Received: 23 October 2024 | Revised: 28 December 2025 | Accepted: 2 January 2026

DOI: 10.1002/esp.70250

CASE STUDY

ESPL WILEY

Multidisciplinary approach to revisit the state of activity of a deep-seated gravitational slope deformation in the frame of the Quaternary geomorphological evolution of the Central Apennines (Italy)

Giorgia Berardo[1] | Gabriele Amato[1] | Irene Cornacchia[2] | Matteo Fiorucci[3,4] | Gian Marco Marmoni[1,5] | Gabriele Scarascia Mugnozza[1,5]

[1]Department of Earth Sciences, Sapienza University of Rome, Rome, Italy

[2]Italian National Research Council-Institute of Environmental Geology and Geoengineering (CNR-IGAG), Department of Earth Sciences, Sapienza University, Rome, Italy

[3]Department of Civil and Mechanical Engineering, University of Cassino and Southern Lazio, Cassino, FR, Italy

[4]European University of Technology, EUt+, European Union, Cassino, FR, Italy

[5]CERI Research Centre on Geological Risks, Sapienza University of Rome, Rome, Italy

Correspondence
Giorgia Berardo, Department of Earth Sciences, Sapienza University of Rome, Piazzale Aldo Moro 5, Rome, 00185, Italy.
Email: giorgia.berardo@uniroma1.it

Funding information
This study was supported by Autorità di Bacino Distrettuale Appennino Centrale and Sapienza University of Rome (000158_2021_ABDAC_Scarascia).

Abstract

Evaluating the state of activity of Deep-Seated Gravitational Slope Deformation (DSGSD) is a challenge that requires multidisciplinary analytical approaches. This research focuses on the slope-scale gravitational process, framing the role of the Quaternary morphodynamics of a river valley where multiple DSGSDs coexist, to reconstruct the causative factors controlling slope instabilities in a long-term evolutionary history. The study area, located in the Velino River Valley (Rieti, Central Italy) and the San Vittorino intermontane plain, experienced a complex geological history significantly influenced by the interplay of tectonic and climatic processes. The Quaternary geomorphological evolution of this sector was framed to shed light on fluvial and slope dynamics and assess the residual landslide hazard along the valley. In this research, we investigated the case study of the Paterno slope, which, according to the previous official risk mapping, was characterized by a high risk. The reported reconstruction is based on numerous breccia outcrops distributed at different elevations along the slope, leading to an updated evolutionary model of the Velino River and Paterno slope system, which is further corroborated by the most current official risk mapping. This study also allows us to infer the preparatory role of karstic and fluvial processes in Quaternary morphoevolution. Geomorphic markers, such as evidence of flat surfaces and a paleolandscape resulting from erosional processes, have been identified at different sites along the Velino Valley, attributed to the Lower Villafranchian (2.58 Ma). The reported findings revealed that these deposits, composed mainly of slope talus breccias, outcrop at elevations lower than that of the relict 'Fontanelle Surface' in the study area since they are partially dislodged by gravitational processes. Geomorphic analysis, together with field investigations and laboratory analyses, focused on these breccias, trying to understand their genesis and Quaternary history. Based on these findings, combined with field surveys, geomorphological analysis and evidence from InSAR satellite data, we revisit the extent and current state of activity of the Paterno DSGSD. As a result, this multidisciplinary approach led us to propose an updated hazard assessment, indicating a low level of associated hazard, also adding pieces of evidence to the morphoevolution of the area with a lookout to the residual risk conditions in this sector of the Apennine mountain chain. This transferable combination of multiple techniques to support the DSGSD hazard assessment can be applied to other mountainous contexts prone to DSGSD. This study aims to provide a comprehensive example of how geomorphological large-scale analysis, integrated with local thin section analysis and remote sensing, can be adopted to make a step in the analysis of DSGSD affecting tectonically active mountain areas.

KEYWORDS
Central Apennines, DSGSD, Italy, karst, landslide hazard, Quaternary

1 | INTRODUCTION

Deep-seated gravitational slope deformations (DSGSDs) are gravity-driven geological processes that may affect entire ridges involving volumes up to several tens of millions of cubic metres (Zischinsky, 1969; Crosta, 1996; Petley & Allison, 1997; Panek & Klimeš, 2016; Discenza et al., 2021). These features are often remnants of past climatic and tectonic conditions (Calderini et al., 1998; Centamore & Nisio, 2002; Ricci Lucchi et al., 2000; Soligo et al., 2002). The morphological features observed in the upper parts of slopes are trenches, double ridges, grabens, scarps and counterslopes, whereas bulging features, scree slopes and buckling folds characterise slope toes (Agliardi, Crosta, & Zanchi, 2001; Amato et al., 2018; Jaboyedoff et al., 2013; Marmoni et al., 2023; Panek & Klimeš, 2016). This set of features, together with ongoing ground deformation (Amato et al., 2018; Di Martire et al., 2016; Frattini et al., 2018), damages to buildings and infrastructures (Catelan et al., 2025; Festi et al., 2023), or evidence of historical or activations (Albano et al., 2023; Del Rio et al., 2021), has been crucial to identifying DSGSD activity and accurately quantifying landslide hazards posed by their potential paroxysmal evolution (Chang, Ge, & Lin, 2015; Della Seta et al., 2017; Marmoni et al., 2017; Vick et al., 2020). Several studies have identified numerous DSGSDs in the Central Apennines, detecting the causes in the Quaternary morphotectonics (Bianchi Fasani et al., 2014; Della Seta et al., 2017; Di Luzio et al., 2022; Esposito et al., 2013; Martino & Prestininzi, 2004). These landforms represent the result of inherited tectonic stresses, rapid stream erosion, periodic hydraulic forcings and steepening of valley sides. All these processes can act separately or in combination with this type of slope movement (Amato et al., 2018; Di Luzio et al., 2004; Maffei, Martino, & Prestininzi, 2005; Radbruch-Hall, 1978; Radbruch-Hall, Varnes, & Colton, 1977). River incision increases slope height and steepness, raising the relative relief energy, which in turn leads to stress concentrations that can lead to progressive slope failure (Eberhardt, Stead, & Coggan, 2004; Marmoni et al., 2023), involving plastic deformation within the rock mass and the formation of contractive or dilatant shear zones (Hou, Chigira, & Tsou, 2014).

The onset and evolution of the latter depend on the geostructural conditions of the ridge (Amadei, Savage, & Swolfs, 1987; Amadei, Swolfs, & Savage, 1988; Scarascia Mugnozza et al., 2006) and are controlled by the geomorphological evolution of slope-to-valley systems, that is, depositional and erosional stages and tectonic activity (Esposito et al., 2013; Moro et al., 2012). All these processes modulate the pace of evolution of slope-to-valley systems and predispose the area to slope deformation. Among other factors, karst processes, which are widely distributed in the Apennine chain, are preparatory processes that control the evolution of structurally constrained slope deformation phenomena (D'Alessandro, Miccadei, & Piacentini, 2003; Demurtas, Orrù, & Deiana, 2021; Hungr, Leroueil, & Picarelli, 2014; Piacentini & Miccadei, 2014).

This study deals with the predisposing and preparatory morphogenesis governing slope evolution in one portion of the right flank of the Velino Valley, near the San Vittorino plain (Rieti, Italy). The middle Velino Valley is characterised by two main DSGSDs: the Peschiera (Martino, Moscatelli, & Scarascia Mugnozza, 2004) and the Paterno DSGSDs, located on opposite sides of the valley. While the Peschiera DSGSD has been deeply investigated and its activity is currently monitored (Fiorucci et al., 2017; Lenti et al., 2012; Maffei, Martino, & Prestininzi, 2005; Martino, Moscatelli, & Scarascia Mugnozza, 2004; Martino & Prestininzi, 2004; Martino, Prestininzi, & Scarascia Mugnozza, 2004), the Paterno DSGSD, despite being mapped in the official Geo-hydrological Hazard Italian Plan, called in Italian "*Piano di Assetto Idrogeologico* PAI" (available at https://aubac.it/piani-di-bacino/piani-di-assetto-idrogeologico) still lacks a detailed analysis that frames its current state of activity and associated residual risk conditions. This study focused on the Paterno slope (Figure 1), which experienced creep deformation within a highly fractured rock mass genetically linked to proximity to main thrust elements (Chigira, 1992). Direct and reverse faults also drive the rise of deep fluids that enhance significant karstic processes (Barberio et al., 2021). Karst processes strongly influenced the geomorphology of the study area, as proved by the presence of numerous karstic forms, such as piping and solution sinkholes and large dolines on slopes.

The area of the Paterno DSGSD falls under the responsibility of the District Basin Authority (DBA) of the Central Apennines. Following the earthquake sequence that struck Central Italy in 2016–2017, this authority, in collaboration with the Commissioner for the Reconstruction of the Municipalities, started updating in a wide area the landslide hazard plans (i.e., PAI), including the revisiting of the state of activity of large slope-scale deformation.

The sequence started with the 24 August 2016 Mw 6.0 earthquake and was composed of thousands of earthquakes up to Mw 6.5 until January 2017, severely damaging tens of villages and causing several fatalities, also inducing several environmental effects (Martino et al., 2019; Michele et al., 2016). In this context, it became essential to reassess the state of activity of gravitational phenomena such as DSGSDs, as post-seismic reactivations or accelerations were observed in many cases. Recent studies have highlighted a marked increase in landslide activity in the epicentral areas following the seismic sequence (e.g., Marc et al., 2015; Martino et al., 2022; Song et al., 2022), further supporting the need for updated hazard assessments based on post-event data. These findings underscore the need to update hazard products such as PAI using near-real-time data and post-event inventories, as static hazard maps become outdated rapidly after earthquakes (Fan et al., 2021; Tanyaş et al., 2021).

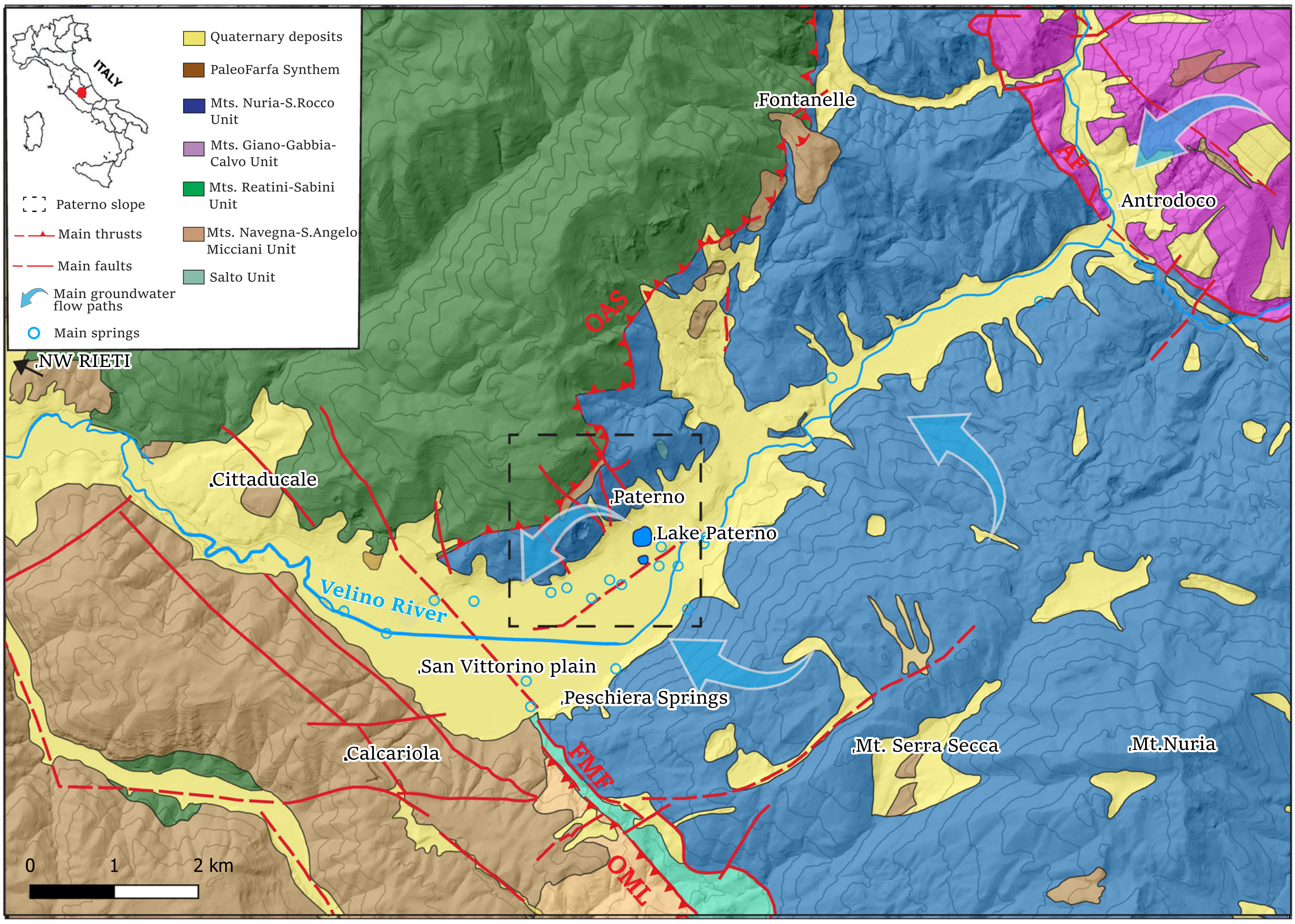

FIGURE 1 Geo-structural scheme of the main tectonic units, distinguished by the main thrusts and faults (dashed line where buried): Olevano-Antrodoco-Sibillini Mts. thrust (OAS), Olevano–Micciani Line (OML), Fiamignano–Micciani Fault (FMF); Antrodoco Fault (AF).

Several European countries, such as France and Norway, have implemented comparable risk mitigation strategies, including the Base de Données Nationale des Mouvements de Terrain – BDMVTS (*Service Geologique National*/BRGM), the Norwegian landslide database Skrednett – NVE (*Norwegian Water Resources and Energy Directorate*).

Adopting a common perspective, Pánek et al. (2019) used LiDAR-based mapping to provide a more complete and accurate representation of landslides, addressing the gaps in the national landslide inventory of the Czech Republic, which underrepresents old large landslides and DSGSDs.

In this perspective, DBA made great efforts on large-scale satellite interferometry (Zocchi et al., 2025), corroborating it with field geomechanical and geomorphic analyses, with the aim of revisiting the state of activity of inventoried DSGSDs. Such studies also supported in the Velino Valley a broader understanding of morphogenetic agents' role in controlling slope dynamics and allowed us to investigate the predisposing, preparatory and potential triggering factors influencing the slope evolution in one of the key sectors of the Central Apennines. However, DSGSDs are generally associated with inherent data limitations, making this analysis particularly challenging. To fully assess their impact within the geomorphological framework of the valley, it is necessary to identify and characterise them on a broader spatial and temporal scale, requiring more effort for a comprehensive analysis.

In this paper, a focused multidisciplinary geomorphological analysis was conducted. In detail, we present the findings from remote, field and laboratory investigations, suggesting their main implications for the reconstruction of landscape dynamics in the middle Velino Valley from the Villafranchian age (about 3.6 Ma) to the present. In particular, the Quaternary evolution of the middle Velino Valley was analysed by reconstructing the distribution and characteristics of its surface deposits, to propose an evolutionary model of the Paterno DSGSD and evaluate the current landslide hazard, as an update to the previous version of PAI, with residual risk affecting the Paterno Village and the underlying infrastructures in the S. Vittorino plain. Our proposed study was further integrated into the updated PAI framework and officially published (Trigila et al., 2025), supporting the validity and usefulness of the approach adopted in this work.

2 | GEOLOGICAL SETTING

The study area (Figure 1) is located in the central-eastern sector of the Apennine chain and is characterised by the overlay of different tectonic units belonging to different paleogeographic domains, that is, the 'Laziale-Abruzzese' carbonate platform and the 'Umbro-Marchigiano-Sabino' basin succession (Argnani & Gamberi, 1995; Cavinato et al., 1989). In particular, the Paterno slope lies north of the San

Vittorino plain, bordered to the north by the basin succession of the Reatini mountains and to the south by the carbonate platform succession of Mt. Nuria. A strong tectonic control influences the area due to three main tectonic lineaments: (i) the N/NE–S/SW trending Olevano-Antrodoco-Sibillini Mts. thrust (OAS) (Di Domenica et al., 2012; Capotorti & Chiarini, 2023), which makes part of the Ancona–Anzio line (*fault line auctt*., e.g., Parotto & Praturlon, 1975; Accordi et al., 1988) characterised by a low-angle and off-sequence thrust system (Cipollari & Cosentino, 1991); (ii) the Fiamignano–Micciani Fault (FMF), a NNW–SSE oriented and SW dipping transtensive fault during the Plio-Pleistocene (Centamore, Nisio, & Rossi, 2009) and (iii) the Antrodoco Fault (AF), a NW–SE striking normal fault (Capotorti, Fumanti, & Mariotti, 1995; Capotorti & Muraro, 2021). The FMF interrupts the OAS, renamed the Olevano–Micciani Line (OML) by Centamore & Nisio (2002), separating the Salto Unit and Mt. Navegna Unit.

One of the distinctive features of the San Vittorino plain is its triangular shape, controlled by normal and transtensional tectonic elements (Annunziatellis et al., 2008; Centamore, Nisio, & Rossi, 2004, 2009). It is placed at the intersection of five tectonic units, each distinguished by regional tectonic elements: Mts. Reatini-Sabini Unit, Mts. Navegna-S.Angelo-Micciani Unit, Salto Unit, Mts. Nuria-San Rocco Unit and Mts. Giano-Gabbia-Calvo Unit (Capotorti, Fumanti, & Mariotti, 1995; Centamore, Nisio, & Rossi, 2009; Di Domenica et al., 2014). These can be observed when moving from Mt. Terminillo towards the reliefs located SE, passing through Mt. Paterno (Figure 1).

