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GEOLOGICAL MODEL OF THE STIFFE-SAN MARTINO D'OCRE RIDGE (CENTRAL APENNINES, ITALY); EVIDENCE OF MULTIPLE FACTORS DRIVING A MOUNTAIN-SCALE DEFORMATION

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EXTENDED ABSTRACT

Il seguente elaborato propone il modello geologico della dorsale di Stiffe-San Martino d'Ocre, che presenta un assetto morfo-strutturale riconducibile a un processo di DGPV (Deformazione Gravitativa Profonda di Versante). Al fine di formulare tale modello è stata applicata una metodologia di indagine multidisciplinare: 1) rilevamento geologico al fine di caratterizzare il substrato carbonatico affiorante, le strutture tettoniche e le coperture quaternarie, restituendo una Carta Geologica originale in scala 1:10.000; 2) rilevamento geomorfologico affiancato da un'attività di telerilevamento, in ragione del criterio essenzialmente gomorfologico utilizzato per determinare se la dorsale di Stiffe-San Martino d'Ocre sia affetta da un processo di DGPV, restituendo una Carta Geomorfologica in scala 1:10.000; 3) rilevamento geologico-tecnico al fine di caratterizzare gli ammassi rocciosi, tramite la determinazione delle proprietà geomeccaniche, restituendo una Carta Geologico-Tecnica in scala 1:10.000; 4) indagini geofisiche al fine di stimare lo spessore dei depositi alluvionali che colmano il settore della Valle dell'Aterno prospiciente l'area investigata. Da quanto emerso dalle varie attività di studio, la dorsale di Stiffe-San Martino d'Ocre risulta interessata da un processo di DGPV, in quanto sono ben visibili, a tutte le scale di osservazione, le morfologie diagnostiche di tali processi, quali ad esempio: doppie creste, depressioni sommitali con aree terrazzate a volte in lieve contropendenza, trincee con aperture anche plurimetriche, fratture da trazione, scarpate e controscarpate, rigonfiamenti e depositi di frana associati. Le predette evidenze morfologiche distribuite su tutto il sistema cresta-scarpata-fondo valle.

In relazione alla distribuzione spaziale degli elementi geomorfologici, è possibile riconoscere due distinti settori della dorsale coinvolti in processi di DGPV con differente estensione areale. Per quanto concerne le DGPV minori, che si sviluppano nei settori basali e marginali della dorsale di Stiffe-San Martino d'Ocre, si ipotizza che si siano sviluppate a ridosso di elementi tettonici pre-esistenti, dal momento che le ampie trincee alle spalle di queste DGPV si impostano in corrispondenza o in prossimità di faglie normali o transtensive sub-parallele al versante. Queste ultime costituiscono delle *rock damage zones* e presentano direzione di immersione favorevole alla deformazione e movimento di masse svincolate verso la Valle dell'Aterno. Le aree in deformazione di estensione maggiore sono delimitate a SW dalla scarpata morfologica di Fonteavignone-Terranera, che in alcuni settori raggiunge dislivelli fino a 500 metri; il rilevamento geologico ha evidenziato come tale lineamento non coincida con alcuno degli elementi tettonici che condizionano altrove l'assetto morfologico del rilievo. Dal momento che sulla dorsale sono evidenti numerose morfologie di origine carsica, quali inghiottitoi e doline, si ipotizza che la scarpata morfologica di Fonteavignone-Terranera possa essersi originata parzialmente da processi di dissoluzione carsica. Chiara testimonianza dell'importante ruolo svolto dal carsismo nell'evoluzione morfologica della dorsale di Stiffe-San Martino d'Ocre sono le Grotte di Stiffe, importante complesso ipogeo.

Da quanto emerso dall'indagine multidisciplinare, la dorsale di Stiffe-San Martino d'Ocre è affetta da una DGPV complessa, suddivisibile in due settori principali e con differenze al loro interno nell'associazione degli elementi deformativi. Il modello morfo-evolutivo della dorsale si può riassumere in tre fasi principali: una prima fase dove la gravità, favorita dall'energia di rilievo pre-colmamento della Valle dell'Aterno, si imposta sulle discontinuità tettoniche ad alto angolo e immergenti verso valle, causando lo sviluppo delle deformazioni gravitative nei settori marginali della dorsale; una seconda fase dove il carsismo si impone sulla dorsale, favorito dalle numerose discontinuità sub-verticali, detensionando la dorsale stessa ed il processo di deformazione gravitativa si sviluppa fino alla scarpata Fonteavignone-Terranera; una terza fase in cui il rapido colmamento della Valle dell'Aterno determina un'ulteriore modificazione delle condizioni tensionali della dorsale, portando il processo deformativo a uno stato di apparente quiescenza.

