Deep-seated gravitational slope deformations in central Sardinia: insights into the geomorphological evolution

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ABSTRACT
In this study, we analyse deep-seated gravitational slope deformations (DSGSDs) in central Sardinia. The area is characterised by plateaus with a prominent limestone scarp overlying metamorphites. A comprehensive mapping of structural, karst, fluvial, and slope morphologies in Pardu and Ullassai valleys is presented herein. The uplift linked to the Plio-Pleistocene tectonic activity leads to high-slope topography, which favours gravitational processes, such as DSGSDs and rock-avalanches. Although DSGSD is a common phenomenon in the relief of the central Mediterranean region, it has never been studied in Sardinia. We describe the kinematic models and geomorphological evolution of DSGSD in Sardinia for the first time. The application of light detection and ranging, high-resolution unmanned aerial vehicle photogrammetry, and geological, structural, and geomorphological surveys enabled a depth morphometric analysis and the development of interpretative three-dimensional models. The geo-structural setting and high relief energy associated with recent upliftment are the major controlling factors of DSGSDs.

1. Introduction
Deep-seated gravitational slope deformation (DSGSD; Dramis & Sorriso-Valvo, 1994) is a complex type of rock slope failure characterised by large dimensions generated in stone rocks (Dramis et al., 2002). DSGSDs are characterised by slow movements that can suddenly accelerate and cause catastrophic collapse of large sections of the deformed slopes (Agliardi et al., 2020; Crosta & Agliardi, 2003; Nemčok, 1972; Ostermann & Sanders, 2017; Radbruch-Hall, 1978). Therefore, this phenomenon represents a major geological hazard associated with the deformation of large infrastructures and the generation of secondary landslides. Although DSGSDs represent a major geological hazard, information about them is scarce so far (Soldati, 2013). Advanced technologies in both remote sensing (e.g. satellite data and space-borne interferometric synthetic aperture radar) (Frattini et al., 2018; Mantovani et al., 2016; Novellino et al., 2021) and proximal sensing such as unmanned aerial vehicle (UAV; Deiana et al., 2021; Devoto et al., 2020; Eker & Aydın, 2021) and light detection and ranging (LiDAR) have enabled a better understanding of these processes. They are characterised by extremely slow deformation rates (Cruden & Varnes, 1996) and landform assemblages such as double-crested ridges, trenches, synthetic and antithetic (uphill-facing) scars, tension cracks, and convex (bulged toes) and deep basal shear zones (Agliardi et al., 2001; Chigira, 1992; Crosta et al., 2013; Mariani & Zerboni, 2020; Panek & Klimeš, 2016). Shear zones exhibit the characteristics of cataclastic breccias with abundant fine matrix (Crosta & Zanchi, 2000) and thicknesses up to tens of metres (Ostermann & Sanders, 2017).

In this study, we present three cases of DSGSDs in Sardinia. The study area is located in Ogliastra (central-east Sardinia) in the Pardu River Valley (Figure 1). The area is characterised by wide plateaus, called Tacchi, with a prominent Jurassic limestone scarp overlying Palaeozoic metamorphites (Carmignani et al., 2016; Pertusati et al., 2002).

The major evidence of DSGSDs in the Pardu River Valley is the presence of large prismatic blocks of dolomitic Mesozoic slab displaced up to tens of metres downstream from the initial altitude. The geomorphological features associated with DSGSDs vary along the slope. A set of ridge-top trenches, with widths up to 50 m, lengths of hundreds of metres, and depths of >50 m is present in the plateau edge. The middle slopes are characterised by tilted blocks, shear zones, and rockfall deposits. Large block deposits with rock avalanche features in the foot-slope are associated with the final-collapse phases of the DSGSDs.

For the first time in this setting, we delineated long-term deformations, such as gravitational slides...
We highlight the occurrence of DSGSDs associated with the evolution of river slope in the uplift setting within the low seismic and low tectonic activity regions of Sardinia. Thus, we analysed the geomorphological evolution of the slope, particularly focusing on the probable and catastrophic evolution of these processes in an urban setting.

A geomorphological map at a scale of 1:10,000 was generated showing: (i) the karst morphology on carbonate plateaus; (ii) the gravity feature on the edge plateau linked to the extensional trenches and tilted blocks; (iii) different landslide deposits on the slopes (rockfalls, palaeo-DSGSDs, slope debris, and rock avalanches); and (iv) hydrographic elements (e.g. creeks, canals, and fluvial elbows).