1. The Mts. Reatini–Sabini Unit is characterised by the pelagic succession belonging to the Umbro–Marchigiano–Sabina basin (Lower Jurassic–Oligocene) and overlies the Navegna and Nuria Units through the Olevano-Antrodoco-Sibillini;
2. The Mts. Navegna–S.Angelo–Micciani Unit represents the north-western edge of the Cretaceous Laziale–Abruzzese platform domain, followed by Lower Messinian syn-orogenic siliciclastic turbidities. It is thrust over the Salto Unit through the Olevano–Micciani Line;
3. The Salto Unit is composed of meso-Cenozoic shallow-water carbonate deposits belonging to the Laziale–Abruzzese platform, bordered to the W by the Olevano–Micciani Line and to the E by the Fiamignano–Micciani Fault;
4. The Mts. Nuria–San Rocco Unit is the outermost tectonic element consisting of Mesozoic carbonate platform facies mainly NE dipping. It is bounded to the SW by the Fiamignano–Micciani Fault and to the NW by the Reatini Unit (Capotorti, Fumanti, & Mariotti, 1995; Centamore & Nisio, 2002; Centamore, Nisio, & Rossi, 2009);
5. The Mts. Giano–Gabbia-Calvo Unit represents the Laziale–Abruzzese carbonate domain (Upper Triassic-Upper Cretaceous), overlain by a Miocene ramp deposit. It is separated from the more internal Mt. Nuria sector of the Laziale–Abruzzese platform by the Antrodoco Fault (Capotorti & Chiarini, 2023; Capotorti & Muraro, 2021; Di Domenica et al., 2014).

After the accretion of the Apennine chain, continental fluvial-lacustrine sediments were deposited during the Pleistocene, filling the local tectonic depressions. These deposits, which belong to the 'PaleoFarfa Synthem' (Centamore & Dramis, 2010; Fubelli, Della Seta, & Amato, 2014), were subsequently affected by extensional tectonics, as along the Fiamignano–Micciani Fault (Figure 1).

Remnants of slope debris, breccias and ancient landslides are currently exposed in the study area and are linked to alternating temperate and arid/cold climates (Ricci Lucchi et al., 2000) and the consequent Quaternary river incision and deposition stages.

Groundwater represents one of the most important resources in the Velino Valley, supported by extensive recharge zones that feed the region's fractured aquifers (Petitta, 2009). Regional faults and folds have imposed a complex jointing system on the carbonate rocks hosting the large carbonate aquifers and facilitating karst processes. The Olevano–Antrodoco-Sibillini thrust marks the boundary between two distinct hydrogeological domains: the Latium–Abruzzi carbonate platform domain (Mts. Giano-Nuria) to the east and the Umbria–Marche–Sabina basinal domain (Mts. Reatini) to the west (Barberio et al., 2021). The groundwater flow path of the Mts. Giano–Nuria hydrogeological system feeds some springs located along the northern edge of the left bank of the San Vittorino plain, such as Peschiera Springs, that have a high discharge (18–20 m^3/s) and are partially captured to supply the city of Rome (Barberio et al., 2021; Martarelli et al., 2008). On the right bank, contributions to regional groundwater recharge also come from the Mt. Paterno ridge. The hydrogeological contact between the carbonate bedrock and the overlying Plio-Quaternary deposits controls the discharge of groundwater and locally affects the position and geochemical composition of springs on the San Vittorino plain (Bersani et al., 2000; Petitta, 2009; Petitta et al., 2003; Salvati & Sasowsky, 2002).

2.1 | Geomorphological evolution of the Middle Velino Valley

During the Pliocene, the area recorded a relative decrease in tectonic activity, followed by a slow and progressive regional uplift and concurrent areal erosion processes in semiarid climatic conditions (Centamore & Nisio, 2002). Thus, a widespread landscape with gentle reliefs developed. This is currently preserved by remnants of low relief paleosurface (Summit Surface; Demangeot, 1965) in the highest parts of the mountain sectors. During this interval, other relict surfaces were formed at lower elevations, enclosed in the Summit surface, and arranged at different heights, marking the stationing of the base level as shaped by uplift and erosive processes (Bosi & Messina, 1991; Centamore & Nisio, 2002; Centamore, Nisio, & Rossi, 2009).

The relict surface named as 'Fontanelle Surface' (FS) was distinguished in the study area (1200–1050 m a.s.l.) (Centamore & Nisio, 2002; Centamore, Nisio, & Rossi, 2009). Several studies (Bosi & Messina, 1991; Centamore & Nisio, 2002; Centamore, Nisio, & Rossi, 2009) interpreted the FS as the basal surface above which the PaleoFarfa Synthem deposition occurred in the Lower Pleistocene. In particular, the Fosso Canalicchio Unit (UFC) is composed of slope deposits lying on the relict surfaces (Barberi & Cavinato, 1993), developed during the Lower Villafranchian as a result of extensional activity (Centamore & Nisio, 2002). In this paper, we refer to the transition between the Late Pliocene and the Lower Pleistocene as the Villafranchian age, which is divided into Lower and Upper Villafranchian (Figure 2) (Centamore & Dramis, 2010).

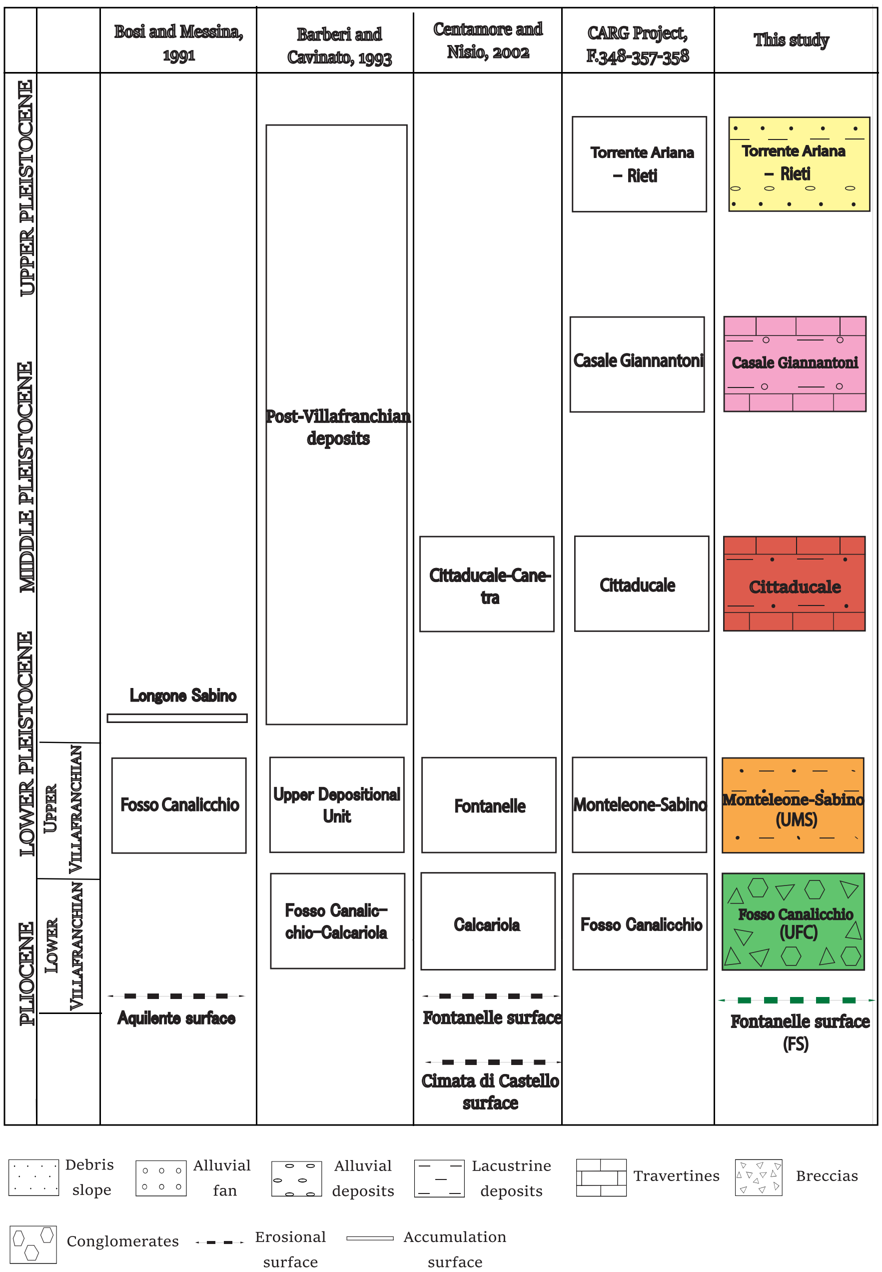

FIGURE 2 Comparison of the lithostratigraphic scheme for the Velino Valley starting from the Upper Pliocene with the principal stratigraphic subdivisions proposed in the previous literature and adopted in this study. The colours refer to the geological units of Figure 3.

The Fosso Canalicchio deposits are interbedded in several levels within an alluvial fan (Barberi et al., 1995), which outcrops in different locations, for example, Mt. Giano (1300–1200 m a.s.l.), Paterno (800–700 m a.s.l.), and Calcariola ridges (700–600 m a.s.l.) (Bigi et al., 1995; Capotorti et al., 1991; Capotorti & Muraro, 2021; Centamore & Dramis, 2010; Centamore & Nisio, 2002; Cosentino et al., 2008). During the Upper Villafranchian, fluvial deposits belonging to the Monteleone Sabino Unit (UMS) were developed in a braidplain system during a relative tectonic quiescence and deposited above the Fosso Canalicchio and the Cenciara Unit (Barberi & Cavinato, 1993; Centamore & Nisio, 2003; Cosentino et al., 2008). These deposits are widely exposed near Calcariola (700–780 m a.s.l.) and Cittaducale (500–550 m a.s.l.) (Figure 3). Uplift and extensional tectonic led to the incision of the Velino Valley, promoting the formation of narrow and deep valleys. V-shaped valleys are typical of strong linear erosion processes that carved both pre-orogenesis units and Plio–Pleistocene successions (Cavinato, 1993; Centamore & Nisio, 2003; Centamore, Nisio, & Rossi, 2004). The post-Villafranchian units filled the valley with talus, debris, alluvial fan deposits and travertine lenses, widely exposed on the right slope of the valley (Figures 2 and 3) (Bersani et al., 2000; Centamore & Nisio, 2002). Several studies (e.g., Carrara et al., 1992; Michetti et al., 1995; Petitta, 2009; Ricci Lucchi et al., 2000) testified four orders of fluvial-lacustrine terraces in the study area, located at different heights above the present floodplain caused by the interaction between alternating cold/temperate climate phases and valley deepening induced by tectonic uplift. From the most ancient to the most recent, the terraced deposits pertain to the Torrente Ariana and Rieti Synthems (Upper Pleistocene), Giannantoni Synthem (Upper-Middle Pleistocene) and Cittaducale Synthem (Middle Pleistocene) (Figure 2) (Barberi & Cavinato, 1993; Bosi & Messina, 1991; Capotorti & Chiarini, 2023; Centamore & Dramis, 2010; Centamore & Nisio, 2002; Cosentino et al., 2008). Geophysical and gravimetric surveys conducted along the San Vittorino plain to identify sinkhole hazard areas indicate that the filling sediments are likely to have a thickness of up to 200 m (Di Filippo et al., 2004; Faccenna et al., 1993).

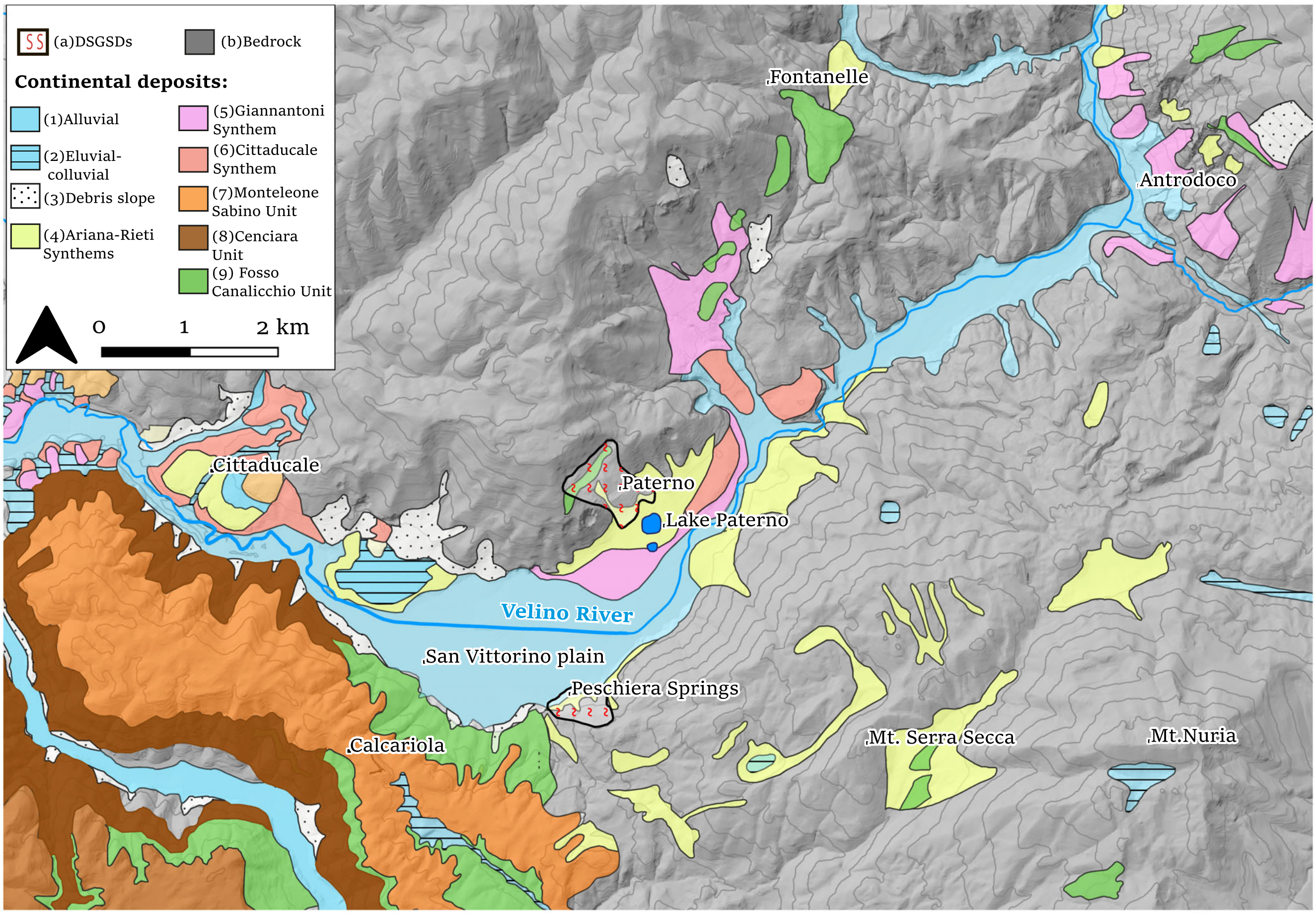

FIGURE 3 Distribution of Pleistocene deposits in the Velino Valley and their relationship with the Paterno DSGSD. (a) Paterno and Peschiera DSGSDs; (b) bedrock; continental deposits: (1) alluvial (Holocene): (2) eluvial–colluvial (Holocene), (3) debris slope (Holocene); (4) Ariana and Rieti Synthems (Upper Pleistocene); (5) Giannantoni Synthem (Upper–Middle Pleistocene); (6) Cittaducale Synthem (Middle Pleistocene); (7) Monteleone-Sabino Unit (Upper Villafranchian); (8) Cenciara Unit (Lower Pleistocene); (9) Fosso Canalicchio Unit (Lower Villafranchian).

Existing landslides databases, such as IFFI (*Inventario Fenomeni Franosi Italiani;* Trigila, Iadanza, & Spizzichino, 2010) and PAI (*Piano di Assetto Idrogeologico)*, document the distribution of DSGSDs affecting this sector of the San Vittorino plain (Figure 4) (Casini et al., 2006; Fiorucci et al., 2017; Lenti et al., 2012;Maffei, Martino, & Prestininzi, 2005; Martino & Prestininzi, 2004). DSGSDs are observed at the Paterno and the Peschiera sites, whereas shallow landslides and corollary features of deep-seated deformation processes are widespread throughout the study area (Figure 4).

Morphogenetic processes exhibit a close connection between the hydrographic right and left sides of the Velino Valley (Maffei, Martino, & Prestininzi, 2005; Martino & Prestininzi, 2004), as shown in Figure 5. Both valley flanks host numerous cavities, including dolines aligned with the primary tectonic lines and piping sinkholes, contributing to the overall instability of the area. These karst processes directly pervade the carbonate bedrock, as stated by the karst dolines, caused by the gradual dissolution processes and the roof collapse of smaller sinkholes, genetically linked to piping or dissolution processes operated by the deep fluids rising along faults during hypogenic karstic processes. Such features characterise the Velino Valley floor, as in the case of Lake Paterno (Figure 5a) (Barberio et al., 2021; Salvati & Sasowsky, 2002). In particular, dolines are considerably abundant on the hydrographic left slope, where the Peschiera Springs are situated (Figure 5), revealing the valley's hydrogeological flow pattern. Nevertheless, signs of water circulation can also be observed on the hydrographic right side, notably along the Paterno slope, through the Baths of Titus (Roman age). Archaeological investigations (McCallum et al., 2019; Payne, 2023) revealed that this site was not just a bathhouse but part of a much larger complex, probably with residential and public functions.

