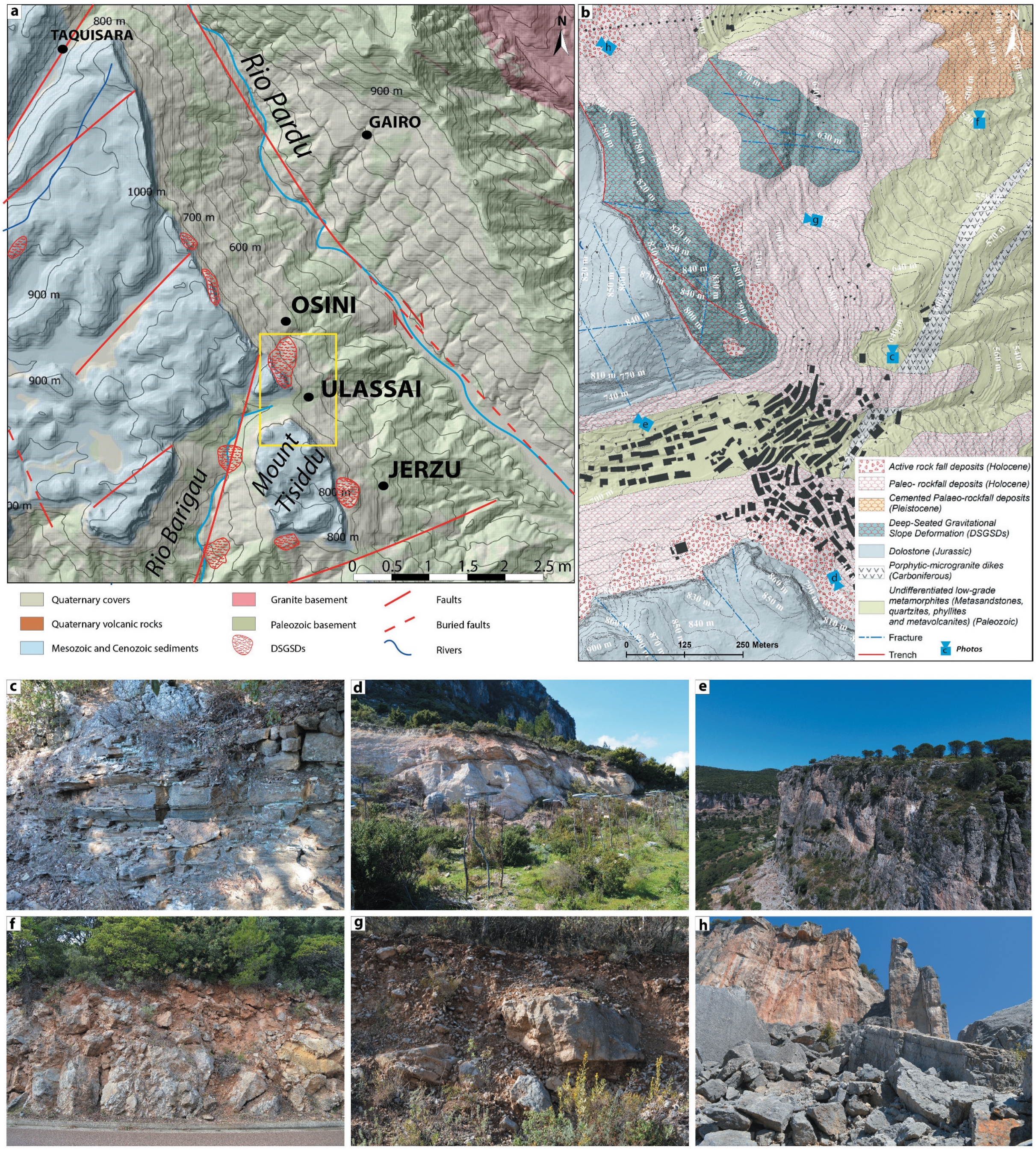


Figure 2. a) Geolithological sketch map of the study area based on geological data of the Autonomous Region of Sardinia. The Yellow box indicates the location of the study area. b) detailed geological map modified from Demurtas et al. (2021a). c) Metamorphic basement, fractured metasandstone and quartzites. Transitional and marine Mesozoic succession:(d) Genna Selole Formation (siliciclastic – carbonate deposits and clays);(e)dolostone of massive Dorgali Formation. Rock-fall deposits: (f) Cemented; (g) Quiescent; (h) active.

magnitudes greater than 5, are documented in the writings of historical times. The state of some faults with low activity does not exclude the possibility of major earthquakes in Sardinia. Significant seismic events also occurred in the eastern sector in the last decades, in particular, three events with a magnitude >4 (26 April 2000, magnitude ML4.2 and 4.7, and 18 December 2004, magnitude ML 4.3) located in the central Tyrrhenian Sea approximately 60 km east of Olbia in the Comino depression (Cimini et al., 2016). The most recent low-magnitude earthquake events were ML1.8 (Escalaplano, 4 April 2019) and ML1.6 (Perdasdefogu, 14 October 2020) (INGV, 2021).

Methods

The methodology is based on a preliminarily conoscitive phase of geological and geomorphological context (Demurtas et al., 2021a, 2021b, 2021c). A highly detailed geo-structural and geomorphological analyses of the area around Ulassai was carried out based on an