1.1. Geological setting

East-central Sardinia (Italy) is characterised by a Jurassic dolomitic plateau (Tacchi) overlying a metamorphic Palaeozoic basement, primarily comprising metasandstone, quartzites, and phyllites (Figure 2) (Carmignani et al., 2016; Pertusati et al., 2002).

The area is characterised by the Pardu River Valley in the east and the Barigau River Valley in the southwest; the central and north-western sectors include 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., 2001, 1994; Elter et al., 2004, 2010). The major Palaeozoic units are the Filladi Grigie del Gennargentu Formation and Monte Santa Vittoria Formation, which constitute metarenites, quartzites, shales, and metavolcanites (Middle Cambrian–Middle Ordovician) (Meloni et al., 2017; Pertusati et al., 2002; Vai & Cocozza, 1974). The metamorphic basement summit has suffered chemical alteration 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), which are overlain by dolomitic limestones of the Dorgali Formation (Middle–Upper Jurassic). (Costamagna et al., 2018; Costamagna & Barca, 2004; Dieni et al., 1983; 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 thickness up to tens of metres. The lower part, with a thickness of approximately 30 m, is affected by marl intercalations, whereas the upper part is typically

Figure 1. Geographical location and structural features of the study area modified after Deiana et al. (2021): red lines represent thrust fronts; white lines are the Sardinian–Corse Block translation 30 Ma; yellow line represents the Sardinian–Corse Block translation 25 Ma (modified after Carminati & Doglioni, 2005); green line represents the Sardinian–Corse Block translation 14 Ma (Gattacceca et al., 2007).
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 direction parallel to the slope owing to the DSGSD.

Quaternary covers, represented by continental deposits, are primarily colluvial and alluvial deposits. The most extensive outcrops represent landslide deposits, including rockfalls, toppling, and collapsed DSGSDs at the foot-slope of the Tacchi, abundant on the right slopes of the Pardu and Barigau rivers. Moreover, terraced alluvial deposits have also been identified in the downslope.

The rockfalls and toppling landslides have been characterised by different sedimentological features based on age. These deposits are associated with rockfalls affecting the plateau edge wall and the collapse of some parts of the DSGSDs.

1.2. Tectonic and geodynamic settings

The geodynamic setting is associated with the collisional dynamics between the African and European plates (Figure 1). 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).

The major features in the study area are the NW–SE faults on which the Pardu Valley is engraved, and the secondary fault directions include ENE–WSW and NNE–SSW (Pertusati et al., 2002).

The Plio-Quaternary tectonic phase is associated with conspicuous N–S faults (Casula et al., 2001). These rectilinear and normal faults are also evident in the continental margin and control its morphology (Figure 2). In the continental region, these N–S faults are associated with alkaline basalts with an age of approximately 3.9 Ma (Lustrino et al., 2007). Quirra River follows this N–S direction from the south of the Pardu River capturing elbows and flows in a straight line for approximately 30 km (Figure 3).

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The landscape is characterised by sub-horizontal carbonate plateaus, separated by deep rectilinear valleys engraved in the Palaeozoic basement for several hundreds of metres (Maxia et al., 1973; Ulzega & Marini, 1973). Erosion primarily acted on the Oligo–Miocene strike-slip faults with an increase in the erosive rate during the Plio-Pleistocene uplift phases (Marini & Ulzega, 1977). A significant karstic process has acted on plateau surfaces, comprising ancient palaeoforms and currently hypogean and superficial morphologies (De Waele et al., 2005, 2012). Karst palaeoforms represented by complex cockpit doline types have been characterised in the area in a humid and warm morphoclimatic setting (Fleurant et al., 2008; Liang & Xu, 2014; Waltham, 2008). These dolines are separated by residual reliefs called Fengcong, sorted along the major structural features. The hypogene karst enabled the development of sinkholes, karst springs, cavities, and caves (e.g. Su Marmuri Cave and Is lianas Cave). The combined action of karst, uplift, river erosion, and gravity has led to the formation and evolution of numerous hanging valleys on the plateau surface (Ulzega & Marini, 1973).