2.1.1 | Main features of the Paterno DSGSD

In the previous PAI maps (https://aubac.it/piani-di-bacino/piani-di-assetto-idrogeologico), the Paterno DSGSD was indicated as active, with a high hazard level (P3) and a high risk (R4). The study area (Figure 6a) also features several sinkholes (Figure 6b,c) and landslides, which express the multiple hazards affecting the area and the intense activity in the plain (Figure 4). The Paterno slope shows many of the typical morphologies of a DSGSD. The slope has an elevation spanning from a maximum of about 1020 m a.s.l. to a minimum of about 420 m a.s.l. and a SE exposure. The top of the slope has a flat/low-angle morphology. Here, a remnant of the FS was mapped by previous authors (Centamore & Nisio, 2002; Centamore, Nisio, & Rossi, 2009) (Figure 6d). Starting from the top of the slope, a steep and circular-shaped scarp of a relict mass movement, extending for about 200 m, is present (Figure 6c). At the base of the scarp, a main counterslope

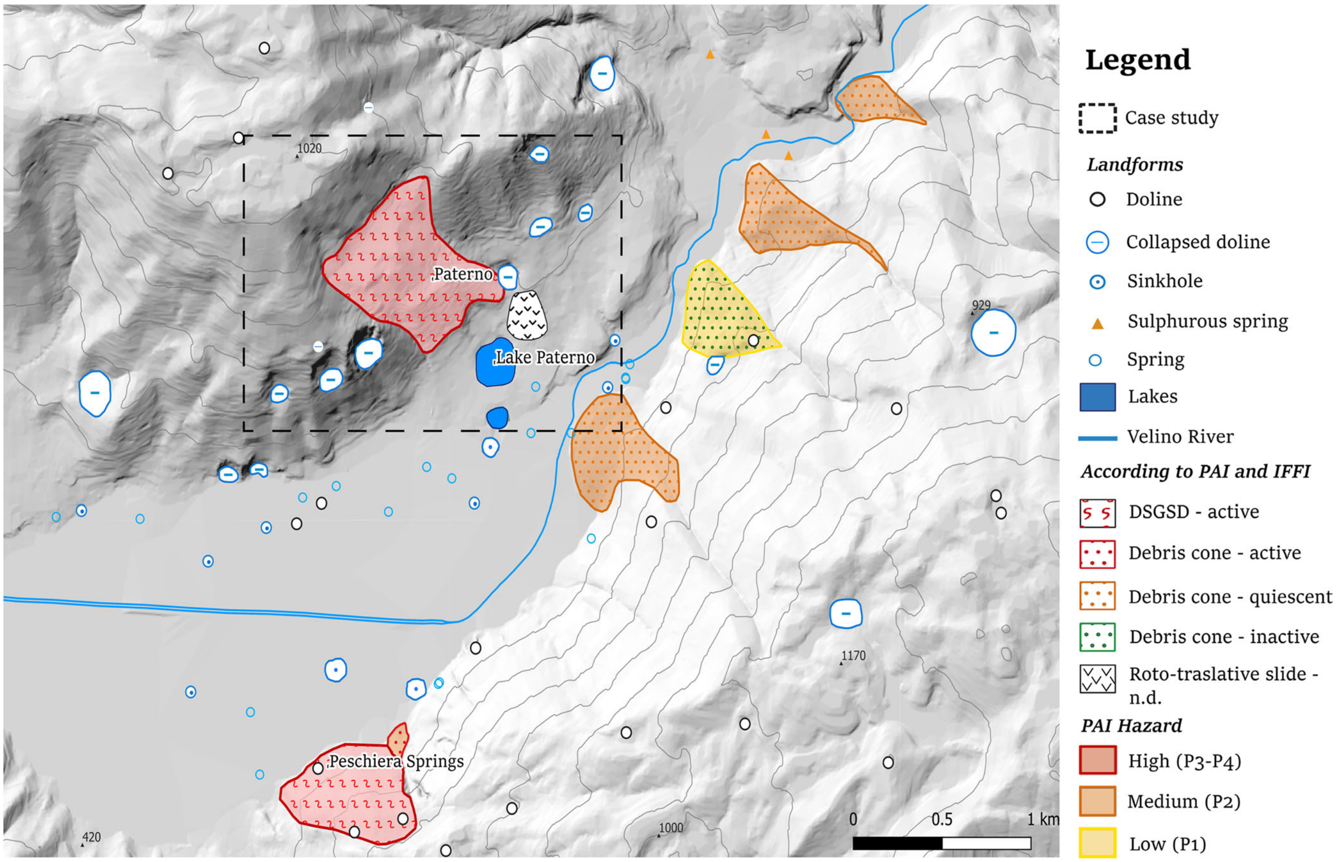

FIGURE 4 Main geomorphological features of the Velino Valley, indicating the distribution and activity of landslides identified in the IFFI and previous version of the PAI inventories. It also shows some landforms, predominantly in the San Vittorino plain, as reported by Centamore, Nisio, & Rossi (2009).

inclined morphological terrace can be recognised. Here, continental cemented breccias crop out backtilted (Figure 6c).

Downslope, a minor terrace is present at 630 m a.s.l., where the Paterno Village stands out (Figure 6c). The slope foot shows a convex profile, with a corollary of smaller landslides.

From a structural point of view, two tectonic units can be found along the slope, separated by the sub-horizontal Olevano–Antrodoco-Sibillini thrust zone, which outcrops at around 850 m a.s.l. The upper sector includes the Reatini Unit, consisting of an overturned succession of Scaglia Detritica and Scaglia Cinerea Detritica formations, that present mesostructures, such as fabric S/C foliations and secondary tectonic lines, observed in proximity to the DSDSG scarp (Figure 7a). The Mt. Nuria Unit delimits the footwall of the thrust that comprises the geological formations of the Marly Argillaceous Unit (Tortonian) (Figure 7d) in contact with the Reatini Unit along the thrust, and the Bryozoan and Lithothamnion Limestone Formation (Burdigalian–Serravallian) (Figure 7b) (Centamore & Nisio, 2002; Centamore, Nisio, & Rossi, 2009; Civitelli & Brandano, 2005).

The slope is also affected by multiple extensional and trans-tensional faults perpendicular to the slope direction, contributing to the high degree of fracturing of the local carbonate rocks. Two high-angle normal faults mark the lateral boundaries of the DSGSD, which extends for more than 300 m in length, leading to the crushed rock conditions near the thrust zone. A complex network of joints is also evident near the main scarps of the Paterno DSGSD and in the Paterno Village, where Jv (Joint Volumetric count) exceeds 70 and Ib (Block size Index) is less than 20 values, as revealed through a geomechanical survey. The lowermost sector of the slope is covered by alluvial deposits belonging to the Rieti Synthem (Figure 7c), which outcrops at an elevation of 500 m to 430 m a.s.l. (Figure 8).

3 | MATERIALS AND METHODS

A combination of field, geomorphological, remote sensing and laboratory analyses was carried out to understand the role that the morphodynamics of the Velino Valley during the Quaternary played in the history and gravity-induced evolution of the Paterno slope and its current state of activity.

3.1 | Geological surveys and geomorphological analyses

We investigated the middle Velino Valley through a review of the relevant literature (Capotorti & Chiarini, 2023; Centamore & Dramis, 2010; Cosentino et al., 2008) and maps (Geological Map Sheets 348 - Antrodoco, 357 - Cittaducale, and 358 - Pescorocchiano at 1:50,000 scale, produced by Servizio Geologico d'Italia - CARG Project 2008, 2010, and 2022) (Figure 2). Reliance was mostly made on geological and geomorphological surveys of the Paterno DSGSD and morphometric analyses along the San Vittorino plain. We used a 5 × 5 m Digital Elevation Model (DEM) to identify optically diagnostic landforms supporting the reconstruction of the Villafranchian

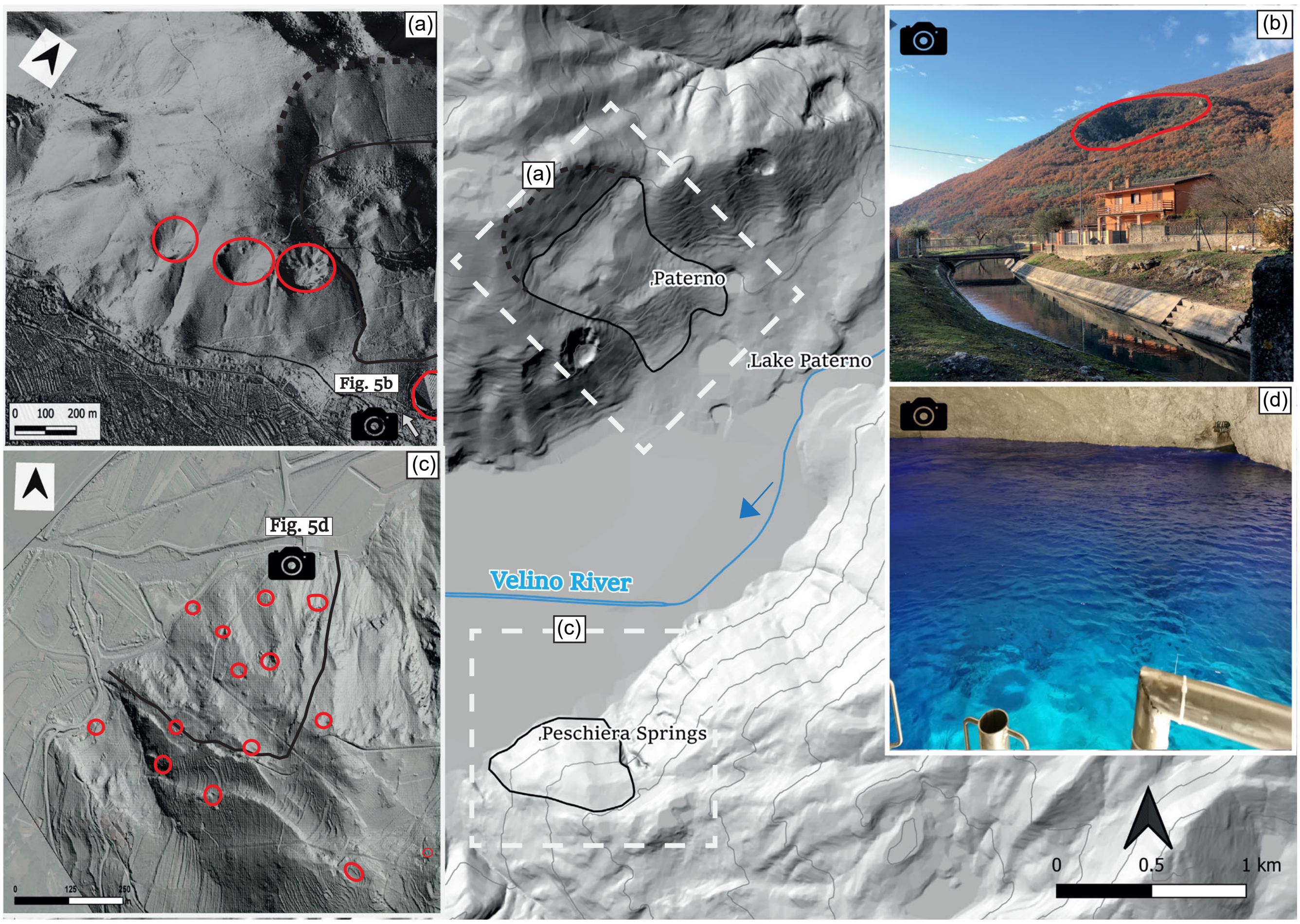

FIGURE 5 Parallelism between karstic landforms on the Peschiera and Paterno DSGSD. (a) Aerial photo of the Paterno DSGSD with the main geomorphological elements, such as scarp (grey), aligned dolines and Lake Paterno (red); the white arrow indicates the direction of the picture 5b; (b) View of a doline from the Velino River; (c) Aerial photo of the Peschiera DSGSD with diffused dolines; (d) Underground picture with presence of water within the dolines, indicative of hydraulic activity.

morphoevolution of the area, as well as to infer indicators of gravity-induced slope deformation processes. We focused on geological and geomorphological surveys of the Paterno slope, covering an area of about 3 km^2. The criteria adopted for the surveys involved an initial recognition and description of the local geological units to identify the bedrock formations and the marly–argillaceous unit. The observation of geomorphological indicators, including scarps, terraces, and sinkholes, was conducted across the middle Velino Valley, beyond the Paterno slope. This geomorphological analysis facilitated a comparison of morphogenetic processes on both sides of the valley and the identification of karst features at various stages of development.

Morphometric datasets and satellite images, collected by Sentinel-1 and Cosmo-SkyMed datasets, allowed to preliminarily identify and interpret the local landforms (i.e., main scarps, secondary scarps, landslides, dolines and relict flat surfaces), and possibly verify them in the field. Then, geological sections focused on Quaternary deposits and traced parallel and perpendicular to the Velino Valley direction. These sections represent the outcrops of FS, UFC, and UMS Villafranchian continental deposits. The analysis aims to identify spatial correlations among the various outcrops and assess the Villafranchian morphodynamics of the Velino Valley using geomorphological indicators from the Paterno DSGSD, taking into account the role of tectonic elements. Breccia outcrops and relict surfaces served as key indicators of geomorphic anomalies in the landscape reconstruction of the middle Velino Valley, following a similar approach to the analysis of knick points by Della Seta et al. (2017), who integrated the spatial analysis of knick points and relict surface, according to Troiani et al. (2014), to detect stream profile anomalies potentially related to tectonic-driven base-level changes in the Central Apennines.

However, this study further integrates this analysis with laboratory investigations, offering a more comprehensive perspective. An average elevation was assigned to each outcrop of the Villafranchian units (UFC, UMS) by using the zonal statistics tool of QGIS and the elevations previously identified in the relevant literature (Capotorti & Chiarini, 2023; Centamore & Dramis, 2010; Centamore & Nisio, 2002; Cosentino et al., 2008). In this regard, we looked for fluvial-lacustrine terraces and relict flat surfaces of similar elevation on the hydrographic right and left of the valley to determine whether the depositional units analysed correspond to similar elevations in the valley or have been influenced by active forces such as tectonics, fluvial erosion or gravitational processes. We interpolated the basal contact between the FS and the UFC, as well as the upper contact with the UMS along the Fiamignano–Micciani Fault, to understand the activity and role of this fault during the Quaternary. These analyses were aimed at reconstructing the Villafranchian landscape of the San

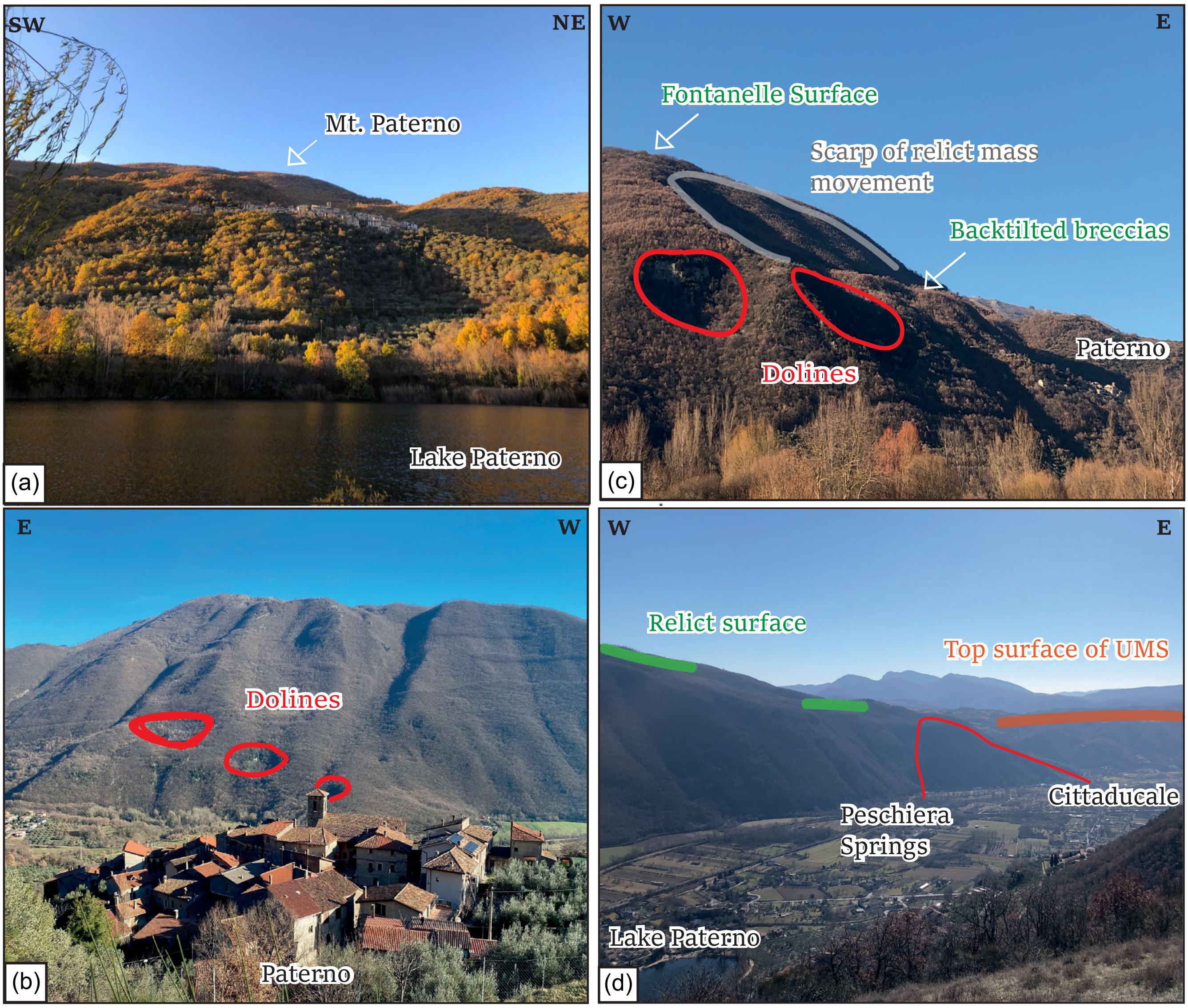

FIGURE 6 Geomorphological features: (a) front view of the Paterno DSGSD; (b) dolines on the opposite slope; (c) location of the Fontanelle Surface with the scarp and the back-tilted breccias, and evidence of dolines (highlighted in red); (d) the Velino Valley with the extension of the relict surface, UMS top surface, and the Peschiera DSGSD.