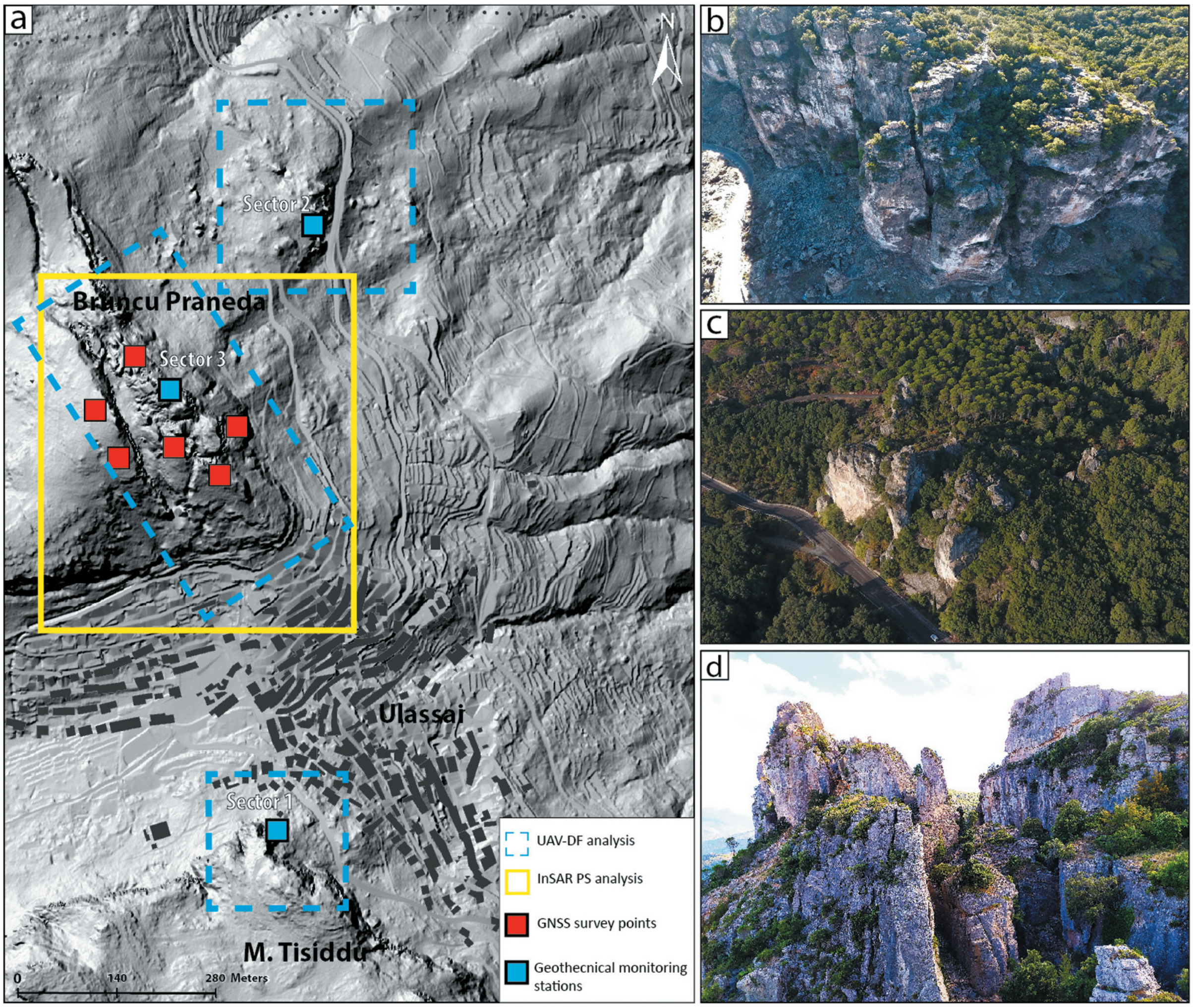


Figure 3. Monitoring station and survey locations. a) Sector of different methods used. b) Monte Tisiddu large toppling (*Torre dei Venti*). c) Middle slope sector of Pranedda DGSD with sackung feature. d) Top slope of Bruncu Pranedda DGSD with lateral spread features.

integrated approach that incorporated a cartographic and morphometric analysis. In particular, a detailed surface system reconstruction was performed, in order to guide the landslide kinematic interpretation. We performed our analysis in the three sectors indicate in Figure 3 because most characteristic and represent the main hazard areas due to the presence of the village.

Bruncu Pranedda Lateral spread displacement trend and speed were evaluated using space borne Persistent Scatter Interferometric synthetic aperture radar (PS-InSAR). Over the last 30 years, InSAR techniques have been widely used to investigate geological (e.g. volcano activity, earthquakes' ground effects, etc.) and geomorphological processes, in particular, DGSD. In different geological and climatic contexts, this technique allows to analyze extremely slow DGSDs and identifies displacements of about 1–2 mm in favorable conditions (Crosetto et al., 2016; Delgado et al., 2011; Devoto et al., 2020; Eker & Aydın, 2021; Frattini et al., 2018; Gaidi et al., 2021; Mantovani et al., 2016; Novellino et al., 2021; Oliveira et al., 2015). Based on these preliminary data, a monitoring based on periodic GNSS antenna measures and a real-time monitoring system with geotechnical instrumentation was started. These data give preliminary indications for risk management in terms of civil protection.

In Table 1, we summarize the main method used for preliminary geomorphological characterization and monitoring.

Geomorphological, LiDAR, and UAV analysis

Multi-scale remote sensing and field surveys were carried out to analyze the geological, structural and morphotectonic setting of the slopes, in particular, the plateaus' edges (Deiana et al., 2019; Demurtas et al., 2021a; Dragićević et al., 2015; Guzzetti et al., 1999; ISPRA & AIGEO, 2018; Melis et al., 2020; Miccadei et al., 2018, 2021; Shi et al., 2018; Yi et al., 2020). Geological and geomorphological field mapping in the walls around Ulassai was performed on a scale of 1:500. Particular attention was paid to the study of

Table 1. Methodology synthesis.

Method	Instrumentation	Data	Information acquired	Spatial scale
Field survey	Geological mapping	Geological and Geomorphological maps	Lithostratigraphic contacts, structural setting, landslide deposits, morphostratigraphy	Local scale 1:500
UAV-DP	Phantom 4 Matrix 200 Methashape software	High-resolution 3D models	High-resolution DGSD topography 10 cm×10 cm cell size	Landslides and DGSD scale
LIDAR	Autonomous region of Sardinia LIDAR data	DEMs	High-resolution topography 1 m × 1 m cell size	Slope scale
InSAR	Sentinel 1 radar data	LOS displacement	Slope displacement	Regional scale
GNSS	Trimble R8	Coordinates differences	Large block displacing	Rock mass
Geothecnical	Extensimeters Tiltmeters	Misuses of distances Tilting degree	Fracture opening and closing Block tilting	Fracture

morphologies related to lateral spread and collateral landslides. A detailed analysis was carried out to understand the interconnection between the surface systems and the tectonic fracturing network, stratigraphic discontinuity, families of junctions from biogenic (Vegetation) or thermoclastic processes and decompression junctions.

Unmanned aerial vehicle digital photogrammetry (UAV-DP) is a robust methodology for the investigation of DGSDs and large landslides (Bounab et al., 2021; Eltner et al., 2016). In particular, it was used for the recognition of large lateral spreads in Malta and Tunisia (Devoto et al., 2020; Gaidi et al., 2021) and to detect large coastal landslides in Sardinia (Deiana et al., 2021). We used UAV-DP and light detection and ranging (LiDAR) to extract high-resolution topographic 3D lateral spread models and perform detailed morphometric analyses. LiDAR and aerial photogrammetric data, produced by the Autonomous Region of Sardinia, were used to perform large-scale remote sensing analysis.

At the local scale UAV surveys were performed, using DJI Phantom 4 and DJI Matrix 200, flying at altitudes of 50–60 m above ground level. The surveys were carried out in optimal conditions, i.e. sunny days with zero wind speed. The acquisitions were carried out in the hours between 13 and 15 in order to minimize the shaded areas. The acquired images were analyzed and processed using the photogrammetric Agisoft MetaShape software and constrained by 10–12 ground control points using GEODETIC LEICA GNSS for each area. The resulting orthorectified mosaic and DTM (WGS 84 datum and UTM 32N projection) had, respectively, a cell size of 5 cm/pixel and 10 cm/pixel. This resolution was used to verify measured known objects.

InSAR Analysis

Space-borne interferometric synthetic aperture radar (InSAR) data were used to analyze the slope deformation speed and rate (Demurtas et al., 2021b; Ietto et al., 2015; Mateos et al., 2018; Mondini et al., 2021; Moretto et al., 2021). Permanent scatter Differential Interferometric Synthetic Aperture Radar (PS-DInSAR) (Crosetto et al., 2016; Ferretti et al., 2000) has been used to investigate the temporal and spatial superficial slope deformation. This technique together with the correct identification of the ground reflectors is widely used to better comprehension of the geomorphological evolution of extremely slow mass movements (Figure 3(a-c)) (Mantovani et al., 2016).

The aim of PS-DInSAR techniques is the analysis of backscattering signals (in terms of phase and amplitude) detected during multiple passages of a survey satellite over the same area (Rosen et al., 2000). The Persistent Scatterers are targets that keep the electromagnetic signature (i.e. their reflection characteristics) unaltered in all the images, depending on the acquisition geometry and climatic conditions; therefore, they preserve the wave amplitude information over time. Permanent scatters are commonly parts of buildings, metal structures and exposed rocks, while the vegetation that continuously changes its electromagnetic characteristics does not constitute a strong diffuser (Figure 4(b,c)). The advantages of the PS technique concern the estimation and removal of atmospheric disturbance, the very high resolution of the results and the estimation of speeds with accuracies of mm/year over long periods. The limits of its applicability are represented by the availability of at least 20 SAR acquisitions, the assumption of a linear trend of displacement and by the presence of vegetated areas.