The presence of major fault systems has influenced the watercourses, which maintain a prevalent N–S direction in the Pardu River (set on the main fault), toward the western side of the map, corresponding with the secondary faults. Considering the descriptive parameters, geometrical conditions, and longitudinal profile, the evolutionary conditions of the Pardu Valley are associated with a cycle of underdeveloped fluvial erosion, suggesting a relatively young age of engraving (Marini & Ulzega, 1977; Maxia et al., 1973; Ulzega & Marini, 1973). The evolution of Pardu River is closely associated with that of Quirra River (Palomba & Ulzega, 1984; Pertusati et al., 2002). Pardu River flows from the NW toward the SE and then abruptly changes direction toward the NE. At this point, a capture elbow adjacent to the present head of the Quirra River is well developed. The upstream part of Quirra River flows at an altitude of approximately 200 m higher than the Pardu River.

It also presents an over-sized and over-flooded valley with respect to the upstream catchment area. Moreover, there are various orders of terraces and deposits in the Pleistocene. This setting indicates that the Pardu River, previously flowing south along with the Quirra River, was captured by Pelau River (De Waele et al., 2012; Palomba & Ulzega, 1984).

Gravity-related mass movements occur along carbonate cornices with rockfalls and toppling. We have focussed on the DSGSDs in this study, as they are important in the morphological evolution of the carbonate plateau.
5 cm/pixel and were considered sufficiently precise to be used for the geomorphological analysis. 3D high-resolution UAV models were used to develop interpretative superficial models using geomorphological evidence and stratigraphic and structural data of the DSGSDs. Geological interpretative cross-sections of geologic features crossing the major DSGSDs were also generated to define the movement kinematics, deformative style, and deep geometries of the DSGSDs.

3. Results

3.1. Geomorphological map

The cartographic synthesis was based on the lithologies on which landforms were highlighted, with distinct morphogenetic processes and relative chronological positions.

Geomorphological map shows the lithology from the Palaeozoic basement to the continental Quaternary covers (Figure 4).

The major physiographic units presented in the geomorphological map are the Tacco of Ulassai, Tisiddu Mountain, and the two main valleys, namely Pardu River and Barigau River valleys. The Ulassai Plateau, which comprises Mesozoic dolomitic lithologies, is affected by various superficial and underground karst morphologies (De Waele et al., 2012). A karst palaeo-landscape with a sub-tropical climate consisting of cockpit and Fengcong was detected (Fleurant et al., 2008). The latter, characterised by gentle relief, is aligned in the direction of the Oligo-Miocene faults. These formations are the major pathways of underground waterfows, on which sinkholes have developed. The plateau surface is affected by extensive polje-type dolines, which deines an extensive hydrography. The catchment area of the plateau flows out of the Santa Barbara area, which flows into the Ulassai stream after an 80-m hydraulic jump (Lequarci waterfall) (Figure 3).

The edge of the plateau was affected by gravitational processes at different scales. Moreover, widespread rockfalls and toppling of various magnitudes were present. Three orders of landslide deposits were identified, namely cemented, quiescent, and active.

The valley floor of the Pardu River in the upper part is characterised by a bed set on rock with major erosive features, whereas in the downstream part near the capture elbow, alluvial deposits exist with two orders of terraces. Downstream of the capture, the river resumes the erosive character with the valley floor set on the rock.

The legend signifying geomorphology in this study was conceived to effectively represent the features of the study area. We highlighted outcropping bedrock lithology, tectonic features, superficial deposits, and the distribution of structural, gravitational, and karst landforms.

3.2. Morphostructural setting of DSGSDs

Various areas affected by DSGSDs located at the edges of the carbonate plateau were identified, with
the major ones located on the east side of Tacco di Ulassai and Tisiddu Mountain. The main structures that indicate the deep gravity phenomenon were large and deep extensional trenches which are evident in the carbonate lithotypes. A complex structural setting was deciphered based on the analysis of faults, foliation, and tectonic-gravitational structures (Figure 5). Trenches had lengths of several hundreds of metres and a decametric opening and depth (Figure 6).