Vittorino plain, namely the influence of the Fiamignano–Micciani Fault and a sharp change to cold-arid climatic conditions (Centamore & Nisio, 2002).

Furthermore, several outcrops of slope breccias and geomorphological indicators (i.e., ridge-top depression, minor scarps) were observed on the Paterno slope (Figure 9). In order to determine whether these deposits were indicative of gravitative processes, we carried out thorough investigations on their outcrops, both macroscopically and in thin sections.

3.2 | Thin section analyses

During the geological surveys, six samples of breccias (average size: 5·8·3 cm) were collected for thin sections. Breccia outcrops are widespread on the slope and represent important markers for morphoevolutionary interpretations. Their sampling was important to understand their diagenetic conditions and infer elements supporting their involvement in gravitational processes. Sanders, Ortner, & Pomella (2018) analysed breccias both in the field and in thin sections to identify distinct pulses of clast fracturing, which were interpreted as evidence of multi-phase deformation of the talus succession. Similarly, Karkani et al. (2023) used thin-section analysis to study beachrocks as indicators of sea level changes. Their findings emphasise that the cement mineralogy and morphology of beachrocks provide valuable insights into the diagenetic environment.

In this study, samples were taken along the slope profile in three sectors (Figure 9): (i) at the top of Mt. Paterno (B04, Figure 9a) with the FS shown in Figure 9b (Centamore & Nisio, 2002), (ii) on the scarp (B03, Figure 9c) near Mt. Paterno, (iii) on the counterslope surface (B01, Figure 9d), where the UFC outcrops (Centamore & Dramis, 2010). Thin sections were observed in plane-polarised light, under crossed nicols, and with crossed nicols plus dark-field illumination to identify their main components and textural and diagenetic features. The thin sections were classified according to Dunham (1962) and Embry & Klovan (1971) for components larger than 2 mm.

In each area, we collected two–three representative samples, on which thin section analysis was carried out. The purpose of the

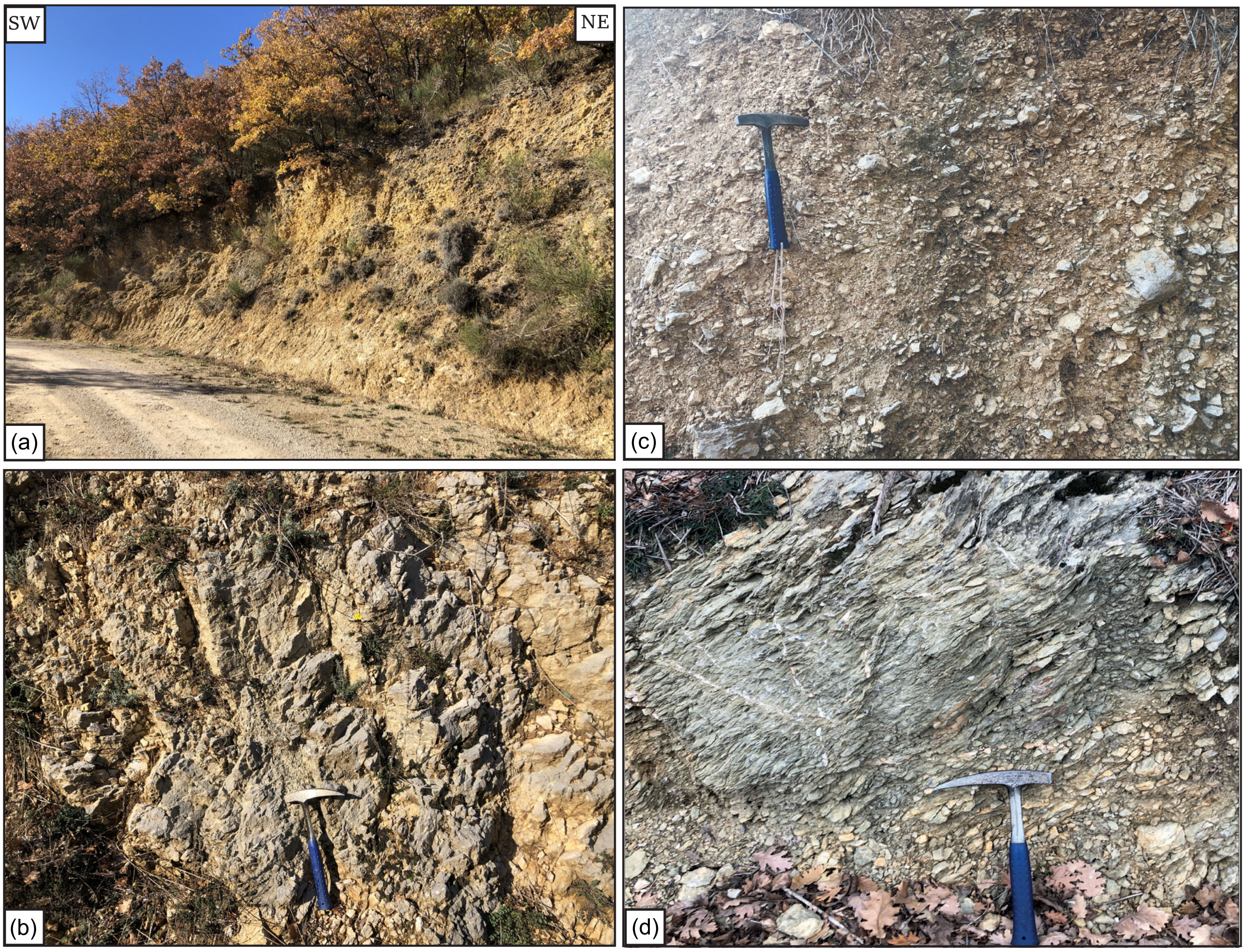

FIGURE 7 Geological features: (a) DSGSD scarp; (b) outcrops of Bryozoan and Lithothamnion Limestone Formation; (c) Rieti Synthem; and (d) outcrops of Marly Argillaceous Unit. Their location on the Paterno slope is shown in Figure 8.

analysis was to document the diagenesis of these breccias by examining their clast fabrics, degree of cementing, and interstitial matrix. The distinction between talus and fault breccias was the first step to understanding the morphoevolution of the Paterno slope. Then, B03 and B04 breccias were compared with those belonging to the UFC (B01). The comparison was intended to reveal whether the deposits were synchronous with each other and to possibly identify fragmentation processes potentially related to the displacement of the UFC breccias.

3.3 | Satellite interferometry

Satellite interferometry analysis was carried out to characterise the state of activity and velocity of slope deformation processes and evaluate its associated level of hazard for regulatory purposes. We identified two stacks of Satellite Synthetic Aperture Radar (SAR) images for conducting interferometric analyses. The latter were performed via Persistent Scatterer Interferometry (PSI) (Ferretti, Prati, & Rocca, 2001). This technique analyses the spatial and temporal evolution of slope instabilities, in particular DSGSDs, which are characterised by low velocities (Antonielli et al., 2019; Cignetti et al., 2023). SAR techniques detect ground deformation velocity along the Line of Sight (LOS) of the satellite.

In the Lazio Region, PAI hazard levels range from P1 (Moderate) to P4 (Very High), covering approximately 15% of the regional territory. Interferometric data enable the identification of active deformation areas, supporting an updated assessment and reclassification of state of activity and, consequently, of hazard levels within the official cartographic products (Marmoni et al., 2025).

The datasets available for the selected area derive from the Sentinel-1 (S1) constellation and were acquired between February 2017 and June 2022. Additional Cosmo–SkyMed (CSK) images were analysed during the observation period from February 2017 to June 2022, guaranteeing a higher PSI density. More in detail, the ascending orbital was available for S1 and the descending orbital was employed for CSK. We considered a stable region when the velocities ranged from ±1.5 (CSK) and ±2 mm/year (S1).

4 | RESULTS

4.1 | Distribution of the UFC deposits and the FS remnants

Field surveys and geomorphological analyses highlighted the distribution of the UFC outcrops with the extension of the FS. The UFC

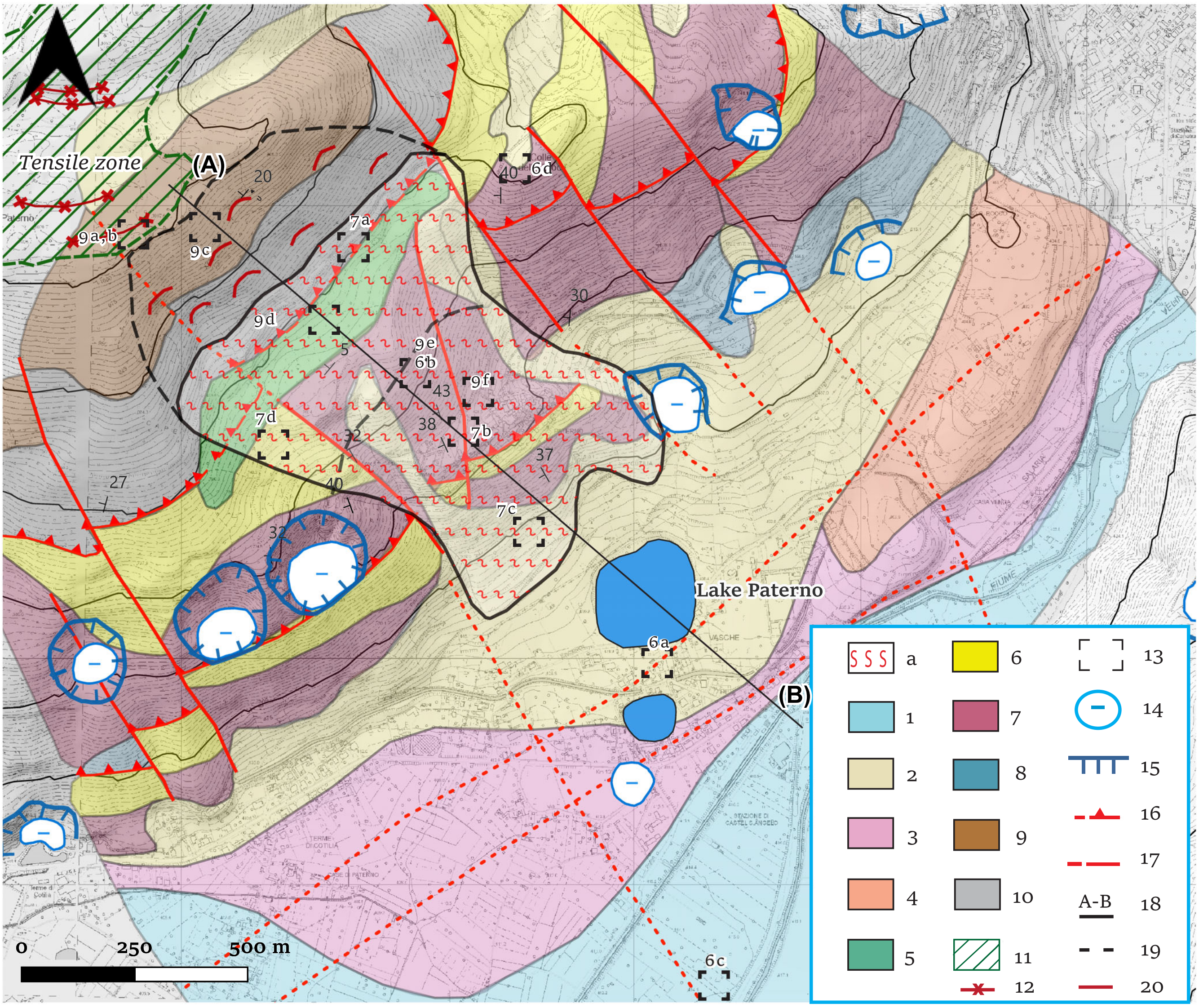

FIGURE 8 Geological map of the Paterno slope: (a) Paterno DSGSD; (1) alluvial deposits (Holocene); (2) Rieti Synthem (Upper Pleistocene); (3) Giannantoni Synthem (Upper–Middle Pleistocene); (4) Cittaducale Synthem (Middle Pleistocene); (5) Fosso Canalicchio Unit (Lower Villafranchian); (6) Marly–Argillaceous Unit (Tortonian); (7) Bryozoan and Lithothamnion Limestone Formation (Langhian–Serravallian); (8) Radiolidit Limestone (Turonian-Santonian); (9) Scaglia Detritica Formation (Cenomanian-Lutetian); (10) Scaglia Cinerea Detritica (Lutetian-Aquitanian); (11) Fontanelle Surface; (12) ridge-top depression; (13) field figure box; 14) main karst landforms; (15) doline scarp; (16) thrust; (17) normal fault (dashed if inferred or buried); (18) trace A-B; (19) relict and secondary scarps; and (20) minor scarps.

outcrops are located at different elevations along the middle Velino Valley flanks, from the villages of Antrodoco to the north and Calcariola to the south. Along the Velino Valley, the UFC outcrops generally have limited extension (450 m) and are less than 10 m thick. Southwards from Calcariola, these deposits reach a maximum thickness of 220 m.

A map of the UFC outcrops and the other Villafranchian deposits is shown in Figure 10. Their elevation range can be seen in sections C-C′-D and E-F (Figure 11). Regarding the FS, its lateral continuity is not well preserved in the study area. Thus, its original extension was inferred by connecting the preserved remnants, which occur on the right flank of the middle Velino Valley, at elevations of 1068 m a.s.l., at Fontanelle and 1019 m a.s.l., at Mt. Paterno and, on its left flank, at elevations of 1000 m to 1170 m a.s.l. As indicated in Figure 2, the UFC base is supposed to have been deposited, in stratigraphic continuity on the FS during the Upper Villafranchian (Bosi & Messina, 1991; Centamore & Nisio, 2002). Therefore, the UFC deposits are expected to outcrop at an elevation slightly higher than that of the nearest FS remnant. However, geomorphological surveys and analyses allowed to identify several UFC outcrops located at elevations lower than FS (Figure 11). In particular, the interpolation of the remnants of the FS resulted in a low-angle SW dipping surface, which shows an abrupt change close to the Fiamignano–Micciani Fault, beyond which the FS is not visible because it is covered by hundreds of metres of the UFC deposits, in the Calcariola area. The distribution of elevations of the UFC outcrops in the study area revealed a gradual decrease of their mean elevation, from Antrodoco (1300 m a.s.l.) on the NE to Calcariola (420 m a.s.l.) on the SW (Figure 10). The main segment of the trace is C′-D, oriented parallel to the Velino River, to which the C-C′ trace (EW oriented) was also projected. Notably, from C to C′, the UFC deposits show to be at the same, or higher, elevations than the Fontanelle remnants. This finding is consistent

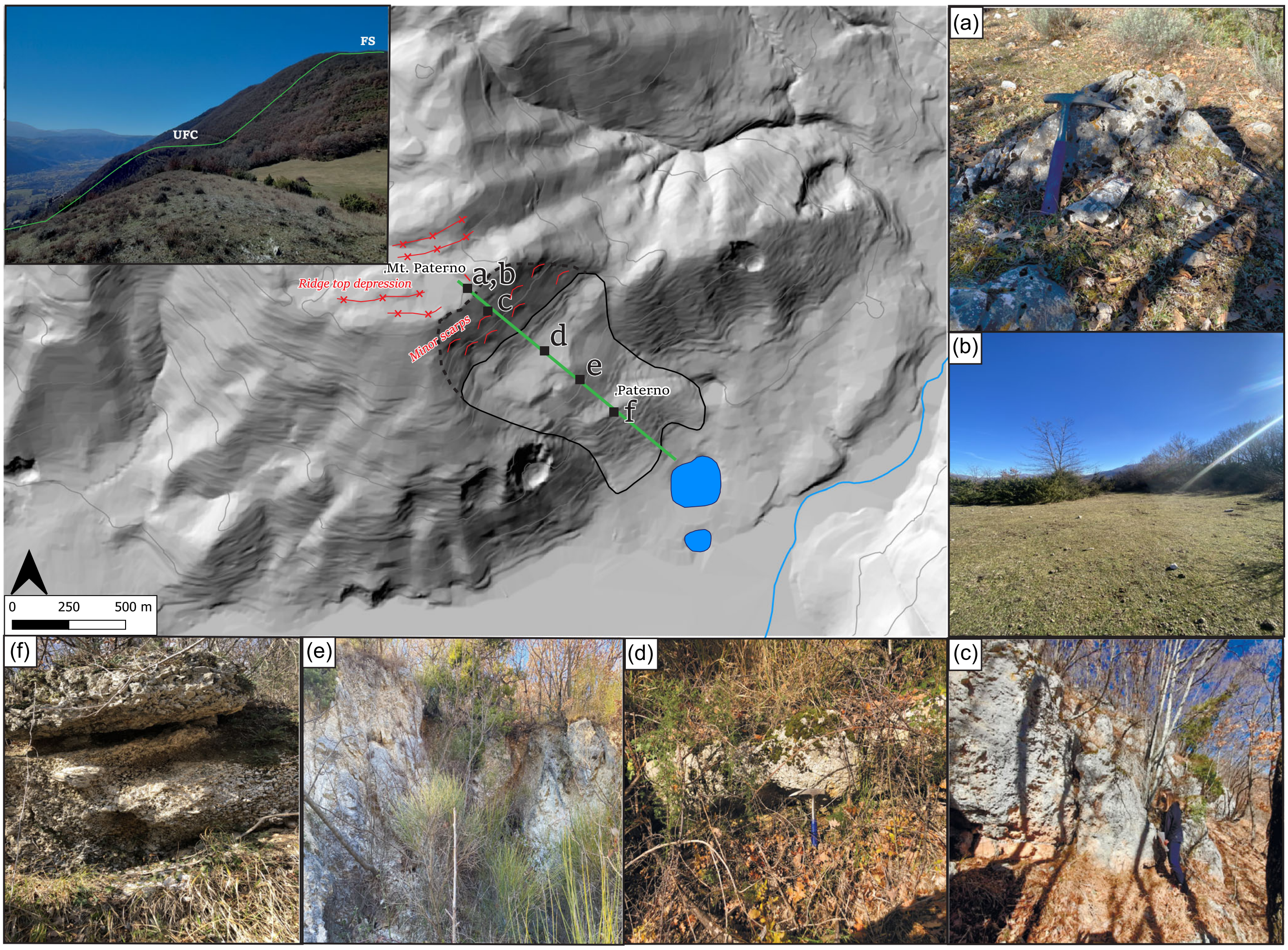

FIGURE 9 Panoramic view of the Paterno slope (point of view from NE to SW). The boxes indicate the outcrops of breccia bodies at various heights along the slope, from Mt. Paterno to its village: (a) Fontanelle Surface outcrop with B04 breccia sample; (b) Fontanelle Surface; (c) high scarp with B03 breccia sample, (d) UFC outcrop counterslope with B01 sample; (e) evidence of a secondary high scarp; and (f) slope breccia bodies. All outcrops reported in these boxes are aligned along the green topographic profile shown in the upper-left box.

with the regional contact between these two elements, as reported in the literature (Bosi & Messina, 1991; Centamore & Nisio, 2002). Nevertheless, section C-C′-D indicated several sites where the UFC basal deposits are at lower elevations than the FS (Figure 11). The lack of a stratigraphic contact between the UFC deposits and the FS was ascribed to post-Villafranchian landslides, which occurred as a result of the gradual deepening of the Velino Valley in the Quaternary (Centamore & Nisio, 2002).