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ABSTRACT

The following paper illustrates the geological model of the Stiffe-San Martino d'Ocre ridge, which features a morpho-structural setting attributable to a Deep-Seated Gravitational Slope Deformation (DSGSD) process. The model reconstruction is based on geological and geomorphological surveys accompanied by remote sensing, geomechanical characterization, and geophysical investigations. Based on the results of the multidisciplinary analyses, it can be supposed that the Stiffe-San Martino d'Ocre ridge is affected by a DSGSD process, as diagnostic morphologies are significant at surface. The geological survey highlighted that the main morphological scarp of Fonteavignone-Terranera, does not coincide with any of the tectonic elements that influence the morphological structure of the relief. On the other way, a possible morphogenetic role for karst processes can be hypothesized, as the mountain ridge features numerous sinkholes and dolines, and the Stiffe Caves.

The morpho-evolutionary setting of the ridge can be summarised in three main phases: a first phase, when gravity-driven deformations favoured by the relief energy of the incised Aterno Valley, affected the tectonic discontinuities, causing the development of minor DGPV in the marginal sectors of the ridge; a second phase, during which karst processes dominated the ridge, facilitated by discontinuities, controlling local lateral unconfinement in the middle part of the ridge thus allowing the gravitational process to extend to the Fonteavignone-Terranera scarp; a third and last phase, when the infilling of the Aterno Valley has redefined the ridge morphology, leading the deformational process to a state of apparent quiescence.

Keywords: DSGSD, tectonics, geological model, karst processes, central Apennines, Italy

INTRODUCTION

The following study presents the geological model of the Stiffe-San Martino d'Ocre mountain ridge (Abruzzi region, central Italy), highlighting numerous clues of a DSGSD (Deep-Seated Gravitational Slope Deformation) (Fig. 1) developing along a rocky slope made by Meso-Cenozoic carbonate. The geological model is based on field surveys aimed at characterising the study area from geological, geomorphological, and geotechnical perspectives. Additionally, the surveys were complemented by remote sensing activities carried out in collaboration with the INGV (National Institute of Geophysics and Volcanology) to acquire further evidence useful for defining and delimiting the area affected by the gravity-driven deformation process.

The primary objective of this study is to understand the role played by geological conditions, structural elements inherited from the Miocene-Pliocene orogenesis, and Quaternary tectonics in the distribution of geomorphological features. An additional goal is to define the geometry and kinematics of the gravitational process.

Fig. 1 - Panoramic view of the Stiffe-San Martino d'Ocre ridge. In the foreground, clear evidence of gravitational deformations of the mountain ridge and karst processes. In the background, the Ocre Mountains

DSGSD refers to a set of complex deformation processes driven by gravity, involving significant volumes of rock masses and evolving over long periods with deformation rates on the order of a few millimetres per year (Ter-Stephanian, 1966; Zischinsky, 1966; Němčok, 1972; Mahr, 1977; Hutchinson, 1988; Dramis & Sorriso-Valvo, 1994; Agliardi *et alii*, 2012; Crosta *et alii*, 2013; Discenza & Esposito, 2021).

The case-history presented in this paper is a further, previously unknown DSGSD documented in the central Apennine (Crescenti *et alii*, 1987; Dramis *et alii*, 1987; Di Luzio *et alii*, 2004A, 2022; Martino *et alii*, 2004; Galadini, 2006; Esposito *et alii*, 2007, 2013, 2014, 2021; Moro *et alii*, 2007, 2009, 2012; Bianchi Fasani *et alii*, 2011, 2014; Discenza *et alii*, 2011, 2023; Gori *et alii*, 2014; Della Seta *et alii*, 2017; Del Rio *et alii*, 2021). The onset and development of most of the Apennine DSGSDs were clearly conditioned by the structural elements inherited by the Neogene-early Pleistocene thrust tectonics and the Plio-Quaternary normal faulting. (*e.g.* Di Luzio *et alii*, 2004; 2022; Esposito *et alii*, 2013, 2021; Moro *et alii*, 2012; Gori *et alii*, 2014). In some cases, the interaction between karst processes and DSGSDs was also evidenced (Martino *et alii*, 2004; Casini *et alii*, 2006).