Large-scale PS-InSAR analysis of the study area has already been performed and presented by Demurtas et al. 2021, to which reference is made for further information on data and processing. We used the Sentinel-1 data and took into account the line-of-sight (LOS) velocities. The acquired period is from 2014 to 2020 in the ascending geometry. The processed data were provided, by the Geological Survey of Norway (https://www.ngu.no/en). To detect the ground displacement, we used only high-PS coherence (0.6–1) located on the built dolomitic blocks and the metamorphic rock outcrops. Low-coherence PSs, which are not useful, are located on rockfall deposits and in vegetated areas.

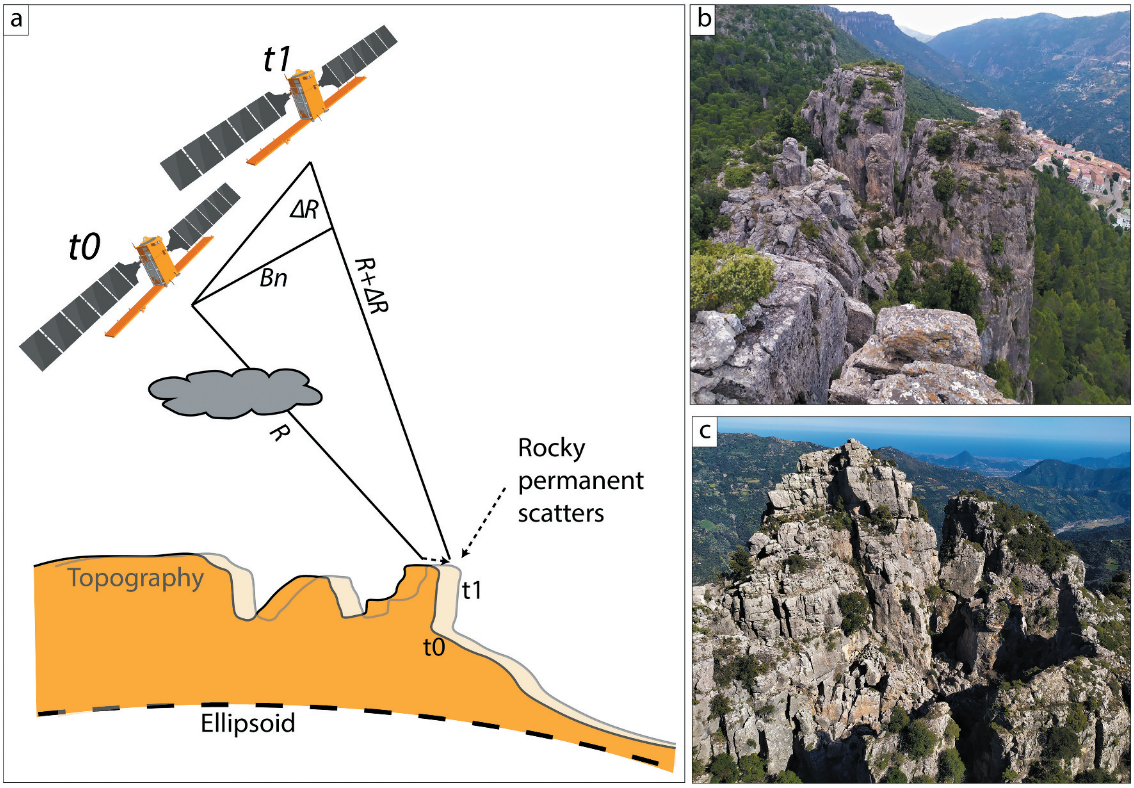


Figure 4. a) Simplified sketch showing InSAR monitoring DGSD. T0 time of first acquisition. T1-tn time of successive acquisition. R distance ground surface and the satellite. b) and c) the rocky peak in Bruncu Pranedda Lateral spread.

GNSS monitoring

Global Navigation Satellite System is a system of global positioning based on the use of the satellite system (Krüger et al., 1994). Topographic monitoring systems such as GNSS surveys measurements have been more commonly used in landslide monitoring (Agnesi et al., 2015; Coe et al., 2003; Gili et al., 2000; Malet et al., 2002; Peyret et al., 2008; Wang, 2012). The monitoring of landslide areas using the GNSS methodology in differential mode consists in measuring the position of one or more stations within the landslide area (monitoring stations) compared to one or more reference stations (Master or Base) positioned in stable areas and determining the displacement vector (baseline) as an expression of the coordinate difference.

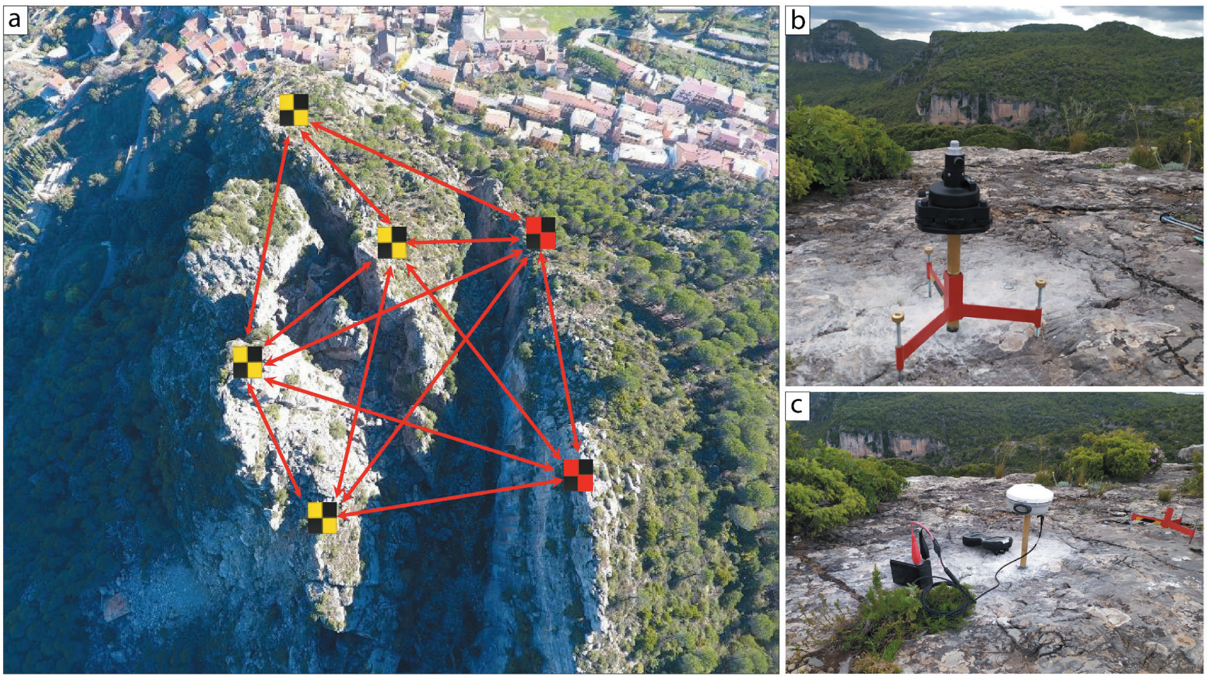


Figure 5. a) Network of GNSS survey points, Black-Yellow monitoring points located in instable are. Black-Red references stations. b) Support for the topographic nails vertical positioning. c) GNSS data acquisition in static mode.