Near Calcariola, on the footwall of the Fiamignano-Micciani Fault, the base of UFC does not outcrop. Therefore, the Fontanelle remnants are not visible. Only the top of the UFC deposits outcrops, highlighting their contact with the upper UMS unit. Here, the UMS base is located at about 650 m a.s.l. (Figure 11). The significant variation in thickness and elevation of the base of the UFC, from the footwall to the hanging wall sectors of the fault, reveals that it was active in the Villafranchian and during the deposition of the UFC. The activity of the fault created accommodation space at the hanging wall, filled by UFC and the accumulation of the upper UMS deposits. According to our reconstruction, this fault displaced the geological boundary between the UFC and the UMS by 600 m, thereby increasing the thickness of the two Villafranchian units in the footwall compared to the hanging wall. Here, the UFC is more than 200 m thick, whereas the UMS is around 100 m. Conversely, in the footwall, the UFC deposits are only a few metres thick, and the UMS is missing.

4.2 | Detailed features of the Paterno slope instability

On the top of Mt. Paterno, remnants of the Fontanelle Surface have been reported at an elevation of 1000 m a.s.l. (Centamore & Nisio, 2002) (Figure 10). During the geological surveys, trenches, ridge-top depression, minor scarps and karst features are observed on the tensile zone of the Mt. Paterno, and UFC outcrops are also revealed present at significantly lower elevation on the counterslope morphological terrace at 780 m a.s.l (Figure 9d). This surface lies at the basis of the main morphological scarp of the Paterno DSGSD (Figure 7a), reported by PAI maps, indicating that the UFC breccias were vertically displaced for more than 200 m (from 1000 to 780 m a.s.l.) from the tensile zone on the Mt. Paterno. Nevertheless, field surveys showed that across both flanks of the Paterno DSGSD, the limits of the bedrock formation are slightly displaced by the DSGSD (Figure 12). In particular, we estimated a vertical displacement of approximately 20 m for the DSGSD along these two lines, significantly lower than 200 m.

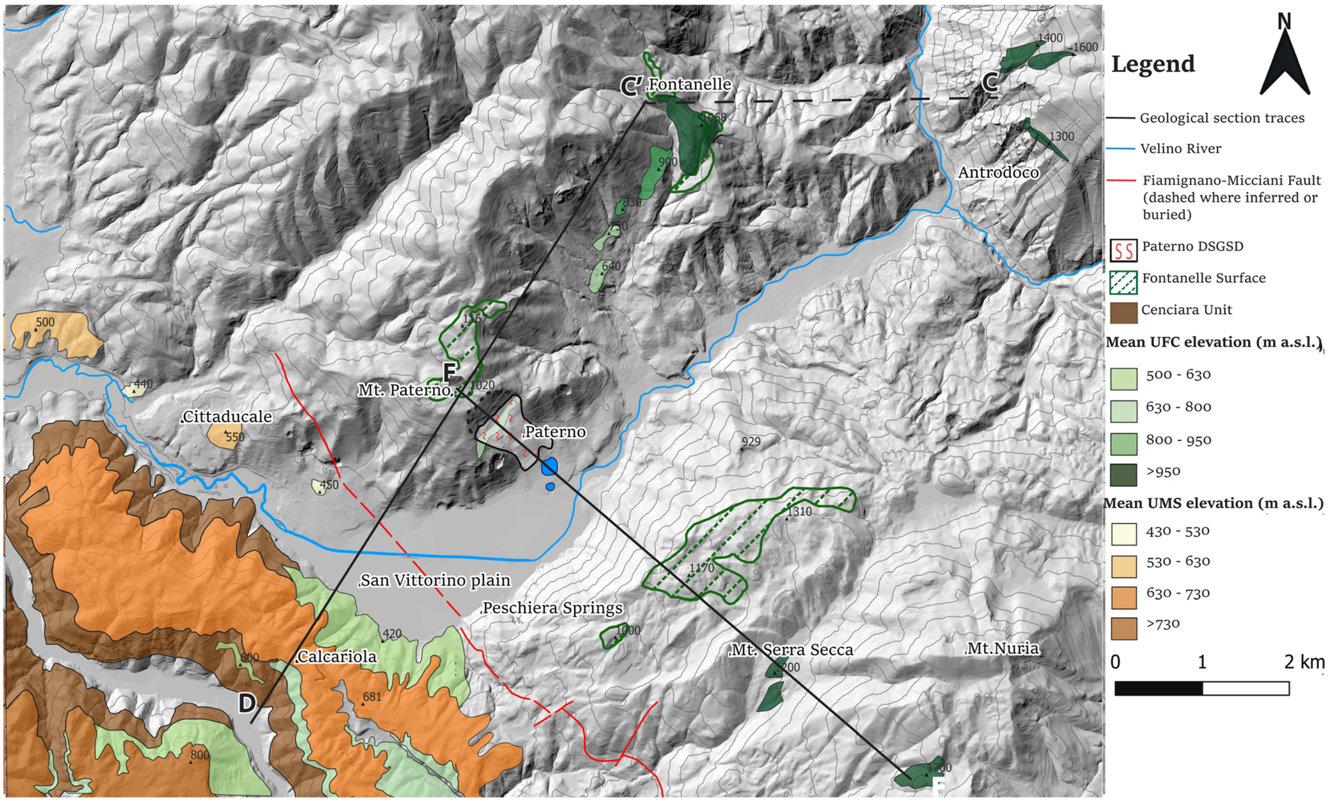

FIGURE 10 Scheme of the Villafranchian units of Fosso Canalicchio and Monteleone Sabino in the Velino Valley, from Antrodoco to Calcariola. The colour tone refers to the mean elevation of the different outcrops, which decreases along the flow direction. Elevations of the UFC and UMS deposits and the FS are also shown. The first segment of the trace C-C′ (dashed line) cuts across the Velino Valley to reach the UFC outcrops near the Antrodoco Village.

In the footslope area, shallow landslide deposits and talus debris are included in the Rieti Synthem, but no evidence of DSGSD related slope movements or internal deformation structures was found in the footslope area.

Distinct karst processes are observed along the slope, as hypogenic with collapse dolines aligned along the main faults of Paterno (Figure 6c) and sinkholes as Lake Paterno (Figure 6a), and epigenic on the Mt. Paterno, where minor scarps, trenches and shallow depressions are identified. The strong relationship between tectonics and karst processes is highlighted by the subsidence of the Lake Paterno basin, which sank by approximately 5–7.5 m following the Avezzano earthquake in 1915 (Bersani et al., 2000).

Nowadays, there is no evidence of the Paterno DSGSD activity, as testified by field surveys and InSAR analyses, which showed no cracks on buildings or other signs of active deformation (Frattini, Crosta, & Allievi, 2013). The dataset that we analysed, consisting of Sentinel-1 and COSMO–SkyMed images, indicated the absence of active displacements in Paterno Village. However, during the observation period, spot deformations were identified in the Velino Valley floor near sinkholes (Figure 13).

4.3 | Thin section results

Breccia outcrops are shown in Figure 13. During the surveys, we collected samples of breccias in three different sites, located on the FS (B04, Figure 14a), on the main scarp (B03, Figure 14b) and on the counterslope surface (B01, Figure 14c). The thin sections showed important features of the samples (B01, B03, B04) integrating our morphoevolutionary reconstruction of the study area.

4.3.1 | B01 sample

This section identifies a polygenic, poorly sorted breccia made of angular to subangular, millimetric to centimetric clasts (Figure 14a) belonging to UFC. The most abundant clasts are wackestones with planktonic foraminifera (Figure 14b,c) belonging to the Scaglia formations. Other clasts consist of packstones containing small bioclastic fragments of molluscs or echinoids. Lastly, one clast consists of a fragmented red algae nodule, while in another, a large benthic foraminifer (*Lepidocyclina*) test and a bryozoan are identifiable. The latter clasts belong to the coarse, resedimented rudstones and breccias that are common within the Scaglia Detritica formation outcropping in the study area.

Different sets of fractures, filled with calcite cement, occur within the clasts. The boundaries of these cemented fractures are sharp and clearly coincide with the clasts in which the fractures developed. This is clear evidence of fracturing of the clasts prior to brecciation. Microcrystalline vadose cement overgrows the bottom edges of the clasts, while meniscus cement is evident between the main clasts. Red oxides, likely Fe-rich, are common in the main voids.

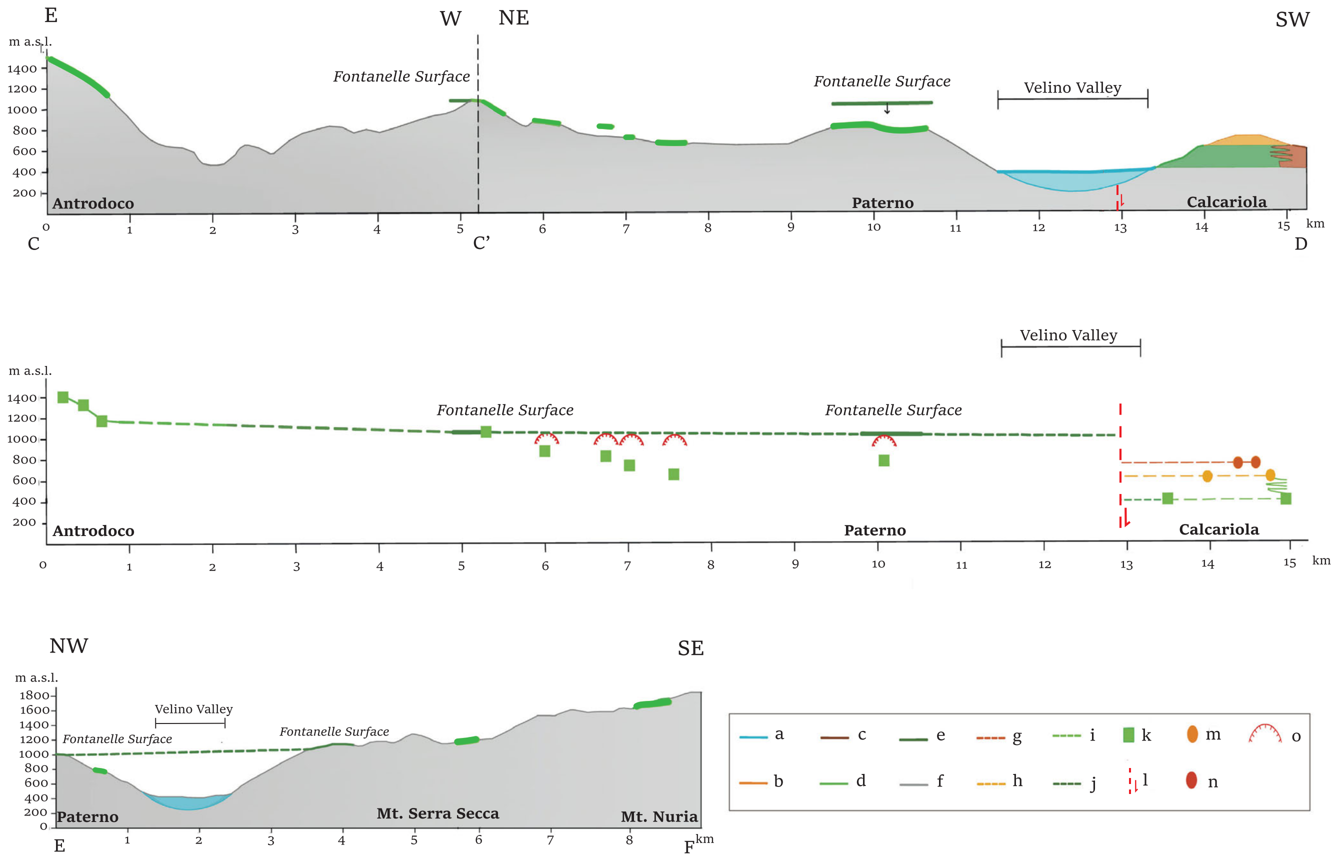

FIGURE 11 Distribution of FS, UFC, UMS along the traces C-C′- D and E-F′, shown in Figure 10: (a) alluvial deposits (Holocene); (b) extension of UMS deposits (Upper Villafranchian); (c) extension of Cenciara Unit deposits (Lower Villafranchian); (d) extension of UFC deposits (Lower Villafranchian); (e) FS; (f) bedrock; (g) supposed top of the UMS; (h) supposed base of the UMS; (i) supposed base of the UFC; (j) supposed original level of the FS; (k) outcrop of the base of the UFC; (l) Fiamignano–Micciani Fault; (m) outcrop of the base of the UMS: (n) outcrop of the top of the UMS; and (o) landslide scarp.

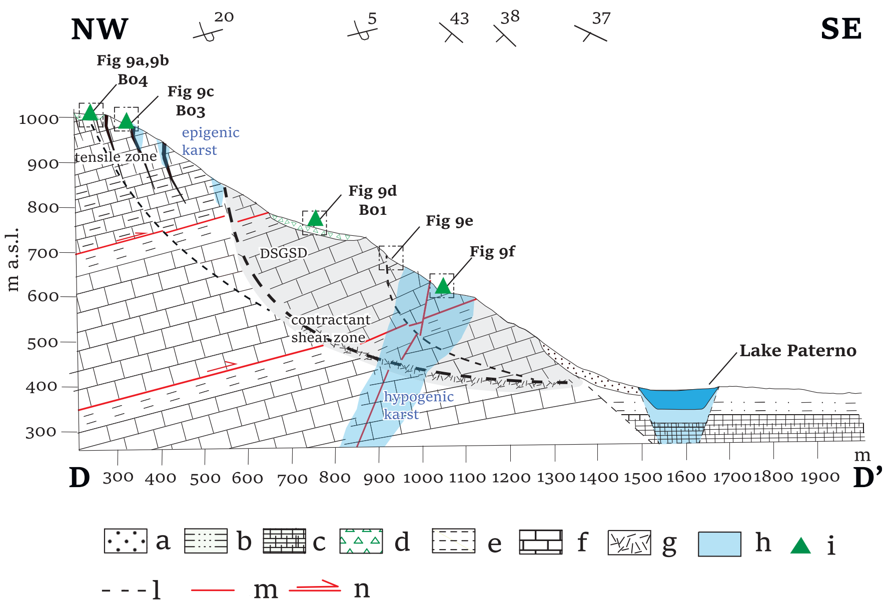

FIGURE 12 Geological cross-section representing the Paterno DSGSD: (a) debris slope; (b) Quaternary alluvial deposits; (c) Travertines with karst processes; (d) outcrop of the Fosso Canalicchio Unit; (e) outcrop of the Marly Argillaceous Unit; (f) outcrop of the Bryozoan and Lithothamnion Limestone Formation; (g) deformation band; (h) karst processes, (i) breccia outcrop; (l) secondary sliding surface; (m) normal fault; (n) thrust.

4.3.2 | B03 sample

Common clasts of the B03 thin section are wackestones with planktonic foraminifera; others are packstones with densely packed, highly fragmented bioclasts, among which mollusc fragments are identifiable, likely belonging to the Scaglia Detritica formation. The biggest clasts are highly fractured and filled with cement (Figure 14d,e). The fractures end with sharp edges at the boundary of the clast, demonstrating fracturing prior to brecciation (Figure 14f). The entire section shows pervasive dissolution processes within some clasts, as testified by internal voids, characterised by blurred edges, filled with calcite cements. Meniscus cements occur, and in between the clasts, micritisation is also evident.