It is worth noting that the criterion used to determine whether the slope is affected by DSGSD (and to characterise its boundaries, geometry, and kinematics) was essentially geomorphological. Indeed, DSGSDs are revealed, at the mountain scale, by a great variety of morphostructures, mainly depending on the local geological scenario (*e.g.* Radbruch-Hall, 1978; Bovis, 1982; Chigira, 1992; Ambrosi & Crosta, 2011; Jaboyedoff *et alii*, 2013; Bianchi Fasani *et alii*, 2014). This approach consists in identifying and inventorying linear elements such as trenches, scarps, counterscarps, double ridges,

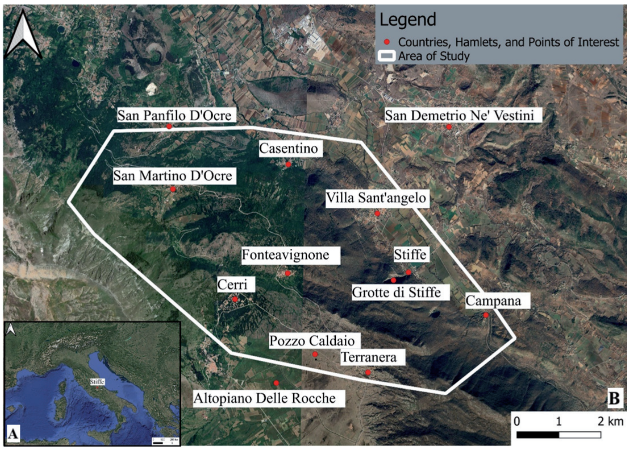

Fig. 2 - A: Geographic framework of the study area on a national scale. B: Geographic framework of the study area on a regional scale

as well as bulge evidence and landslides; successively, their spatial distribution along the slope is being analysed.

The area of interest is located in central Italy (Fig. 2A) in the axial zone of the central Apennine belt, specifically within the Sirente-Velino Regional Natural Park. Bordered to the West by the Ocre Mountains and to the East by the Aterno Valley (Fig. 2B), it extends approximately 30 km² and is characterised by high relief energy, with elevations ranging from about 500 metres a.s.l. in the Aterno Valley to approximately 1400 meters a.s.l. south of Fonteavignone village.

Apart from the gravitational deformations, the area is influenced by significant karst processes, which affect the entire investigated mountain ridge, with evidence of numerous sinkholes, dolines and residual clays.

A clear testimony of the important role played by karst in the Stiffe-San Martino d'Ocre ridge is the Stiffe Caves (Fig. 3), a karst complex that can be visited in part for a length of 700 metres with a vertical drop of 50 metres. The karst system appears to be young, as it has not yet reached the base level of the opposing valley and exhibits numerous "steps," indicating its immaturity (in some cases corresponding to fault zones). The main infiltration zone of the karst system is the sinkhole located in the Altopiano delle Rocche (Fig. 2B), with another secondary infiltration zone situated at Fonteavignone.

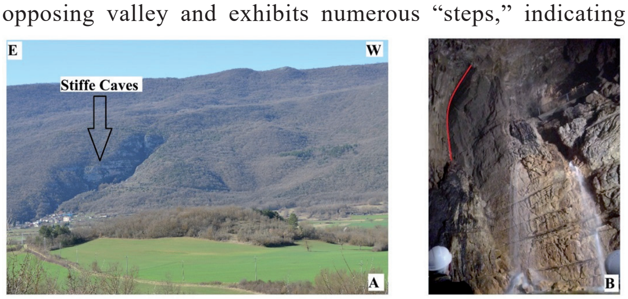

Fig. 3 - A: panoramic view of the Stiffe-San Martino d'Ocre ridge, with the Stiffe Caves on the left in the foreground and various surrounding karstic and gravity-driven features. B: the accessible section of the Stiffe Caves: the waterfall is an evidence of the cave's immaturity; in red, a fault that is part of the NNW-SSE oriented system bordering the mountain ridge towards the Aterno valley

The multidisciplinary analysis of the Stiffe-San Martino d'Ocre DSGSD allows us to discern the role played by tectonic structures and karst processes in driving the gravitational deformation in different sectors of the mountain ridge, where the morphological elements show different maturity. This testifies to a complex evolution of the local geological environment where endogenic and exogenic processes coexist.