In the top slope of Bruncu Pranedda, based on geomorphological and PS-InSAR data, a network of topographic nails was built to measure the displacement by Static mode GNSS techniques. The transmission of the satellite signal is independent of weather conditions and does not require intervisibility between the individual GNSS stations, but it is, however, disturbed by the presence of obstacles (plants, foliage, anthropogenic structures, etc.). Therefore, the measuring stations were installed at the top of the rocky peaks of the lateral spread. The aim is to measure the movement blocks of rock mass blocks separated by trenches to understand the differential movements (Figure 5(a)). Topographic survey points with brass support have been created to mount the GNSS antenna and reduce the positioning error to fractions of mm (Figure 5(b,c)). GNSS survey points were installed in December 2020, and measurements have been realized at intervals of 4 months. The GNSS data acquisition surveys are currently underway. During each survey, two measurements were made for each point on different closing days to correctly estimate the error associated with the measurement. These two acquisitions are called: the first, acquisition measure and the second (performed the following day at the same time) calibration measure. The acquisitions are performed with Trimble R8 GNSS in static mode with an acquisition of 1 h and 30 min with a recording rate of 5 s. The acquisition parameters (frequency and duration) were chosen to make the best compromise between the quality of the acquired data and the times used. Five acquisition points were installed. In the GNSS monitoring, four phases can be identified:

- Pre-data acquisition phase (choice of equipment, choice of sites);
- Data acquisition phase;
- Data quality control (pre-processing);
- Processing and interpretation.

To achieve the maximum precision possible, the data were processed post-acquisition using the RINEX files of the SARNET network recorded by the antenna (TERNENIA) at 14.6 km from the acquisition points in the study area. The data was processed with the TRIMBLE BUSINESS CENTER software.

Geotechnical monitoring

A geotechnical monitoring network, consisting of six extensometers and two tiltmeters, in extension fractures, was designed in three sites (Figure 6(a)). The sensors installed are Extensimeters GEFRAN GSF1800 (Figure 6(b)) and Tiltmeters MEMS Earth System (Figure 6(c)). Extensometers were used to quantitatively evaluate the opening/closing of cracks in rock/soil with sub-millimeter precision (Figure 6(d-f)). They consist of a measurement sensor (protected inside a stainless steel box) and a wire, made of a material with a low coefficient of thermal expansion, held in tension by a spring system. To obtain maximum representativeness of the data, the extensometer lines were installed parallel to the vector of maximum expected displacement of the DGSDs evaluated through geomorphological evidence. Since the measurement can be conditioned by environmental variables (e.g. snow on the wire, wind, the passage of animals, etc.) the wires have been protected with external aluminum pipes. Tiltmeters were installed to monitor changes of large block inclination, related to rotational downslope movement of the rock mass that is evident in the strata attitude of the Dorgali formation. The tiltmeters consist of a dual-axis inclinometer sensor which measures in two directions orthogonal to each other with an accuracy of 0.1° mounted in the rock surface. The two tiltmeters were connected to a data logger recording tilt angles. The monitoring system is powered by batteries recharged from a photovoltaic panel. The data with continuous acquisition are managed by Campbell scientific CR1000× control unit with Sierra Wireless RV50× remote data transmission system. The data are managed through the HMS-WED online platform created by *Hortus srl.*

Results

Lateral spread and large toppling analysis

Different gravitational processes affecting the inhabited center of the Ulassai were mapped (Figure 7(a)). In particular, were identified widespread rockfalls in the walls projecting the inhabited center; topplings of dolomitic giant prismatic block in the plateau marginal sectors; The DGSD in the north side of the Ulassai slope (Bruncu Pranedda).

The sector north of Ulassai represented by the side of Bruncu Pranedda is affected by an extended DGSD with different evolutionary stages. The top slope is an active lateral spread that triggers collateral landslides of rockfalls and toppling (Figure 7 b1,4,5 c1,2). The middle part of the slope consists of a paleo sackung with a residual hazard linked to a possibly large Toppling (Figure 7e) (Demurtas et al., 2021). On the top slope, a large extensional trench with NNW-SSE direction, called Pranedda Canyon, is present. Eastward, the rock mass shows high fracturing and the strata attitude of the Dorgali Formation is toward the east, with a dip up to 40°. The shear basal surface is located in the marls and clay between the dolomitic plateau and the metamorphic basement. This setting indicates a deformation kinematics-type lateral spread (Cruden & Varnes, 1996, Demurtas et al., 2021). The lateral spread led to an important and widespread fracturing, therefore source areas for surface landslides