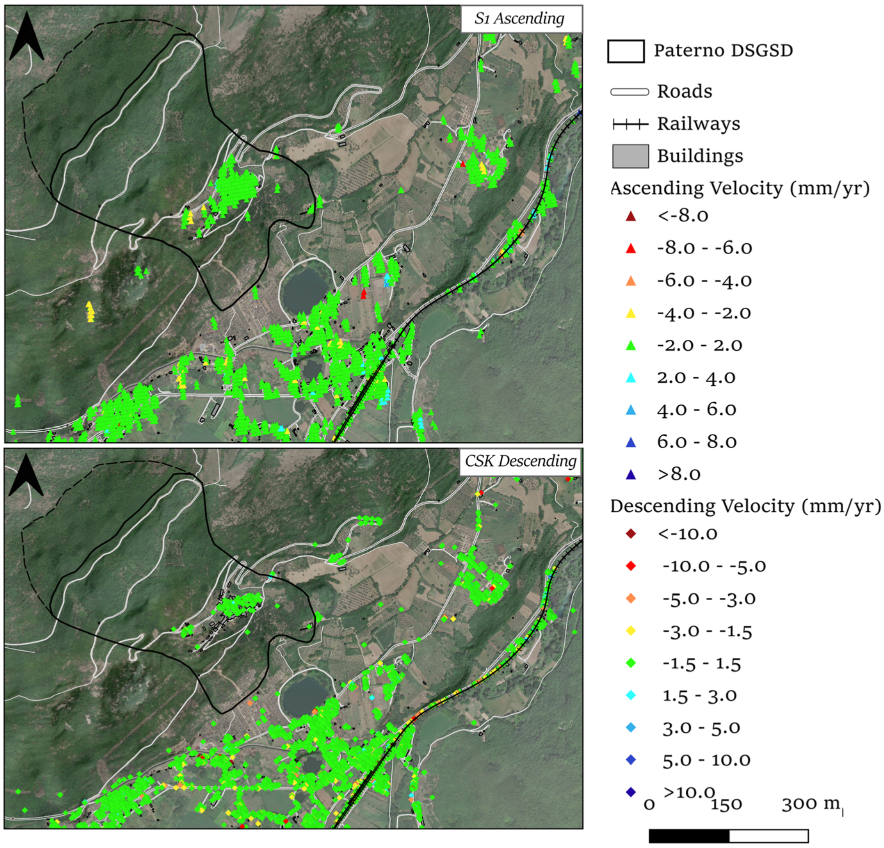

FIGURE 13 Mean displacement rate maps for Sentinel-1 (5 February 2017–21 June 2022), top; and Cosmo–SkyMed (7 February 2017–29 June 2022) datasets, bottom.

4.3.3 | B04 sample

This section consists of a polygenic, poorly sorted breccia with angular millimetric to centimetric clasts, belonging to the Scaglia formation. The main clasts are packstones to grainstones with highly fragmented bioclasts, likely molluscs, such as rudists, and Cretaceous large benthic foraminifera tests (Figure 14h). Overall, the heterogeneity of the clasts can be ascribed to resedimented intervals that are common within the Scaglia Detritica formation. Different sets of fractures occur in the mudstone clasts. Fractures are filled by cement that ends at the edge of the clasts, testifying fracturing prior to the brecciation event. Dissolution of the clasts is a common feature. Vadose and meniscus calcite cement occur between the clasts. Micritisation, too, is evident. Dog-tooth cement crystals occur at the edges of the micritised and partially dissolved areas (Figure 14i). Lastly, red oxides, likely Fe-rich, are common in the main voids.

To accurately determine the compositional similarities and differences among the analysed samples, statistical analysis should have been performed on a high number of clasts belonging to the different breccias. Such a statistical approach would have been needed, considering the intrinsic heterogeneity of the formations outcropping in the study area, and its complex polyphasic brecciation history. However, a detailed study would have gone beyond the scope of this study, since the observation of the above-mentioned three key samples, carefully selected upon field surveys, had already provided us useful information. Among the three analysed samples, B01 and B03 had more similarities than B04. The first two samples, in fact, were mostly composed of similar lithoclasts, such as wackestones or fine packstones belonging to the Cenozoic Scaglia formations. B03 showed a higher degree of cementation and more evidence of partial dissolution and micritisation, potentially indicating a longer subaerial exposure of this breccia than B01. Both samples, however, have the typical features of continental breccias. B04, on the other hand, differed from the other samples in terms of both compositional and diagenetic features, testifying to the longer history of this breccia. In fact, this sample shows clasts and components belonging to different environments of the 'Laziale–Abruzzese' Cretaceous platform, resedimented together in the Cenozoic Scaglia Detritica formation. The clean edges of the mud clasts of sample B04A (Figure 14h) indicated that this lime mud was already lithified when it was resedimented together with rudist fragments, suggesting fragmentation in a marine environment. On the other hand, sample B04B showed the most pervasive evidence of dissolution and karst development (Figure 14i). The latter demonstrated a long-lasting subaerial exposure, during which dissolution and recrystallisation processes could also have partially masked the evidence of a continental fragmentation event. In this regard, a key sample was B04, representing breccias found above the FS. Indeed, its identification with the UFC would confirm that a dislocation occurred after the Villafranchian.

5 | DISCUSSION

Based on the integration of the results coming from the geomorphological field surveys, the InSAR dataset, and the thin section analyses, we unravel key elements in the morphoevolution of the Paterno DSGSD. The three flat surfaces (Figure 9a, d, f) on the Mt. Paterno slope are connected to three different processes:

(i) a relict mass movement from remnants of the low-relief FS surface in the tensile zone, displacing UFC breccias downslope; (ii) a deep-seated deformation process that tilted UFC breccias on the counterslope surface; and (iii) a secondary sliding surface linked to the formation of the flat surface where the Paterno Village is located.

The Mt. Paterno highest surface (1000 m a.s.l.) belongs to the FS, where the UFC breccias are preserved, as demonstrated by observations of thin section on sample B04. The microfacies analyses of thin sections generally showed that the UFC breccias and their clasts experienced one or more fracturing stages before the latest brecciation event. The cement between the main clasts formed within the vadose zone, testifying to the cementation of these breccias in the meteoric zone. Pervasive dissolution and micritisation processes in Mt. Paterno were suggestive of subaerial exposure and karstification processes, as were the oxides often occurring in the main voids of these breccias, representing the insoluble fraction of limestone dissolution. It was not possible to estimate the duration of subaerial exposure. However, among the samples analysed, B04 showed widespread, severe dissolution evidence, which might indicate that this sample was exposed significantly longer, in several phases, than the others (Figure 14). The measured vertical displacement of 20 m was significantly lower than 200 m, indicating a complex deep-slope gravitational process (Figure 12). In this proposed reconstruction, the upper part of the slope was affected by ancient mass movements, activated along the main high-angle scarp of the slope in a post-Villafranchian age and/or after the UFC deposition. These mass movements displaced the UFC breccias around 200 m downslope, on the flat surface at an elevation of 780 m a.s.l., where they are preserved (Figure 12), as demonstrated by field survey and thin section analysis on sample B01.

The progressive evolution of the fractured joint system promotes the tensile zone on the Mt. Paterno, where the FS extends. Along this surface, the joint systems are affected by active epigenic karst processes where several dolines have formed, and by the regional tectonic activity, resulting in mechanical weakening of the rock mass and favouring the genesis of a gravitational displacement of 200 m of UFC breccias from the high scarp to the downslope flat surface with a significant vertical component. Therefore, the presence of the tensile zone of the Paterno DSGSD favoured the post-depositional displacement of the UFC breccias in the Lower Villafranchian to the flat surface at 780 m a.s.l. It appeared to be associated with the Velino River incision processes, as it shows a discontinuous and uneven morphology, comparable to other irregular morphologies and given the existence of similar flat surfaces observed in the Velino Valley. The UFC

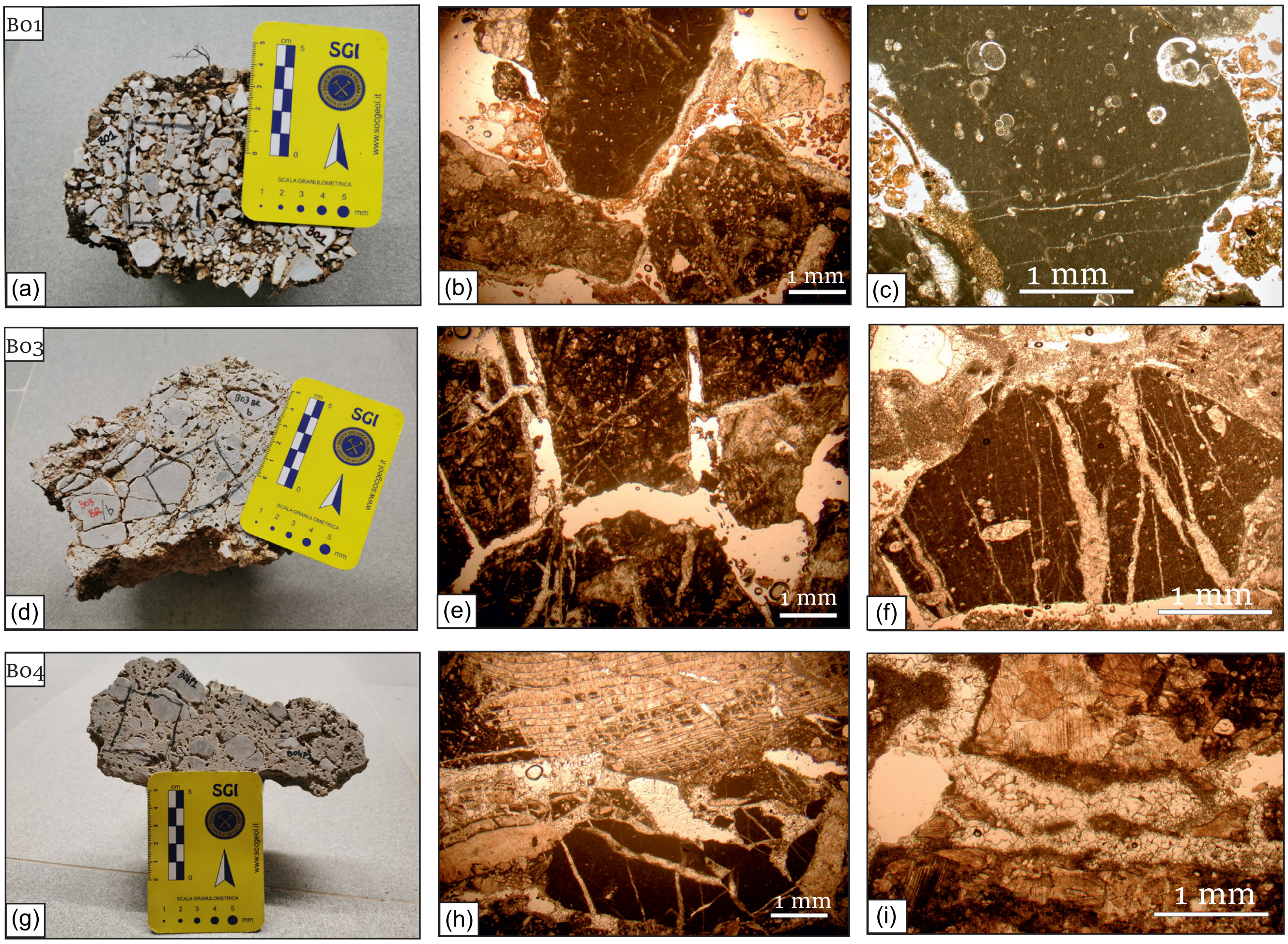

FIGURE 14 Samples of breccia and thin sections: (a) B01 macroscopic UFC breccia sample; (b) angular to subangular B01 clasts edged by meniscus vadose cement cut by fractures filled with microcrystalline calcite cement; (c) detail of a mildly fractured B01 clast of a wackestone with planktonic foraminifera (Scaglia formations), surrounded by vadose cements and iron minerals; (d) B03 macroscopic breccia sampled from the high scarp of Mt. Paterno; (e) B03 evidence of sets of fractures on the Scaglia Detritica Formation; (f) B03 fractures filled with cement developed prior to brecciation; (g) B04 macroscopic breccia sampled from the FS; (h) bioclasts of rudist fragments on the B04 sample; (i) evidence of pervasive micritization and dissolution that modified and partially erased the original texture of the rock on the B04 sample.

breccias would have subsequently backtilted, as shown by their bedding of 310/5 (dip direction/dip) measured in the field, due to their involvement in the main DSGSD. According to the reconstruction presented in this study, this process represents the real Paterno DSGSD, which displaced approximately 20 m of bedrock formations (Figure 12), and its extension reaches the maximum elevation of 780 m a.s.l., in correspondence with the aforementioned counterslope (Figure 6c). We therefore assumed that this process was activated after the occurrence of the landslides that affected the highest part of the slope.

The presence of a secondary sliding surface on trace A-B is supported by the occurrence of slope breccias near the Paterno Village (Figure 9f) and by evidence collected during field surveys (Figure 9e). This surface is located above the second flat area of the slope, which was ascribed to a terrace of gravitational origin, testified by the absence of lateral continuity and its different elevation with respect to other terraces of fluvial origin. Chaotic and highly fractured outcrops and additional bodies of slope breccias that we identified substantiated our assumption. However, it was unclear whether these breccias were the same as those exposed on the high terrace, situated at an elevation of 780 m a.s.l. and belonging to the UFC.

No signs of recent activity were observed in the Rieti Synthem, where neither tectonic nor gravitational displacements were measured, thus suggesting a volumetric compensation within the DSGSD mass. Considering the Upper Pleistocene age of the Rieti Synthem, the fact that it was not involved in the Paterno DSGSD, marking a minimum temporal constraint of dormant state for the DSGSD. Morphometric analyses conducted along the middle Velino Valley, including the Paterno DSGSD, proved that the deposition of this synthem occurred under non-deforming conditions. This inference is supported by the presence of alluvial river terraces at the same elevation as the deposited synthem on both the left and right sides of the river, proving that it was deposited in a stable environment without significant deformation. Furthermore, InSAR data did not provide any evidence of the current ground deformation ascribable to the gravity process. Therefore, the Rieti Synthem deposition during the Upper Pleistocene represents the upper temporal constraint attributed to the DSGSD, during which the process was no longer active. Contextually, after the Upper Pleistocene, karst processes became mainly active at the toe of the slope and within the valley floor, as indicated by the position of Lake Paterno. To understand the relationship among slope deformations, river incision, and karst processes, the identification of the Paterno DSGSD has been set within the framework of the geological evolution of the area since the Villafranchian. Primarily, the enhanced complex system of jointing and tectonic elements on the Paterno slope might have played a major role in the localisation of the deformation process. These rock mass conditions might have promoted karst processes to the development of landforms such as sinkholes and dolines along the slope. And, in analogy to what is documented on the Peschiera slope (Figure 5) (Maffei, Martino, & Prestininzi, 2005; Martino, Prestininzi, & Scarascia Mugnozza, 2004), karst processes have to be included within the list of the preparatory factors of the Paterno DSGSD.

Finally, river incision from the Villafranchian age has significantly increased the relief energy, representing the engine of the mass rock creep process. In conclusion, geomorphic analyses and field surveys confirmed the perimeter of the deformed area on the Paterno slope, as published in the updated PAI maps. Morphometric analyses provided valuable insights into the spatial extent of the deformed area, as a result of comparing the elevations of geological units and relief forms in this investigated zone of the Velino Valley, while field surveys complemented these findings with direct observations and site measurements.

Based on the here proposed reconstruction, the Paterno DSGSD is well framed in the geomorphological and morphoevolutionary setting of the Central Apennines, where several Quaternary DSGSDs detached from carbonate mountain ridges from Middle-Late Pleistocene to Holocene in age (Bianchi Fasani et al., 2014; Discenza et al., 2011; Maffei, Martino, & Prestininzi, 2005).

The integration of geomorphological analyses and satellite monitoring revealed an operative solution for the definition of hazard conditions associated with DSGSD. It is worth pointing out that the confirmed perimeter of the DSGSD directly corresponds to the degree of risk assigned to the current PAI maps, following the reclassification of the state of activity. The study area is located in a high seismicity region, which has recorded significant earthquakes (up to Mw 6.5) during the 2016–2017 seismic sequence, and no evidence of slope movement has been observed. The diagnostic indicators related to the state of activity, including landforms, PS analysis, and damage assessment, led us to consider the Paterno DSGSD as dormant. Consequently, we assigned a low hazard level and a limited residual risk to the Paterno DSGSD.

6 | CONCLUSIONS

In this study, we reconstructed the Quaternary morphodynamics of the middle Velino Valley by investigating the remnants of the Fontanelle relict surface and the Villafranchian continental deposits (UFC, UMS), located at various elevations in the study area. Our study was focused on the Paterno slope located near the San Vittorino Plain (Central Italy) and inventoried in the PAI cartography as a high-risk area due to the presence of a DSGSD. Outcrops of the UFC breccias on the Paterno slope and morphological evidence of concave scar areas might erroneously indicate that the DSGSD caused a 200 m displacement along the investigated slope. Based on field surveys, geomorphological methods, and thin section analyses, this study suggested that the deformation involved a smaller volume with a significantly lower displacement. Relative temporal constraints allowed us to infer that most of its activity was confined to the Pleistocene. Persistent Scatterer Interferometry based on Sentinel-1 and COSMO SkyMed SAR images also corroborated the general stability of the area.

The analyses conducted in this study made it possible to determine the extent of the phenomenon. The integration of geomorphological, geomechanical, microstructural analysis and remote sensing approaches allows the development of the Quaternary evolutionary model of the slope-to-valley system under review. We observed that the Paterno DSGSD does not currently represent a high hazard and consequent risk. No sign of recent deformation activity was identified, either following the recent seismic sequence that affected Central Italy as post-seismic reactivations or accelerations, thereby suggesting a state of dormant and the relict nature of the landforms.

The findings contribute to a better understanding of the morphoevolution of the Velino Valley, adding a piece of evidence to the geological history of the San Vittorino intermontane plain and providing important constraints for assessing the potential risks associated with DSGSD processes in the Central Apennines. Finally, this study proposes a methodological approach that integrates multiple techniques, leading to a hazard assessment that can be adopted in other active mountain contexts prone to DSGSDs.