Finally, it is acknowledged how DSGSD phenomena can have significant implications for geological risk. These slow and progressive processes can compromise the long-term stability of slopes and infrastructures, posing both direct and indirect risks to communities. As documented in the literature (*e.g.*, Crosta *et alii*, 1999, 2002; Gunzburger & Merrien-Soukatchoff V. 2002; Casson *et alii*, 2003; Di Luzio *et alii*, 2004B; Merrien-Soukatchoff V. & Gunzburger Y. 2006; Bianchi Fasani *et alii*, 2011, 2014; Loew *et alii*, 2016, 2024), slopes affected by DSGSD may evolve into catastrophic landslides, mobilising massive volumes of rock. Roads, bridges, dams, and other infrastructures built on slopes affected by DSGSD are susceptible to deformations, subsidence, or structural damage due to the slow and progressive movements (*e.g.*, Agliardi *et alii*, 2001; Frattini *et alii*, 2013). In tectonically active areas, DSGSD can exacerbate earthquake effects by triggering landslides or amplifying ground motion, thereby increasing overall the seismic risk (*e.g.*, Martino *et alii*, 2020).

GEOLOGICAL-STRUCTURAL FRAMEWORK

The study area is located in the Central Apennines, specifically within the axial sector of the belt, which is characterised by complex geological, paleogeographical, and tectonic frameworks (e.g., Centamore *et alii*, 2006; Patacca *et alii*, 2008; Cosentino *et alii*, 2010; Vezzani *et alii*, 2010). According to Patacca *et alii* (2008), the Stiffe-San Martino d'Ocre ridge belongs to the Marsica-Meta Western Unit and is situated along the regional thrust front that separates the carbonate platform units of the Velino-Sirente-Monti d'Ocre domain from the slope-to-basin units of the Gran Sasso-Genzana domain (Fig. 4). In particular, the study area straddles a sector where the compressive axes change direction from NW-SE to E-W (Fig. 4).

This sector of the belt entered the orogenic wedge and the thrust system between the Late Miocene and the Early Pliocene; the thrusting phase was followed by extensional tectonics that began in the Late Pliocene-Early Pleistocene (*e.g.*, Cavinato & De Celles, 1999). Finally, a regional uplift processes has been affecting the Central Apennines from the end of the Early Pleistocene (Dramis, 1992; Faccenna *et alii*, 1996) to the present day.