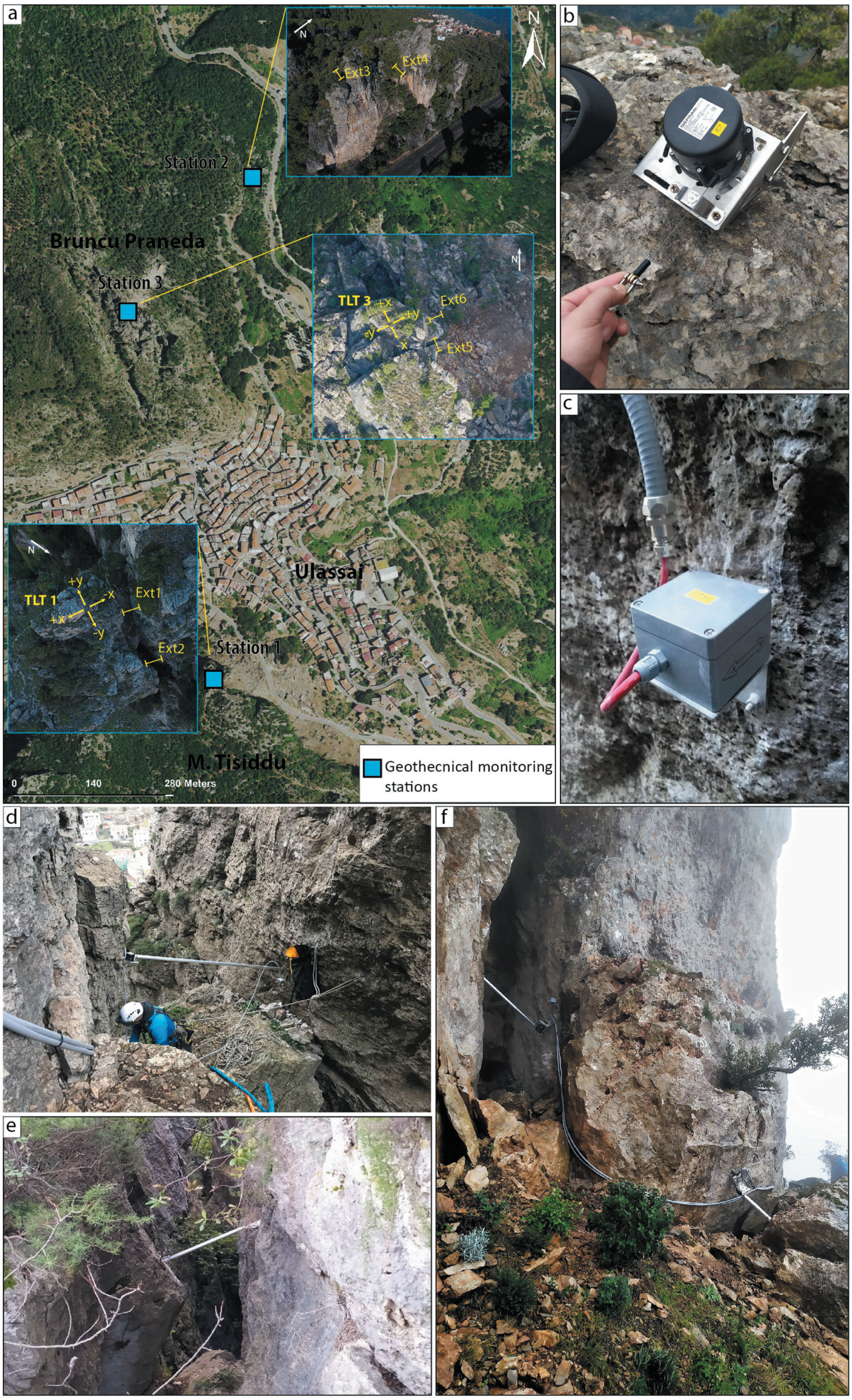


Figure 6. a) Geotechnical station instrumentations location. b) Extensimeter GEFRAN GSF1800 d c) Tiltmeter T1 MEMS Earth System (from Demurtas V. et al 2021); d) Extensimeter Ext 1; e) Extensimeter Ext 3; f) Sensor installed in the station 3.

are often triggered by the creeping of the slope. Widespread mega block deposits sometimes with dimensions up to 30/40 m per side are present at the base of the lateral spreads. These deposits are linked to the collapse phase of DGSD parts. Rock avalanche deposits have been found to exhibit sedimentological and geomorphological characteristics of a very recent event. The evidence of current activity is demonstrated by the detachment of a rock avalanche that occurred in November 2014, involving a total volume of rock more than 1500 m^3.

A more evolutionary stage with the partial sinking of Dorgali Formation in the altered and fractured metamorphites was identified in the middle slope.

Figure 7. a) main landslides distribution around Ulassai Village (Mod. from Demurtas et al. 2021). b) UAV-DF acquisition and output. b1) Ground control points acquired by GNSS. b2)phantom 4; b3) DJI Matrix 200; b4) textured 3D model of Bruncu Pranedda. b)5 particular of b5. C1)Bruncu Pranedda Lateral spread. C2) particular of C1. The large unstable block inside an extensional trenches. d) Monte Tisiddu large toppling in urban areas. e) middle slope Bruncu Pranedda sackung affected by large toppling.

The basal shear surface involves the top of the metamorphites with high fracturing and chemical alteration. The kinematic deformation of this area is Sackung type (Demurtas et al., 2021; Zischinsky, 1966). Here, three large vertical prismatic blocks of dolostone show evidence of toppling (Figure 7(e)). Between these rocky pillars, there are partially cemented paleo landslides with evident fractures in the matrix.

In the Tisiddu sector, a rock pillar with a size of about 40,000 cubic meters is completely separated from the plateau by an important fracture with an opening of up to 5 m. This coherent block with dimensions of about 25 × 20 m per side and 80 m thick rests on the Genna Selole Formation and on the altered metamorphites. At the base of the slope, paleo-deposits of large collateral landslides with large blocks privy of vegetation were identified, indicating a recent age of the event. Most of the deposits of these past events are currently urbanized by the town of Ulassai.

InSAR analysis

Space-borne Interferometric Synthetic Aperture Radar (InSAR) data have been used to analyze the slope deformation in the Bruncu Pranedda area. According to the geomorphological evidence, PS-InSAR analysis showed that most PSs were located inside the Bruncu Pranedda Lateral spread (Figure 8 (a,b)). As a result of applying the PS technique, we obtain a map of the PSs identified in the images and their spatial coordinates. The average movement speed of each single PS along LOS is expressed in mm/year.

The data on the period 2014–2020 allowed the recognition of an active state of the lateral spread. The deformation speed ranging from 4 to 10 mm/year. A longer time-scale analysis of the same area is described in (Demurtas et al., 2021b) where European Remote Sensing (ERS) data from 1992 have also been used. The data appear coherent since the 1992. In this paper, we show only the sentinel data with higher spatial resolution. It was possible to observe seasonal deformation trends with an excellent correlation among all the PSs analyzed. Generally, no movement was observed during the winter and spring, but acceleration was observed during the summer and autumn (Figure 8(c)). No movement was individuated in the urban area, in the middle slope of Bruncu Pranedda paleo DGSD and in the Tisiddu large toppling.

GNSS movement vectors

The GNSS survey carried out from December 2020 to current days in the lateral spread of Bruncu Pranedda showed data consistent with the geomorphological evidence and the InSAR data (Figure 9). The movement data are representative of the large Dolomite blocks with differential displacements that modulate a large-scale shift of the entire portion of the slope. The data showed error values of approximately ±3 mm. To validate the error, the calibration acquisitions were performed within 24 h. In accordance with the geomorphological and InSAR data, the survey points G1 and G2 located in the stable sector did not show any movement. The difference between the coordinates is always less than 3 mm within the instrumental accuracy of ±3 mm. While the three points measured in the deformation sector showed comparable values with the radar displacement rates between 7 and 14 mm. These data will be used for a future design and installation of a real-time GNSS detection system for alert purposes.

Geotechnical data

The data were acquired in continuous by the data logger with a sensor sampling interval of 30 s and an automatic data transmission to HMS-WEB platform of 5 min. The data have been continuously acquired since installation, and there were some interruptions of some nights caused by persistent conditions of high cloudiness that did not allow to recharge the batteries. This problem will be compensated by increasing the photovoltaic panel and modifying the setting of the acquisition parameters based on the warning thresholds that will be defined. Preliminary data analysis acquired since January 2021 to December 2021 show a very low-velocity deformation (Table 2) (Figure 10). In particular, the extensometers show a total closing movement between 0.6 and 1.2 mm. Only the E 4 show a stable condition for the entire year. Tiltmeter 1 shows a Tilting through SSW indicating a rotational movement of the Block of 1.2°. However, tiltmeter 2 shows a toppling-type movement through NE of 2.4°.

Discussion

Landslide hazard

Geomorphological, InSAR, GNSS and geotechnical data allowed to understand the kinematic and deformation speed Lateral Spread and Large collateral landslides (Angeli et al., 2000; Giordan et al., 2013, Demurtas et al. 2021). These data will allow us to estimate the landslide's future behavior (Pánek & Klimeš, 2016). The Lateral Spread is associated with numerous large collateral rockfalls and toppling landslides that affected since the past the area where the village is located. Dolomitic blocks with sizes of up to 30 m on each side (Figure 2(h)) were identified as widespread linked to mega-rockfall events with rock avalanche features. Evidence of collateral landslides is reported in historical memory with the most recent