ACKNOWLEDGEMENTS

The present study was conducted in the frame of the research project "Review of PAI landslides high and very high (P3-P4) hazard areas interacting with the reconstruction in municipalities affected by the 2016-2017 Central Italy earthquake" funded by "ABDAC" (Autorità di Bacino Distrettuale Appennino Centrale), (PI: Prof. Gabriele Scarascia Mugnozza) managed by "CERI- Research Center for Prediction and Prevention of Geological Hazards" of Sapienza University of Rome. COSMO-SkyMed Product ©ASI processed by CERI under a license of the Italian Space Agency (ASI). In addition, the authors thank Vladimiro Verrubbi for his suggestions and Lorenzo Di Biagio for his contribution to field surveys.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

DISCLOSURE

The author confirms that permission has been obtained to reproduce any material from other sources.

ORCID

Giorgia Berardo https://orcid.org/0000-0002-3279-7347
Gabriele Amato https://orcid.org/0000-0002-5014-5924
Irene Cornacchia https://orcid.org/0000-0002-5658-2367
Matteo Fiorucci https://orcid.org/0000-0003-4616-7108
Gian Marco Marmoni https://orcid.org/0000-0002-0443-4389
Gabriele Scarascia Mugnozza https://orcid.org/0000-0002-2917-0324

REFERENCES

Accordi, G., Carbone, F., Civitelli, G., Corda, L., De Rita, D., Esu, D., et al. (1988) Note illustrative alla carta delle litofacies del Lazio-Abruzzo ed aree limitrofe. Quaderni de "La Ricerca scientifica", 114, 5, Consiglio nazionale delle ricerche, Rome.

Agliardi, F., Crosta, G.B. & Zanchi, A. (2001) Structural Constraints on Deep-Seated Slope Deformation Kinematics. *Engineering Geology*, 59(1–2), 83–102. Available from: https://doi.org/10.1016/S0013-7952(00)00066-1

Albano, M., Saroli, M., Beccaro, L., Moro, M., Doumaz, F., Discenza, M.E., et al. (2023) Multi-Source Data Analysis to Assess the Past and Present Kinematics of the Pisciotta Deep-Seated Gravitational Slope Deformation (Southern Italy). *Remote Sensing of Environment*, 296, 113751. Available from: https://doi.org/10.1016/j.rse.2023.113751

Amadei, B., Savage, W.Z. & Swolfs, H.S. (1987) Gravitational Stresses in Anisotropic Rock Masses. *International Journal of Rock Mechanics and Mining Science and Geomechanics Abstracts*, 24(1), 5–14. Available from: https://doi.org/10.1016/0148-9062(87)91227-7

Amadei, B., Swolfs, H.S. & Savage, W.Z. (1988) Gravity-Induced Stresses in Stratified Rock Masses. *Rock Mechanics and Rock Engineering*, 21, 1–20. Available from: https://doi.org/10.1007/BF01019673

Amato, G., Devoti, R., Fubelli, G., Aringoli, D., Bignami, C., Galvani, A., et al. (2018) Step-Like Displacements of a Deep-Seated Gravitational Slope Deformation Observed During the 2016–2017 Seismic Events in Central Italy. *Engineering Geology*, 246, 337–348. Available from: https://doi.org/10.1016/j.enggeo.2018.10.014

Annunziatellis, A., Beaubien, S.E., Bigi, S., Ciotoli, G., Coltella, M. & Lombardi, S. (2008) Gas Migration Along Fault Systems and Through the Vadose Zone in the Latera caldera (Central Italy): Implications for CO2 Geological Storage. *International Journal of Greenhouse Gas Control*, 2(3), 353–372. Available from: https://doi.org/10.1016/j.ijggc.2008.02.003

Antonielli, B., Mazzanti, P., Rocca, A., Bozzano, F. & Dei Cas, L. (2019) A-DInSAR Performance for Updating Landslide Inventory in Mountain Areas: An Example From Lombardy Region (Italy). *Geosciences*, 9(9), 364. Available from: https://doi.org/10.3390/geosciences9090364

Argnani, A. & Gamberi, F. (1995) Stili strutturali al fronte della catena appenninica nell'Adriatico centro-settentrionale. *Studi Geologici Camerti*, 1, 19–27. Available from: https://doi.org/10.15165/studgeocam-884

Barberi, R. & Cavinato, G.P. (1993) Analisi sedimentologiche ed evoluzione paleogeografica del settore meridionale del bacino di Rieti (Appennino Centrale). *Studi Geologici Camerti*, 1992(1), 39–53.

Barberi, R., Cavinato, G.P., Gliozzi, E. & Mazzini, I. (1995) Late Pliocene–Early Pleistocene Palaeoenvironmental Evolution of the Rieti Basin (Central Apennines). *Il Quaternario*, 8, 515–534.

Barberio, M.D., Gori, F., Barbieri, M., Boschetti, T., Caracausi, A., Cardello, G.L., et al. (2021) Understanding the Origin and Mixing of Deep Fluids in Shallow Aquifers and Possible Implications for Crustal Deformation Studies: San Vittorino Plain, Central Apennines. *Applied Sciences*, 11(4), 1353. Available from: https://doi.org/10.3390/app11041353

Bersani, P., Biagi, P., Ferranti, C. & Piotti, A. (2000) Gli sprofondamenti nella Piana di San Vittorino (Rieti). Prima parte. Tevere. Rivista trimestrale dell'Autorità Bacino del Tevere, 17, 8–-13.

Bianchi Fasani, G., Di Luzio, E., Esposito, C., Evans, S.G. & Scarascia Mugnozza, G. (2014) Quaternary, Catastrophic Rock Avalanches in the Central Apennines (Italy): Relationships With Inherited Tectonic Features, Gravity-Driven Deformations and the Geodynamic Frame. *Geomorphology*, 211, 22–42. Available from: https://doi.org/10.1016/j.geomorph.2013.12.027

Bigi, S., Cantalamessa, G., Centamore, E., Didaskalou, P., Dramis, F., Farabollini, P., et al. (1995) La fascia periadriatica marchigiano-abruzzese dal Pliocene medio ai tempi attuali: evoluzione tettonico-sedimentaria e geomorfologica. *Studi Geologici Camerti*, 1, 37–49.

Bosi, C. & Messina, P. (1991) Ipotesi di correlazione tra successioni morfo-litostratigrafiche tra successioni plio-pleistoceniche nell'Appennino Laziale-Abruzzese. *Studi Geologici Camerti*, 1991-2, CROP 11, 257–263. Available from: https://doi.org/10.15165/studgeocam-1011

Bureau de Recherches Géologiques et Minières (BRGM). Base de Données Mouvements de terrain. Retrieved from https://www.brgm.fr/fr

Calderini, G., Calderoni, G., Cavinato, G.P., Gliozzi, E. & Paccara, P. (1998) The Upper Quaternary Sedimentary Sequence at the Rieti Basin (Central Italy): A Record of Sedimentation Response to Climatic Changes. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 140(1–4), 97–111. Available from: https://doi.org/10.1016/S0031-0182(98)00024-8

Capotorti, F., Centamore, E., Chiocchini, M., Civitelli, G., Corda, L., Mancinelli, A., et al. (1991) Dati preliminari geologico-stratigrafici sull'unità di M. Giano e M. Gabbia. *Studi Geologici Camerti (Nuova Serie)*, II, 119–123. Available from: https://hdl.handle.net/11573/472651

Capotorti, F. & Chiarini, E. (2023) Note illustrative della Carta Geologica d'Italia alla scala 1: 50.000, F. 348 Antrodoco, APAT-Servizio Geologico d'Italia. https://www.isprambiente.gov.it/Media/carg/note_illustrative/348_Antrodoco.pdf

Capotorti, F., Fumanti, F. & Mariotti, G. (1995) Evoluzione tettonico-sedimentaria e strutturazione del settore di piattaforma carbonatica laziale-abruzzese nell'alta Valle del F. Velino. *Studi Geologici Camerti*, 1995/2, 101–111. Available from: https://doi.org/10.15165/studgeocam-923

Capotorti, F. & Muraro, C. (2021) Post-Rift Extensional Tectonics at the Edge of a Carbonate Platform: Insights From the Middle Jurassic-Early Cretaceous Monte Giano Stratigraphic Record (Central Apennines, Italy). *Geologica Acta*, 19(12), 1–22. Available from: https://doi.org/10.1344/GeologicaActa2021.19.12

Carrara, C., Brunamonte, F., Ferreli, L., Lorenzoni, P., Margheriti, L., Michetti, A.M., et al. (1992) I terrazzi della medio-bassa Valle del F. Velino. *Studi Geologici Camerti*,1992/1, 97–102. Available from: https://hdl.handle.net/11383/12255

Casini, S., Martino, S., Petitta, M. & Prestininzi, A. (2006) A Physical Analogue Model to Analyse Interactions Between Tensile Stresses and Dissolution in Carbonate Slopes. *Hydrogeology Journal*, 14, 1387–1402. Available from: https://doi.org/10.1007/s10040-006-0064-x

Catelan, F.T., Bossi, G., Schenato, L., Tondo, M., Critelli, V., Mulas, M., et al. (2025) Long-Term Monitoring of Active Large-Scale Landslides for Non-Structural Risk Mitigation-Integrated Sensors and Web-Based Platform. *Journal of Mountain Science*, 22(1), 1–15. Available from: https://doi.org/10.1007/s11629-024-9211-x

Cavinato, G.P. (1993) Recent Tectonic Evolution of the Quaternary Deposits of the Rieti Basin (Central Apennines, Italy): Southern Part. *Geologica Romana*, 29, 411–434.

Cavinato, G.P., Chiaretti, F., Cosentino, D. & Serva, L. (1989) Caratteri geologico-strutturali del margine orientale della Conca di Rieti. *Bollettino della Società Geologica Italiana*, 108(2), 207–218.

Centamore, E. & Dramis, F. (2010) Note Illustrative della Carta Geologica d'Italia alla scala 1: 50.000, F. 358 Pescorocchiano. ISPRA-Servizio Geologico d'Italia, Regione Lazio. 358_Pescorocchiano.pdf (isprambiente.gov.it).

Centamore, E. & Nisio, S. (2002) Quaternary Geology and Morphostructural Evolution Between the Velino and Salto Valleys. *Studi Geologici Camerti*, 2002, 37–44.

Centamore, E. & Nisio, S. (2003) Effects of Uplift and Tilting in the Central-Northern Apennines (Italy). *Quaternary International*, 101-102, 93–101. Available from: https://doi.org/10.1016/S1040-6182(02)00092-7

Centamore, E., Nisio, S. & Rossi, D. (2004) Aspetti geologici-strutturali in relazione alla formazione della sinkhole plain di S. Vittorino. In Proceedings of the State of the Art on the Study of Sinkhole Phenomena and Role of the National and Local Government in the Territory Administration, Rome, Italy, 285–297.

Centamore, E., Nisio, S. & Rossi, D. (2009) The San Vittorino Sinkhole Plain: Relationships Between Bedrock Structure, Sinking Processes, Seismic Events and Hydrothermal Springs. *Italian Journal of Geosciences*, 128(3), 629–639. Available from: https://doi.org/10.3301/IJG.2009.128.3.629

Chang, K.T., Ge, L. & Lin, H.H. (2015) Slope Creep Behaviour: Observations and Simulations. *Environmental Earth Sciences*, 73, 275–287. Available from: https://doi.org/10.1007/s12665-014-3423-2

Chigira, M. (1992) Long-Term Gravitational Deformation of Rocks by Mass Rock Creep. *Engineering Geology*, 32, 157–184. Available from: https://doi.org/10.1016/0013-7952(92)90043-X

Cignetti, M., Godone, D., Notti, D., Zucca, F., Meisina, C., Bordoni, M., et al. (2023) Damage to Anthropic Elements Estimation due to large Slope Instabilities Through Multi-Temporal A-DInSAR Analysis. *Natural Hazards*, 115(3), 2603–2632. Available from: https://doi.org/10.1007/s11069-022-05655-7

Cipollari, P. & Cosentino, D. (1991) La linea Olevano-Antrodoco: contributo della biostratigrafia alla sua caratterizzazione cinematica. *Studi Geologici Camerti*, 1991/2, 143–149.

Civitelli, G. & Brandano, M. (2005) The "Calcari a Briozoi e Litotamni" in the Latium-Abruzzi Carbonate Platform (Central Apennines, Italy): Atlas of the Lithofacies and Depositional Model. *Bollettino Della Società Geologica Italiana*, 124(3), 611–643.

Cosentino, D., Miccadei, E., Barberi, M., Basilici, G., Cipollari, P., Parotto, M., et al. (2008) Note illustrative della Carta Geologica d'Italia alla scala 1: 50.000, F. 357 Cittaducale, APAT-Servizio Geologico d'Italia. 357_Cittaducale.pdf (isprambiente.gov.it).

Crosta, G. (1996) Landslide, Spreading, Deep-Seated Gravitational Deformation: Analysis, Examples, Problems and Proposals. *Geografia Fisica e Dinamica Quaternaria*, 19(2), 297–313. Available from: http://hdl.handle.net/10281/1528

D'Alessandro, L., Miccadei, E. & Piacentini, T. (2003) Morphostructural Elements of Central-Eastern Abruzzi: Contributions to the Study of the Role of Tectonics on the Morphogenesis of the Apennine Chain. *Quaternary International*, 101, 115–124. Available from: https://doi.org/10.1016/S1040-6182(02)00094-0

Del Rio, L., Moro, M., Fondriest, M., Saroli, M., Gori, S., Falcucci, E., et al. (2021) Active Faulting and Deep-Seated Gravitational Slope Deformation in Carbonate Rocks (Central Apennines, Italy): A New "Close-Up" View. *Tectonics*, 40(10), e2021TC006698. Available from: https://doi.org/10.1029/2021TC006698

Della Seta, M., Esposito, C., Marmoni, G.M., Martino, S., Scarascia Mugnozza, G. & Troiani, F. (2017) Morpho-Structural Evolution of the Valley-Slope Systems and Related Implications on Slope-Scale Gravitational Processes: New Results From the Mt. Genzana Case History (Central Apennines, Italy). *Geomorphology*, 289, 60–77. Available from: https://doi.org/10.1016/j.geomorph.2016.07.003

Demangeot, J. (1965) Géomorphologie des Abruzzes Adriatiques. Me'met Doc du CNRS, Paris, 287.

Demurtas, V., Orrù, P.E. & Deiana, G. (2021) Evolution of Deep-Seated Gravitational Slope Deformations in Relation With Uplift and Fluvial Capture Processes in Central Eastern Sardinia (Italy). *Land*, 10(11), 1193. Available from: https://doi.org/10.3390/land10111193

Di Domenica, A., Bonini, L., Calamita, F., Toscani, G., Galuppo, C. & Seno, S. (2014) Analogue Modeling of Positive Inversion Tectonics Along Differently Oriented Pre-Thrusting Normal Faults: An Application to the Central-Northern Apennines of Italy. *GSA Bulletin*, 126(7–8), 943–955. Available from: https://doi.org/10.1130/B31001.1

Di Domenica, A., Turtù, A., Satolli, S. & Calamita, F. (2012) Relationships Between Thrusts and Normal Faults in Curved Belts: New Insight in the Inversion Tectonics of the Central-Northern Apennines (Italy). *Journal of Structural Geology*, 42, 104–117. Available from: https://doi.org/10.1016/j.jsg.2012.06.008

Di Filippo, M., Nolasco, F., Rizzo, S. & Toro B. (2004) Indagini geofisiche per l'individuazione di aree a rischio sinkhole nella piana di San Vittorino (RI). Proceedings ISPRA Sinkholes, APAT, 20–21 May 2004, Rome, Italy, 390–397.

Di Luzio, E., Bianchi Fasani, G., Esposito, C., Saroli, M., Cavinato, G.P. & Scarascia Mugnozza, G. (2004) Massive Rock-Slope Failure in the Central Apennines (Italy): The Case of the Campo di Giove Rock Avalanche. *Bulletin of Engineering Geology and the Environment*, 63, 1–12. Available from: https://doi.org/10.1007/s10064-003-0212-7

Di Luzio, E., Discenza, M.E., Di Martire, D., Putignano, M.L., Minnillo, M., Esposito, C., et al. (2022) Investigation of the Luco dei Marsi DSGSD Revealing the First Evidence of a Basal Shear Zone in the Central Apennine Belt (Italy). *Geomorphology*, 408, 108249. Available from: https://doi.org/10.1016/j.geomorph.2022.108249

Di Martire, D., Tessitore, S., Brancato, D., Ciminelli, M.G., Costabile, S., Costantini, M., et al. (2016) Landslide Detection Integrated System (LaDIS) Based on In-Situ and Satellite SAR Interferometry Measurements. *Catena*, 137, 406–421. Available from: https://doi.org/10.1016/j.catena.2015.10.002

Discenza, M.E., Esposito, C., Komatsu, G. & Miccadei, E. (2021) Large-Scale and Deep-Seated Gravitational Slope Deformations on Mars: A Review. *Geosciences*, 11(4), 174. Available from: https://doi.org/10.3390/geosciences11040174

Discenza, M.E., Esposito, C., Martino, S., Petitta, M., Prestininzi, A. & Scarascia Mugnozza, G. (2011) The Gravitational Slope Deformation of Rocchetta Ridge (Central Apennines, Italy): Geological-Evolutionary Model and Numerical Analysis. *Bulletin of Engineering Geology and the Environment*, 70, 559–575. Available from: https://doi.org/10.1007/s10064-010-0342-7

Dunham, R.J. (1962) Classification of Carbonate Rocks According to Depositional Texture. In: Ham, W.E. (Ed.) *American Association of Petroleum Geologists (AAPG) Mem. 1, Tulsa, Oklahoma*, pp. 108–121.