The Bruncu Pranedda DSGSD depicted two regions with different settings located in the top and middle slopes. In the top slope toward the east of the largest extensional trenches called Pranedda Canyon (Figure 6(A1–A3); Figure 7(A,A1,D)), the rock mass fracturing increased, and the attitude of the Dorgali Formation is toward the east, with a dip amount of up to 40°. In this area, both facies of the Dorgali Formation were visible, with the summit comprising dolomitic banks and the lower part characterised by
an alternation of well-stratified dolomites and marls. This subdivision was not observed in the middle slope (Figure 6(A4)), where basal marly levels do not appear on the surface. This indicates that the basal facies (approximately 30 m) were partially covered by slope deposits; however, they also sank a few metres inside the fractured and altered Palaeozoic metamorphic basement. This can be correlated with the field observations at the same altitude, with the basement and the massive facies of the Dorgali Formation.

The Scala San Giorgio DSGSD is located north of Osini Village (Figures 6(B) and 7(C)) and is characterised by two major extensional trenches parallel to the slope that affect the Dorgali Formation with dip amount up to 20°. All the sequences of the Dorgali Formation are exposed; however, the Genna Selole Formation is covered by rockfall deposits.

The Tisiddu Mountain DSGSD in the south of Ulassai Village is characterised by a highly fractured segment of the Dorgali Formation located tens of metres downstream. Only the top massive banks of dolostones are visible. The basal level was partially sinking in the metamorphic basement.

Shear zones are located in different geological units that represent structural weaknesses (Figure 8).

1. The top of the metamorphites was affected by sub-horizontal foliation (Figure 5) and advanced weathering, and the rock exhibited a reddish or whitish colour. This type of alteration could be linked to the pre-transgressive Mesozoic period (Marini, 1984); (II) Genna Selole Formation exhibited plastic clay layers; (III) basal levels of Dorgali Formation were characterised by the alternations of marl and dolomite.

Geomorphological evidence and stratigraphic and structural analyses enabled the identification of various DSGSDs characterised by different kinematics. From the structural analysis (Figure 5), the major faults with NW–SE and NE–SW directions were in concordance with the main trenches. The secondary trenches and the joints did not exhibit a good correlation with the large-scale structures because they were associated with the features inside the deformation rock mass. Lateral spreads were developed at the plateau edge due to the sub-vertical pre-existing fractures (Figure 5). Consequently, there was a predominant horizontal movement associated with vertical fractures in the carbonate and a zone of ductile basal deformation that affected the Genna Selole Formation and the summit, which altered the metamorphites (Bruncu Pranedda top slope and San Giorgio DSGSD). DSGSDs with a higher vertical shift represented a more advanced stage with sackung features (Tisiddu Mountain and middle slope of Bruncu Pranedda). A large part of the deformation affected the Palaeozoic basement, which was evidenced by the sinking of the carbonate sequence in the metamorphites.

These DSGSs were associated with numerous rockfalls and toppling landslides that affect carbonate walls. Dolomitic blocks with sizes up to 30 m on each side were identified, moving up to 900 m away from the detachment points, which were linked to mega-rockfall events with rock avalanche features (Figure 6(D)). We also identified mega-blocks of Dorgali Formation in the downslope that were associated with collapsed palaeo-DSGSD.

4. Discussion

Geomorphological data regarding the DSGSD of Bruncu Pranedda, Scala San Giorgio, and Tisiddu Mountain were used to generate geological sections for reconstructing a hypothetical surface of basal rupture and deep geometries (Figure 8).

Geological and geomorphological analyses using high-resolution topographic data enabled the identification of different DSGSD kinematic and evolutionary models. Based on the collected data, it was possible to identify three evolutionary stages.

The initial movement stage was characterised by lateral spread kinematics (Delgado et al., 2011; Dramis...
& Sorriso-Valvo, 1994; Fioraso, 2017; Gutiérrez-Santolalla et al., 2005; Pánek & Klimes, 2016; Taramelli & Melelli, 2008) (Figure 8(1,2a)), with a separation of the DSGSD from the edge of the plateau. This occurred via horizontal movement without vertical sinking.

The stratigraphic setting is characteristic of the lateral spreads because the Dorgali Formation (hard formation) rests on the Genna Selole clays and on an altered and fractured schist basement (plastic formations). In the carbonate lithologies, the deformation is brittle and develops with a
major fracture; however, in the basement, it is ductile with a sub-horizontal movement. The basal sub-horizontal shear zone is primarily located in the Genna Selole Formation and in the summit altered metamorphites.