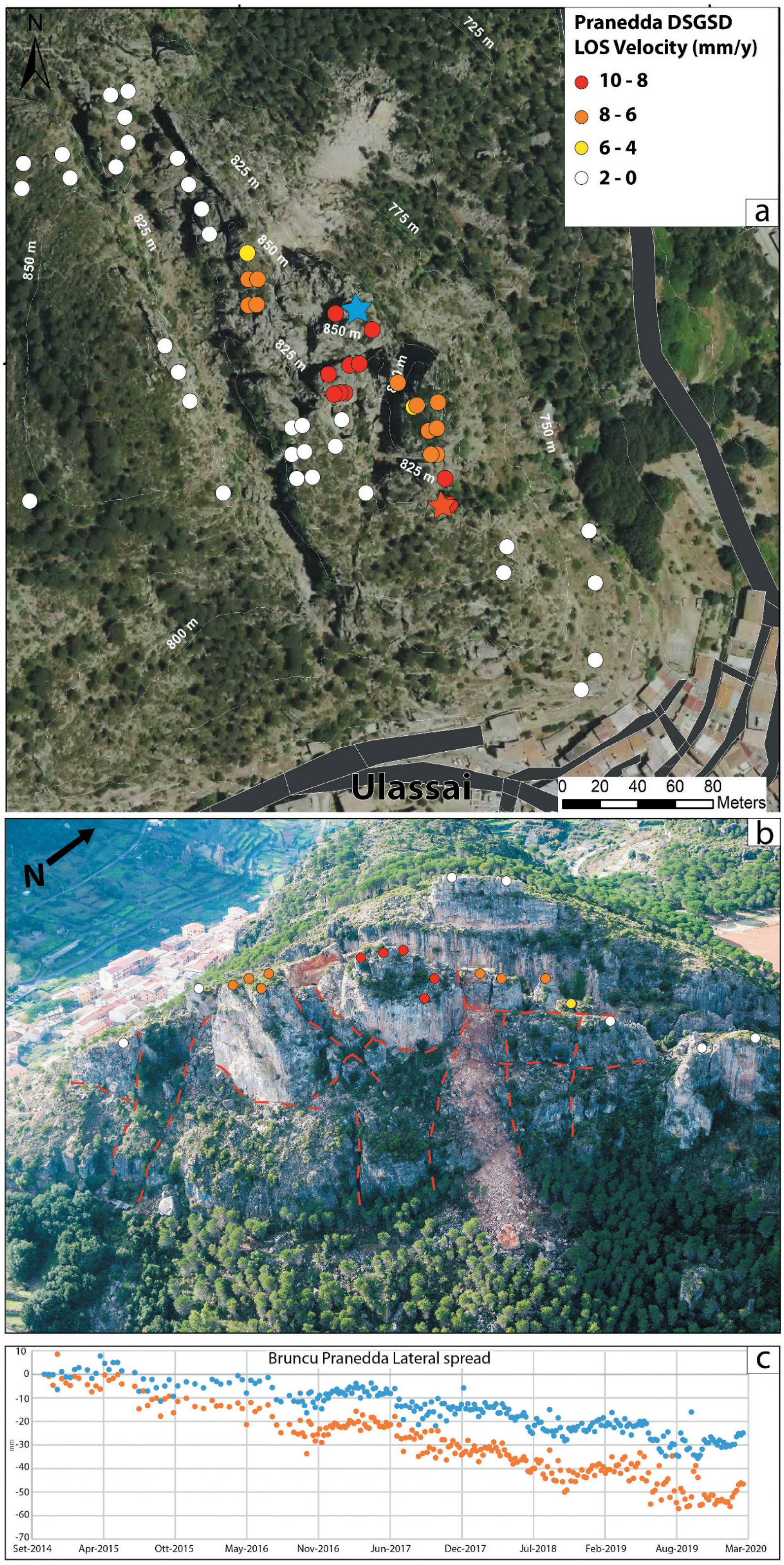


Figure 8. Analysis of the InSAR data. The points represent high-coherence permanent scatters located on rocky outcrops. The stars in a represent the PSs used to analyze the time series shown in c. (a) Bruncu Pranedda lateral spread, b) UAV photo with localization of the permanent scatters. C) Time series extracted with the representative permanent scatters. The vertical axes represent the cumulative LOS displacement; the horizontal axes represent the time. (a) Bruncu Pranedda lateral spread – seasonal displacement trend, the maximum displacement of 5 cm from 2014 to 2020.

event of 2014 (Demurtas et al. 2021a) which led to tremors in the center inhabited (Figure 7 c1). Currently, a reactivation of quiescent parts of the DGSDs or an acceleration of movements can be triggered by extreme weather events or earthquakes. Therefore, an acceleration of slope movements leading to a potentially catastrophic failure poses a threat to communities, and the monitoring of these slopes is

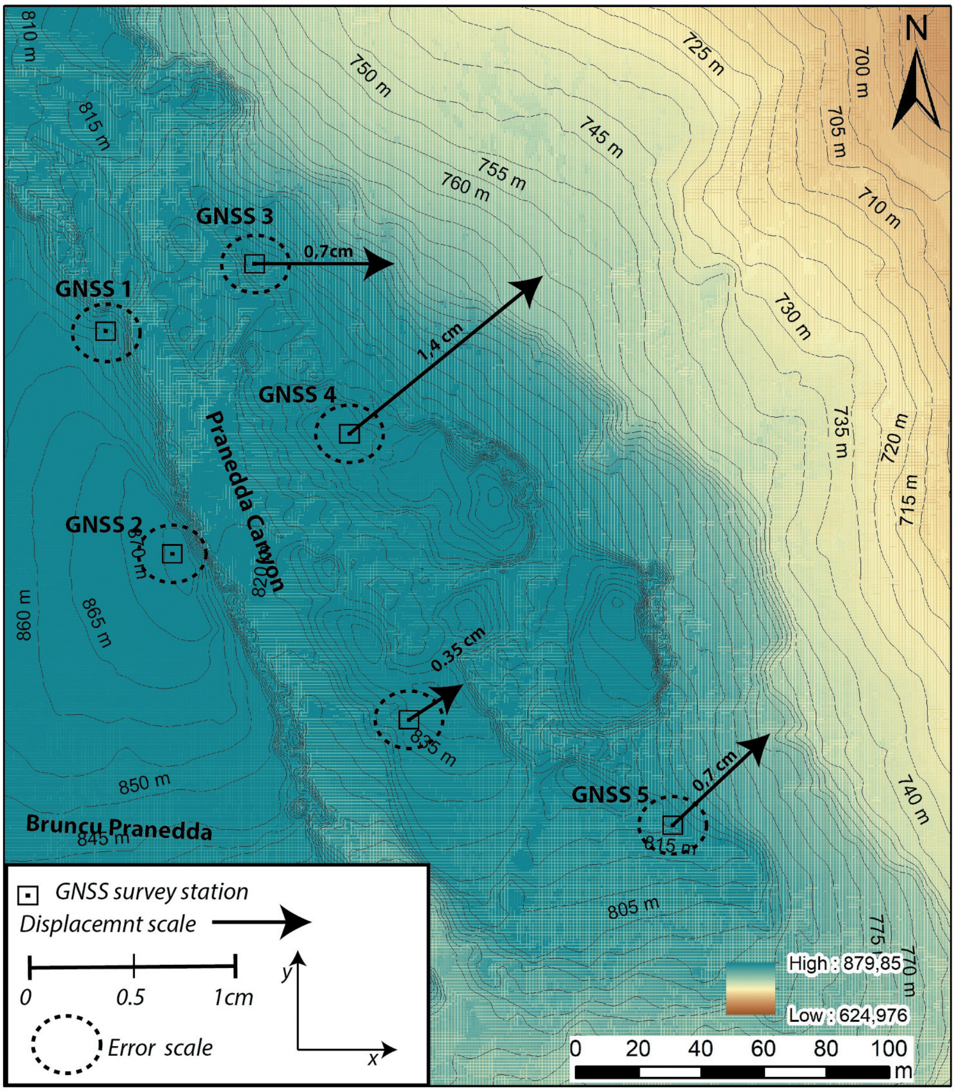


Figure 9. GNSS Displacement of Bruncu Pranedda Lateral Spread. The black arrow represents the direction and the speed of the measured points.

Table 2. Geotechnical monitoring data synthesis.