Eberhardt, E., Stead, D. & Coggan, J.S. (2004) Numerical Analysis of Initiation and Progressive Failure in Natural Rock Slopes—The 1991 Randa Rockslide. *International Journal of Rock Mechanics and Mining Sciences*, 41(1), 69–87. Available from: https://doi.org/10.1016/S1365-1609(03)00076-5

Embry, A.F. & Klovan, J.E. (1971) A Late Devonian Reef Tract on Northeastern Banks Island, Northwest Territories. *Bulletin of Canadian Petroleum Geology*, 19(4), 730–781.

Esposito, C., Bianchi Fasani, G., Martino, S. & Scarascia Mugnozza, G. (2013) Quaternary Gravitational Morpho-Genesis of Central Apennines (Italy): Insights From the Mt. Genzana Case History. *Tectonophysics*, 605, 96–103. Available from: https://doi.org/10.1016/j.tecto.2013.06.023

Faccenna, C., Florindo, F., Funiciello, R. & Lombardi, S. (1993) Tectonic Setting and Sinkhole Features: Case Histories From Western Central Italy. *Quaternary Proceedings*, 3, 47–56.

Fan, X., Yunus, A.P., Scaringi, G., Catani, F., Siva Subramanian, S., Xu, Q., et al. (2021) Rapidly Evolving Controls of Landslides After a Strong Earthquake and Implications for Hazard Assessments. *Geophysical Research Letters*, 48, e2020GL090509. Available from: https://doi.org/10.1029/2020GL090509

Ferretti, A., Prati, C. & Rocca, F. (2001) Permanent Scatterers in SAR Interferometry. *IEEE Transactions on Geoscience and Remote Sensing*, 39(1), 8–20. Available from: https://doi.org/10.1109/36.898661

Festi, P., Bossi, G., Francioni, M., Marcato, G., Staboli, C. & Borgatti, L. (2023) Structural Health of a Road Tunnel Intersecting a Large and Active Rock-Block Slide. *Italian Journal of Engineering Geology and Environment*, 2023/1, 49–55. Available from: https://doi.org/10.4408/IJEGE.2023-01.S-07

Fiorucci, M., Iannucci, R., Lenti, L., Martino, S., Paciello, A., Prestininzi, A., et al. (2017) Nanoseismic Monitoring of Gravity-Induced Slope Instabilities for the Risk Management of an Aqueduct Infrastructure in Central Apennines (Italy). *Natural Hazards*, 86(Suppl 2), S345–S362. Available from: https://doi.org/10.1007/s11069-016-2516-5

Frattini, P., Crosta, G.B. & Allievi, J. (2013) Damage to Buildings in Large Slope Rock Instabilities Monitored With the PSInSAR™ Technique. *Remote Sensing*, 5, 4753–4773. Available from: https://doi.org/10.3390/rs5104753

Frattini, P., Crosta, G.B., Rossini, M. & Allievi, J. (2018) Activity and Kinematic Behaviour of Deep-Seated Landslides From PS-InSAR Displacement Rate Measurements. *Landslides*, 15, 1053–1070. Available from: https://doi.org/10.1007/s10346-017-0940-6

Fubelli, G., Della Seta, M. & Amato, G. (2014) Drainage System Adjustment in Response to the Opening of the Rieti Intermontane Basin (Central Italy): Geostatistical Reconstruction of the PaleoFarfa River Alluvial Plain. *Rendiconti Lincei*, 25, 167–176. Available from: https://doi.org/10.1007/s12210-014-0322-0

Hou, Y., Chigira, M. & Tsou, C.Y. (2014) Numerical Study on Deep-Seated Gravitational Slope Deformation in a Shale-Dominated Dip Slope due to River Incision. *Engineering Geology*, 179, 59–75. Available from: https://doi.org/10.1016/j.enggeo.2014.06.020

Hungr, O., Leroueil, S. & Picarelli, L. (2014) The Varnes Classification of Landslide Types, an Update. *Landslides*, 11(2), 167–194. Available from: https://doi.org/10.1007/s10346-013-0436-y

Jaboyedoff, M., Penna, I., Pedrazzini, A., Baroň, I. & Crosta, G.B. (2013) An Introductory Review on Gravitational-Deformation Induced Structures, Fabrics and Modeling. *Tectonophysics*, 605, 1–12.

Karkani, A., Evelpidou, N., Saitis, G., Tsanakas, K., Drinia, H., Vassilakis, E., et al. (2023) Coastal Evolution and Relative Sea Level Changes at Psatha (Alkyonides Bay, Greece). *Journal of Marine Science and Engineering*, 11(1), 199. Available from: https://doi.org/10.3390/jmse11010199

Lenti, L., Martino, S., Paciello, A., Prestininzi, A. & Rivellino, S. (2012) Microseismicity Within a Karstified Rock Mass due to Cracks and Collapses Triggered by Earthquakes and Gravitational Deformations. *Natural Hazards*, 64, 359–379. Available from: https://doi.org/10.1007/s11069-012-0245-y

Maffei, A., Martino, S. & Prestininzi, A. (2005) From the Geological to the Numerical Model in the Analysis of Gravity-Induced Slope Deformations: An Example From the Central Apennines (Italy). *Engineering Geology*, 78, 215–236. Available from: https://doi.org/10.1016/j.enggeo.2004.12.009

Marc, O., Hovius, N., Meunier, P., Uchida, T. & Hayashi, S. (2015) Transient Changes of Landslide Rates After Earthquakes. *Geology*, 43(10), 883–886. Available from: https://doi.org/10.1130/G36961.1

Marmoni, G.M., Antonielli, B., Caprari, P., Di Renzo, M.E., Marini, R., Mastrantoni, G., et al. (2025) Semi-Automatic Ranking of Landslide Candidate Areas at a Regional Scale Using EGMS InSAR Data for Territorial Planning and Risk Management. *Landslides*, 22, 4077–4095. Available from: https://doi.org/10.1007/s10346-025-02597-6

Marmoni, G.M., Martino, S., Censi, M., Menichetti, M., Piacentini, D., Scarascia Mugnozza, G., et al. (2023) Transition From Rock Mass Creep to Progressive Failure for Rockslide Initiation at Mt. Conero (Italy). *Geomorphology*, 437, 108750. Available from: https://doi.org/10.1016/j.geomorph.2023.108750

Marmoni, G.M., Martino, S., Heap, M.J. & Reuschlé, T. (2017) Gravitational Slope-Deformation of a Resurgent Caldera: New Insights From the Mechanical Behaviour of Mt. Nuovo Tuffs (Ischia Island, Italy). *Journal of Volcanology and Geothermal Research*, 345, 1–20. Available from: https://doi.org/10.1016/j.jvolgeores.2017.07.019

Martarelli, L., Petitta, M., Scalise, A. R. & Silvi, A. (2008) Cartografia idrogeologica sperimentale della Piana Reatina (Lazio). Memorie descrittive della Carta Geologica d''Italia, 81, 137–156.

Martino, S., Bozzano, F., Caporossi, P., et al. (2019) Impact of Landslides on Transportation Routes During the 2016–2017 Central Italy Seismic Sequence. *Landslides*, 16, 1221–1241. Available from: https://doi.org/10.1007/s10346-019-01162-2

Martino, S., Fiorucci, M., Marmoni, G.M., Casaburi, L., Antonielli, B. & Mazzanti, P. (2022) Increase in Landslide Activity After a Low-Magnitude Earthquake as Inferred From DInSAR Interferometry. *Scientific Reports*, 12, 2686. Available from: https://doi.org/10.1038/s41598-022-06508-w

Martino, S., Moscatelli, M. & Scarascia Mugnozza, G. (2004) Quaternary Mass Movements Controlled by a Structurally Complex Setting in the Central Apennines (Italy). *Engineering Geology*, 72(1–2), 33–55. Available from: https://doi.org/10.1016/j.enggeo.2003.06.005

Martino, S. & Prestininzi, A. (2004) Interazioni tra carsismo e deformazioni gravitative profonde di versante nella genesi di sinkholes. Atti del 1° Primo Seminario APAT. Stato dell'arte e sullo studio dei fenomeni di sinkholes e ruolo delle amministrazioni statali e locali nel governo del territorio, 519-532.

Martino, S., Prestininzi, A. & Scarascia Mugnozza, G. (2004) Geological-Evolutionary Model of a Gravity-Induced Slope Deformation in the Carbonate Central Apennines (Italy). *Quarterly Journal of Engineering Geology and Hydrogeology*, 37(1), 31–47. Available from: https://doi.org/10.1144/1470-9236/03-030

McCallum, M., Beckmann, M., Nardelli, S. & Munro, M. (2019) The Excavations at the so-Called Villa of Titus (Castel Sant'Angelo, Rieti). Fasti Online Documents and Research (FOLD&R), 1–19.

Michele, M., Di Stefano, R., Chiaraluce, L., Cattaneo, M., De Gori, P., Monachesi, G., et al. (2016). The Amatrice 2016 Seismic Sequence: A Preliminary Look at the Mainshock and Aftershocks Distribution. *Annals of Geophysics*, 59, Fast Track 5, Available from: https://doi.org/10.4401/ag-7227

Michetti, A.M., Brunamonte, F., Serva, L. & Whitney, R. A. (1995) Seismic Hazard Assessment From Paleoseismological Evidence in the Rieti Region (Central Italy). *Perspectives in Paleoseismology*, Association of Engineering Geologists Bulletin, Special Publication, (6), 63–82.

Moro, M., Saroli, M., Gori, S., Falcucci, E., Galadini, F. & Messina, P. (2012) The Interaction Between Active Normal Faulting and Large Scale Gravitational Mass Movements Revealed by Paleoseismological Techniques: A Case Study From Central Italy. *Geomorphology*, 151, 164–174. Available from: https://doi.org/10.1016/j.geomorph.2012.01.026

Pánek, T., Břežný, M., Kapustová, V., Lenart, J. & Chalupa, V. (2019) Large Landslides and Deep-Seated Gravitational Slope Deformations in the Czech Flysch Carpathians: New LiDAR-Based Inventory. *Geomorphology*, 346, 106852. Available from: https://doi.org/10.1016/j.geomorph.2019.106852

Panek, T. & Klimeš, J. (2016) Temporal Behaviour of Deep-Seated Gravitational Slope Deformations: A Review. *Earth Science Reviews*, 156, 14–38. Available from: https://doi.org/10.1016/j.earscirev.2016.02.007

Parotto, M. & Praturlon, A. (1975) Geological Summary of Central Apennines. *Quaderni della Ricerca Scientifica* 90, 257–311.

Payne, R. (2023) Understanding the Villa di Tito and the Velino Valley Within Central Italy by Creating Spatial Connections. Halifax, Nova Scotia. http://library2.smu.ca/xmlui/handle/01/31737

Petitta, M. (2009) Idrogeologia della media Valle del fiume Velino e della Piana di S. Vittorino (Rieti, Italia Centrale). *Italian Journal of Engineering Geology and Environment*, 1, 157–181. Available from: https://hdl.handle.net/11573/105711

Petitta, M., Tallini, M., Benedetti, G. & Del Monaco, F. (2003) Fracture Pattern Influence on Groundwater Discharge Along the Tectonic Border of Karst Aquifers (Velino Valley, Central Italy). *Proceedings Groundwater in fractured rocks*, Int. Congress of IAH, Prague, 85–86.

Petley, D.N. & Allison, R.J. (1997) The Mechanics of Deep-Seated Landslides. *Earth Surface Processes and Landforms: The Journal of the British Geomorphological Group*, 22(8), 747–758. Available from: https://doi.org/10.1002/(SICI)1096-9837

Piacentini, T. & Miccadei, E. (2014) The Role of Drainage Systems and Intermontane Basins in the Quaternary Landscape of the Central Apennines Chain (Italy). *Rendiconti Lincei*, 25(Suppl 2), 139–150. Available from: https://doi.org/10.1007/s12210-014-0312-2

Piano stralcio di Assetto Idrogeologico (PAI), Available at https://aubac.it/piani-di-bacino/piani-di-assetto-idrogeologico

Radbruch-Hall, D., Varnes, D.J. & Colton, R.B. (1977) Gravitational Spreading of Steep-Sided Ridges ("Sackung") in Colorado. *Journal of Research of the US Geological Survey*, 5(3), 359–363. Available from: https://doi.org/10.1007/BF02634754

Radbruch-Hall, D.H. (1978) Gravitational Creep of Rock Masses on Slopes. In: Voight, B. (Ed.) *Rockslides and Avalanches*. Amsterdam: Elsevier, pp. 607–658 https://doi.org/10.1016/B978-0-444-41507-3.50025-8

Ricci Lucchi, M., Calderoni, G., Carrara, C., Cipriani, N., Daniela, E., Ferreli, L., et al. (2000) Late Quaternary Record of the Rieti Basin, Central Italy: Paleoenvironmental and Paleoclimatic. *Giornale di Geologia*, 62, 105–136.

Salvati, R. & Sasowsky, I.D. (2002) Development of Collapse Sinkhole in Areas of Groundwater Discharge. *Journal of Hydrology*, 264(1–4), 1–11. Available from: https://doi.org/10.1016/S0022-1694(02)00062-8

Sanders, D., Ortner, H. & Pomella, H. (2018) Stratigraphy and Deformation of Pleistocene Talus in Relation to a Normal Fault Zone (Central Apennines, Italy). *Sedimentary Geology*, 373, 77–97. Available from: https://doi.org/10.1016/j.sedgeo.2018.05.013

Scarascia Mugnozza, G., Bianchi Fasani, G., Esposito, C., Martino, S., Saroli, M., Di Luzio, E., et al. (2006) Rock Avalanche and Mountain Slope Deformation in a Convex, Dip-Slope: The Case of the Majella Massif (Central Italy). In: Evans, S.G., Scarascia Mugnozza, G., Strom, A.L. & Hermanns, R.L. (Eds.) *Landslides from Massive Rock Slope Failure*, Nato Science Series Book, IV Earth and Environmental Sciences, Vol. 49. Netherlands: Springer Publisher, pp. 357–376 https://doi.org/10.1007/978-1-4020-4037-5_19

Servizio Geologico d'Italia. (2008) Foglio 357 "Cittaducale" della Carta Geologica d'Italia alla scala 1:50,000. https://www.isprambiente.gov.it/Media/carg/357_CITTADUCALE/Foglio.html

Servizio Geologico d'Italia. (2010) Foglio 358 "Pescorocchiano" della Carta Geologica d'Italia alla scala 1:50,000. http://www.isprambiente.gov.it/Media/carg/358_PESCOROCCHIANO/Foglio.html

Servizio Geologico d'Italia. (2022) Foglio 348 "Antrodoco" della Carta Geologica d'Italia alla scala 1:50,000. https://www.isprambiente.gov.it/Media/carg/348_ANTRODOCO/Foglio.html

Soligo, M., Tuccimei, P., Barberi, R., Delitala, M.C., Miccadei, E. & Taddeucci, A. (2002) U/Th Dating of Freshwater Travertine From Middle Velino Valley (Central Italy): Paleoclimatic and Geological Implications. *Palaeogeography. Palaeoclimatology. Palaeoecoology*, 184, 147–161. Available from: https://doi.org/10.1016/S0031-0182(02)00253-5

Song, C., Yu, C., Li, Z., Utili, S., Frattini, P., Crosta, G., et al. (2022) Triggering and Recovery of Earthquake Accelerated Landslides in Central Italy Revealed by Satellite Radar Observations. *Nature Communications*, 13(1), 7278. Available from: https://doi.org/10.1038/s41467-022-35035-5

Tanyaş, H., Kirschbaum, D., Görüm, T., van Westen, C.J. & Lombardo, L. (2021) New Insight Into Post-Seismic Landslide Evolution Processes in the Tropics. *Frontiers in Earth Science*, 9, 700546. Available from: https://doi.org/10.3389/feart.2021.700546

Trigila, A., Iadanza, C. & Spizzichino, D. (2010) Quality Assessment of the Italian Landslide Inventory Using GIS Processing. *Landslides*, 7, 455–470. Available from: https://doi.org/10.1007/s10346-010-0213-0

Trigila, A., Lastoria, B., Iadanza, C., Bussettini, M., Mariani, S., D'Ascola, F., et al. (2025) Dissesto idrogeologico in Italia: pericolosità e indicatori di rischio - Edizione 2024. ISPRA, Rapporti 415/2025.

Troiani, F., Galve, J.P., Piacentini, D. & Della Seta, M. (2014) Spatial Analysis of Stream Length Gradient (SL) Index for Detecting Hillslope Processes: A Case of the Gállego River Headwaters (Central Pyrenees, Spain). *Geomorphology*, 214, 183–197. Available from: https://doi.org/10.1016/j.geomorph.2014.02.004

Vick, L.M., Böhme, M., Rouyet, L., Bergh, S.G., Corner, G.D. & Lauknes, T.R. (2020) Structurally Controlled Rock Slope Deformation in Northern Norway. *Landslides*, 17, 1745–1776. Available from: https://doi.org/10.1007/s10346-020-01421-7

Zischinsky, U. (1969) Uber Sackungen. *Rock Mechanics*, 1, 30–52.

Zocchi, M., Masciulli, C., Mastrantoni, G., Troiani, F., Mazzanti, P. & Scarascia Mugnozza, G. (2025) Automatic Landslide Prioritization at Regional Scale Through PS-InSAR Cluster Analysis and Socio-Economic Impacts. *Remote Sensing Applications: Society and Environment*, 37, 101414. Available from: https://doi.org/10.1016/j.rsase.2024.101414

How to cite this article: Berardo, G., Amato, G., Cornacchia, I., Fiorucci, M., Marmoni, G.M. & Scarascia Mugnozza, G. (2026) Multidisciplinary approach to revisit the state of activity of a deep-seated gravitational slope deformation in the frame of the Quaternary geomorphological evolution of the Central Apennines (Italy). *Earth Surface Processes and Landforms*, 51(3), e70250. Available from: https://doi.org/10.1002/esp.70250