The second stage (Figure 8(2b,3)) is associated with the deformation pattern of the sackung type (Ambrosi & Crosta, 2006, 2011; Audemard et al., 2010; Bovis & Evans, 1996; Coquin et al., 2015; McCalpin & Irvine, 1995; Oppikofer et al., 2017; Soldati et al., 2004), which can be deduced from the partial sinking of the DSGSD body inside the Palaeozoic basement. This stage is the observable downslope of the plateau edges located in the parts of the Dorgali Formation.

Figure 7. LiDAR 3D model of the DSGSD. (A1) Bruncu Pranedda. (B) Tisiddu Mountain. (C) Scala San Giorgio. (1) High fracturing area with active extensional trenches. (2) Collapse deposits of rock avalanches. The black dashed lines represent the major extensional trenches. White dashed lines represent the major stratigraphic discontinuity between marine Mesozoic sequence and the metamorphic basement. (D) UAV 3D model of Bruncu Pranedda. (4) Detachment niche. (5) Transit area. (6) Collapse deposits of rock avalanches.
tens of metres away from the original stratigraphic altitude. They are separated from the plateau by an extensive transit area characterised by the presence of slope deposits with limited outcrops of the Palaeozoic basement. This is an advanced stage assimilable at a sackung landslide and is associated with a major basal deformation that allows the movement of the bodies even for several hundreds of metres. The shear zone is located in the metamorphic basement with a sub-circular shape.

The third stage is the consequence of the collapse of the peripheral margins of DSGSDs and is manifested through rock avalanche deposits (Figure 6(D)). These deposits, comprising blocks with a size of several thousands of cubic metres, cover the most recent slope deposits and represent one of the major evidence for present movements of the DSGSDs. In fact, 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 which occurred in November 2014, involving a total volume of rock more than 1500 m$^3$.

The type and evolutionary characteristics of rockfalls and rock avalanches represent high risk factors in some sectors of the inhabited centre below; a monitoring network is being created based on satellite and geotechnical technologies with the aim of developing an early warning system.

5. Conclusions

A kinematic model and geomorphological evolution characteristics of DSGSD in Sardinia were described for the first time in this study. The study highlighted an extremely young territory conformation, associated with the Neogene and Quaternary geodynamic events, implying a series of problems related to the slope process. The causes of the DSGSDs are associated with the structural characteristics of the area and the Neogene and Quaternary geomorphological evolution of the river valley associated with the recent uplift. In the main map, a comprehensive mapping of structural, karst, fluvial, and slope morphologies in Pardu and Ulassai valleys is presented.

The predisposing factors of DSGSDs can be identified in the following points:

1. The tectonic history of the slope with a passive influence has been caused by a major uplift associated with the Neogene and Quaternary geodynamic events. The upliftment has increased the erosion rates, thereby leading to the deepening of the valleys and detente of the slopes. The energy of the relief of the slopes is the decisive morphological element which initiates the DSGSDs; in the cases studied, it is higher than 650 m.

   - Cenozoic tectonics have also conferred the structural conditions that predisposed the development of DSGSD, particularly in the Dorgali Formation. In fact, the major DSGD trenches are evidently parallel to the major faults and primarily parallel to that of Pardu Valley in the NW–SE direction, on which the slope is also set.

   - The lithostratigraphic conditions are represented by the Mesozoic units on the foliated and altered metamorphic basement.

The initiation of rapid catastrophic processes such as rock avalanche is associated with the accelerations of DSGSDs. These accelerations are linked to seismic activities and extreme rainfall events. The latter
cause the hydration of the rocks in the shear zones, thereby decreasing the geomechanical characteristics.

High-resolution topographic data and geological and geomorphological field surveys enabled the identification of three evolutionary stages of DSGSDs.

- The first stage preceding the capture of the Rio Pardu by the Rio Pelau associated with the uplift and the Plio-Quaternary tectonics.
- The second phase associated with a major erosive activity following the capture of the Rio Pardu which triggered the oldest DSGSDs with sackung features.
- The present evolution of plateau edges through lateral spread DSGSDs and rock avalanches.

Software

The map was digitised using ESRI ArcGIS * 10.6 software. UAV photogrammetry data were processed by Agisoft Metashape Professional *. The digital terrain models were generated using the Global Mapper * 21.0. Geological sections were created using Adobe Illustrator * CC2015.

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Disclosure statement

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

Data availability statement

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

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