Monitoring station	sensor	Max opening (mm)	Max closing (mm)	Max excursion (mm)	Total movement (mm)
Extensimeters					
1 Mt Tisiddu	EXT E1	+1.2	−2.2	2.2	−0.6
	EXT E2	+1.8	−2.2	2.2	−0.8
2 Bruncu Pranadda East	ETX E3	+4.6	−5.6	5.6	−1
	EXT E4	+0.4	−0.2	0.4	+0.2
3 Bruncu Pranadda west	EXT E5	+1.1	−2.4	2.4	−0.7
	EXT E6	+0.5	−1.1	1.1	−1.2
Tilitimeters					
Monitoring station	Sensor	Max degree (°)	Direction		
1 Mt Tisiddu	TLT 1x	0.1	WNW		
	TLT 1Y	1.2	SSW		
3 Bruncu Pranadda west	TLT 2X	0.4	SSW		
	TLT 2Y	2.4	NE		

important for early warning and risk reduction. Similar behaviour has been pointed out in analogous study areas before (Gutiérrez et al., 2012; Mantovani et al., 2013; Pasuto & Soldati, 2013; Tomás et al., 2018). This landscape constitutes a geomorphosite of great interest for environmental tourism activities and for moving climbs (Migoń & Pijet-Migoń, 2022; Selmi et al., 2019). This anthropogenic presence increases the risk associated with the presence of collateral rockfalls and toppling landslides of small and large magnitude.

The PS-InSAR analysis reveals a good tool for mapping and monitoring landslides and DGSDs (Bianchini et al., 2013; Colesanti & Wasowski, 2006; Demurtas et al., 2021a; Greif & Vlcko, 2012;

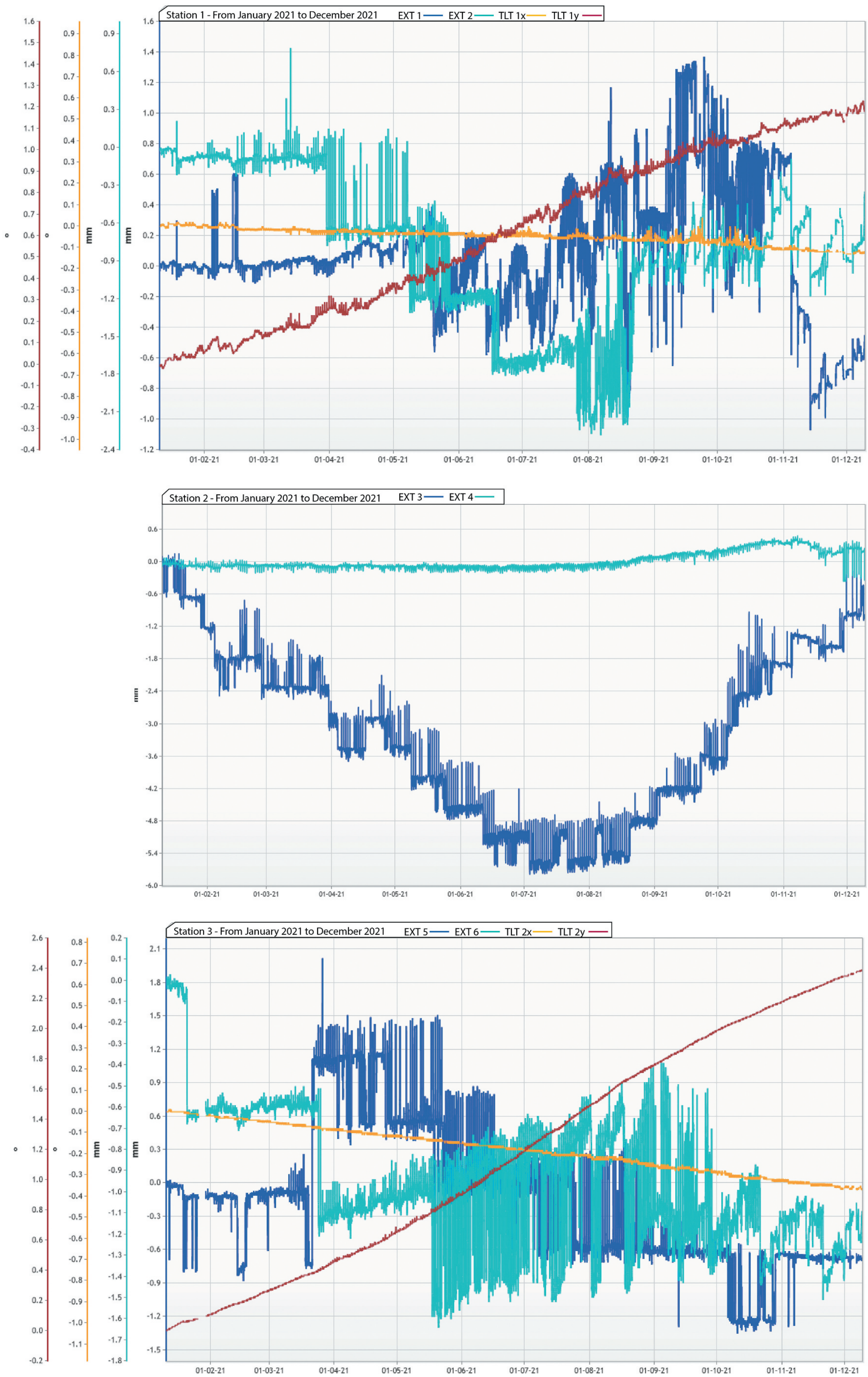


Figure 10. Extensometers and tiltmeters movements. The location of the sensor is shown in Figure 6.

Mantovani et al., 2016). InSAR data indicate that in the lateral spread of Bruncu Pranedda a large slope side is affected by an average deformation of about 1 cm/y downslope in the last 6 years. Similar remote sensing studies that utilized InSAR to analyze lateral spread show comparable displacement rate in the eastern Betic Cordillera of Spain (Delgado et al., 2011) and in Malta (Mantovani et al., 2016) and in Tunisia (Gaidi et al., 2021). The highest speeds are recorded in the summer and autumn. This acceleration is linked to the groundwater regime (Figure 8(c)). The carbonate plateau is home to an important karst aquifer that records maximum water levels during the winter while during the dry seasons it tends to empty with consequent dehydration of the porous levels at the base of the carbonate lithologies.

The availability of an integrated monitoring system made it possible to correlate the displacements measured with the InSAR technique with the data acquired on the ground. Since December 2020, the ground monitoring network using geotechnical instrumentation and GNSS has provided important information on surface displacements. Monitoring by periodic GNSS measures, it is a methodology used in different lateral spread and shows a goon correlation with InSAR analysis (Mantovani et al. 2022) It is necessary to take into account that the movements measured with GNSS are representative of the top of the rocky reliefs on which the measurement was acquired and could be different in depth due to tilting movements that may have affected the block. In our case, there is a need to acquire the data for a longer period to have more representative data of the kinematics in progress.

In the paleo-DGSD with sackung characteristics, there are no InSAR data due to a quiescent state of the deformation. In this contest, the geological hazard is linked to the overturning of large dolomitic pillars separated by paleo-trenches and landslides. These are filled with collapsed deposits, and internal movement can trigger secondary landslides. In this context, monitoring is necessary both in anticipation of the toppling of the great Dolomite bodies and for secondary landslides. The extensometers installed made it possible to measure the internal movements of the paleo DGSD. In particular, the extensometer E3 showed a closure trend of 5 mm and reopening of 5 mm during the year, this linked to the weak rocks (located in the shear surface) between the formation of Dorgali and the formation of Genna Selole and the altered base (Figure 2(c-e)).

In the Monte Tisiddu sector, the rock pillar is monitored with two extensometers and a tiltmeter (Figures 3(b) and 6(c,d)). The fracture separates it from the planking by up to 5 m, indicating a prevalent kinematic of distension with a slightly larger opening in the upper part. This indicates a slight tilting component downstream of the block. The data from the geotechnical instrumentation indicate a cumulative deformation enclosure of up to 0.8 mm and a tilting of the block up to 1.2 ° upstream, indicating a sliding movement of the foot downstream.

It should be emphasized that these data are preliminary and fundamental as they are for conoscitive monitoring purposes. The monitoring system will be integrated and appropriately sized based on the information acquired. In general, the main deformation kinematic is linked to the dynamics associated with the lateral spread at various scales. The rigid formation of the Dorgali dolomites slides with a speed of up to 1 cm per year on the formation of Genna Selole and the altered metamorphites. This process is observable on a lower scale in the paleo-Sackung of Bruncu Pranedda and Mount Tisiddu.

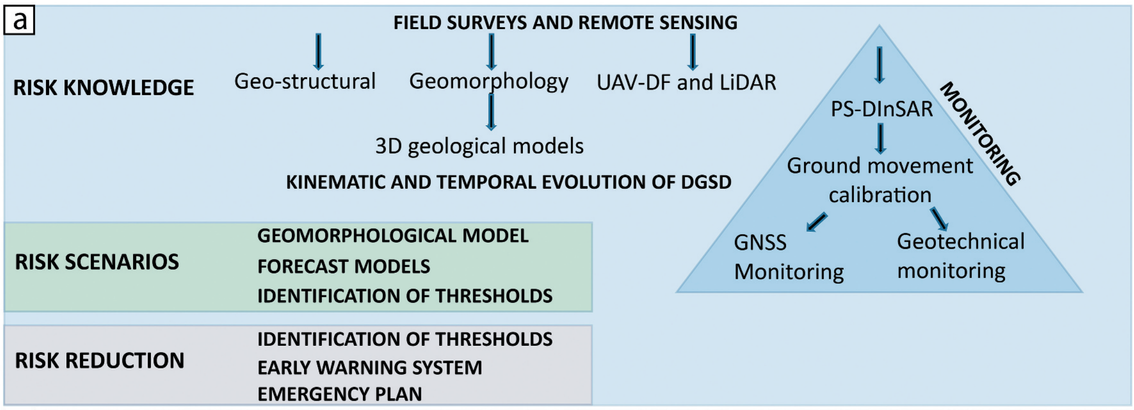
Early warning system

In order to mitigate the geomorphological risk and guarantee safety conditions for the inhabitants of the municipality of Ulassai and the users of the tourist activities, it is necessary to set up a real-time monitoring system with the aim of early warning (Figure 11). Based on the typology and volumes involved by the lateral spread and the large toppling, it is not possible to build engineering works to counteract the state of activity of the processes in place. The simplicity of the early warning system management system is a fundamental component for the correct functioning of the system. It is, therefore, necessary to propose a management system that is editable by the population. In emergency conditions, the action to be taken must be clear and rapid. Predicting the imminent failure of a landslide and alerting people is a very complicated task and the parameters to be taken into consideration are the following:

- Type and kinematics of the process.
- Evidence of historical landslides
- Evolutionary trend based on the PS-InSAR time series validated by ground data using GNSS
- Constant monitoring of geotechnical data and validation of alert thresholds.

The early warning system will be based on the measurements of the geotechnical instrumentation, in particular, by continuously monitoring the opening or closing of fractures with extensometers and the inclination of large blocks with tiltmeters and with widespread GNSS antenna that is acquired in continuous to monitor the differential displacement of the blocks.

The next step consists in the selection of appropriate thresholds. The choice of reliable values depends



b

WARNING LEVEL	TRIGGER	DEFINITION	RESPONSE
ORDINARY LEVEL	Default level	Normal activity encompassing to some degree, seasonal variation	Data are checked daily. Half yearly monitoring bulletin
ATTENTION LEVEL	Acceleration of movement below the threshold	Increased activity possibility due to prolonged rainfalls. Seismic event of interest. Potentially dangerous events.	Data are checked more frequently. Daily monitoring bulletin. Evaluation of false alarms. H24 personnel from each stakeholder are alerted. Preparing for alarm.
ALARM LEVEL	Exceeding the thresholds. Forecast evaluation by experts	Accelerating trend far beyond any seasonal fluctuation. Collapse is expected	Data are checked even more frequently. evaluation of false alarms. Two monitoring bulletins per day. partial evacuation of areas at greatest risk.

Figure 11. a) Conceptual model. b) Alarm levels. c) Monitoring station 1 with the siren.

on both scientific and social considerations. Lower and more conservative thresholds are more likely to produce false alarms that may have strong impacts on society. Conversely, higher values result in a shorter time left for taking action or, in the worst case, in missing events. In other words, the thresholds can only vary within a range between two boundaries defined by the tolerability of false alarms and acceptable risk criteria (Segalini et al., 2018; Segoni et al., 2014; Tiranti & Rabuffetti, 2010).

The most popular approach for the definition of a threshold is to define the relationship between landslide displacement and external parameters (rainfall intensity-duration; earthquakes, snow avalanche, volcano activity, soil temperature, etc.) (Crosta & Frattini, 2001; Fazzini et al., 2021; Quesada-Román et al., 2019; Saito et al., 2018; Segoni et al., 2018). In this study, we define threshold base on the historical displacements rate valuated by multi-source measures independent of the triggering factors (Demurtas et al., 2021; Giri et al., 2018; Segalini et al., 2018). Based on InSAR displacement rates which correspond to about 10 mm/y, the provisional alert thresholds have been defined. The thresholds are 2.5 mm/h and 5 mm/day for extensometers and 0.3°/h and 0.5°/day for tiltmeters. These thresholds will be calibrated through the analysis of the movements recorded by the sensors over a year. The basic concept is that with the increase in the large main landslide speed, the risk of their collapse and the triggering of collateral landslides increases. The alert measures proposed are based on information actions such as visual and audible alarms by siren and evacuation of the areas affected by collateral landslides.

Conclusions

Deep-Seated Gravitational Slope Deformations are phenomena of great importance from a scientific point of view, both for the role they play in the evolution of relief and for the significant social impact should they occur in proximity to peoples and infrastructures.

Monitoring data of DGSDs in Sardinia were described for the first time in this study.

Analysis of the geological and geomorphological settings of plateau edge in Ulassai using UAV photogrammetry and high-resolution field surveys allowed to identify different gravitational geological hazards. Landslides with different kinematics and magnitudes have been identified: DGSDs with sackung and lateral spread kinematics, giant toppling and widespread rockfalls. Different techniques aiming to understand the temporal evolution of DGSD and giant toppling and future dynamics have been applied in three areas in Ulassai. InSAR data indicate that in the lateral spread of Bruncu Pranedda a large slope side was affected by a deformation of about 1 cm/y downslope in the last 6 years. In this area, we started a geodetic monitoring system to validate and calibrate satellite data and to understand the differential movement under deformation slope.

To analyse the deformation at fracture scale, three geotechnical monitoring stations were installed with continuous acquisition. In conclusion, based on a high-resolution geomorphological model of the gravitational process affecting Ulassai, we have provided preliminary data for designing an early warning system for alert purposes.

Data availability statement

Raw data were generated at the University of Cagliari (Italy). Derived data supporting the findings of this study are available on request from the corresponding author.

Disclosure statement

No potential conflict of interest was reported by the author (s).

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