The stratigraphic sequence of the Marsica-Meta Western Unit

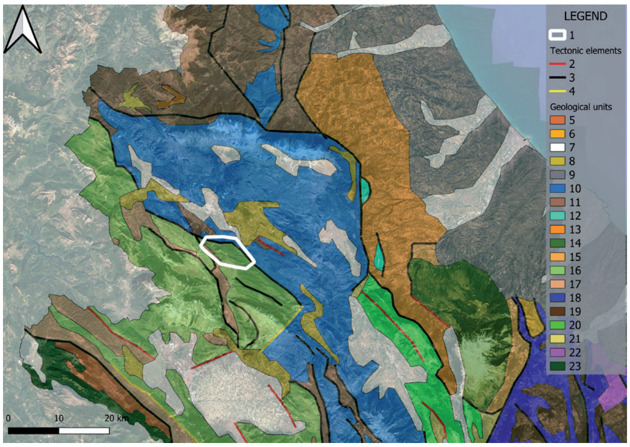

Fig. 4 - Geological-structural framework of the Central Apennines (modified from Patacca et alii, 2008). Key to the legend: 1) Study area; 2) Normal faults; 3) Thrust faults; 4) Strike-Slip fault; 5) Renga Breccias (Lower Tortonian- lower Messinian); 6) Casoli-Bomba syn-orogenic siliciclastic sequence (Lower Pliocene); 7) Continental clastic deposits (Pliocene–lower Pleistocene); 8) Intra-belt marine and continental deposits (Pliocene–lower Pleistocene); 9) Peri-Adriatic marine and continental deposits (Pleistocene-Holocene); 10) Gran Sasso-Genzana pre-orogenic carbonate sequence (Upper Triassic–Lower Cretaceous); 11) Gran Sasso-Genzana syn-orogenic siliciclastic sequence (Messinian); 12) La Queglia pre-orogenic carbonate sequence (Upper Cretaceous–Paleogene); 13) La Queglia syn-orogenic siliciclastic sequence (Messinian–lower Pliocene); 14) Majella pre-orogenic carbonate sequence (Lower Cretaceous–Paleogene); 15) Majella syn-orogenic siliciclastic sequence (lower Pliocene); 16) Marsica-Meta pre-orogenic carbonate sequence (Upper Triassic–Upper Cretaceous); 17) Marsica-Meta syn-orogenic siliciclastic sequence (Messinian); 18) Molise units pre-orogenic carbonate sequence (Jurassic/Lower Cretaceous to Tortonian); 19) Molise units syn-orogenic siliciclastic sequence (uppermost Tortonian–Messinian); 20) Morrone-Porrara pre-orogenic carbonate sequence (Jurassic–Upper Cretaceous); 21) Morrone-Porrara syn-orogenic siliciclastic sequence (Messinian); 22) Sannio-Molise thrust top basin (Miocene); 23) Simbruini-Matese pre-orogenic carbonate sequence (Upper Triassic–Upper Cretaceous)

consists of Late Triassic-Late Cretaceous, shallow-water carbonate deposits belonging to a carbonate platform environment (Accordi, 1988; Patacca & Scandone, 2007, Patacca *et alii*, 2008), which experienced significant subaerial exposure events during the Albian and Aptian. In the study area, the carbonate sequence is characterised by Lower Cretaceous formations, showing a large amount of detritic and biodetritic material, dominated by Rudist assemblages. The Mesozoic sequence ends with a significant Paleogene hiatus and is overlain by Middle to Late Miocene carbonate ramp deposits, which are followed upward by Upper Messinian flysch deposits, preceding the salinity crisis event.

Quaternary deposits unconformably overlain the carbonate units and, include alluvial terrains along the northeastern edge of the mountain ridge (Civico *et alii*, 2017) and colluvial and detrital deposits filling small depressed sectors within the middle and upper part of the mountain slope.

METHODOLOGY

Geological survey

The geological survey was conducted at a 1:10.000 scale and primarily focused on the characterisation of the Cretaceous-Miocene carbonate bedrock and the definition of the geological-structural setting of the Stiffe-San Martino d'Ocre ridge. Secondarily, the Quaternary units were identified along the piedmont junction zone and within the mountain ridge.

The carbonate substrate was analysed using a lithostratigraphic criterion, with the help of macro- and micro-fossil observations and following the guidelines from the CARG sheet 359 "L'Aquila". The geometric attitude and spatial relationships between the various formations were investigated through intensive bedding measurements (dip direction/dip value), even useful for a dip domain analysis. The Quaternary deposits were subdivided based on their depositional processes, texture and granulometry.

Tectonic elements were mapped, taking observations of kinematic indicators (where present) and of the geometric relationships between geological units. In several sites, tectonic elements exhibited multiple series of kinematic indicators, evidencing different phases of activity with varying kinematics.

Outcropping lithologies

- *Cyclothemic Limestone with Gastropods (CCG)*

This unit forms the backbone of the lower sectors of the Stiffe-San Martino d'Ocre ridge. It consists of massive to well-layered beds of mud-supported limestone with frequent intercalations, in the upper section (Fig. 5A), of plurimetric beds of wackestones and packstones with Nerineids (Fig. 5B). According to the CARG Guideline, the upper boundary of this formation unit is defined by the appearance of Rudist assemblages belonging to the overlying RCO Unit; finally, the CCG estimated thickness is estimated approximately 600 metres. (Age: Valanginian - Early Barremian).

- *Limestone with Requienia, Caprotinae, and Ostreidae (RCO)*

This unit is made by biodetritic limestone, primarily packstones-grainstones with Rudist assemblages, arranged in thick (100-150 cm) to very thick or even massive layers.

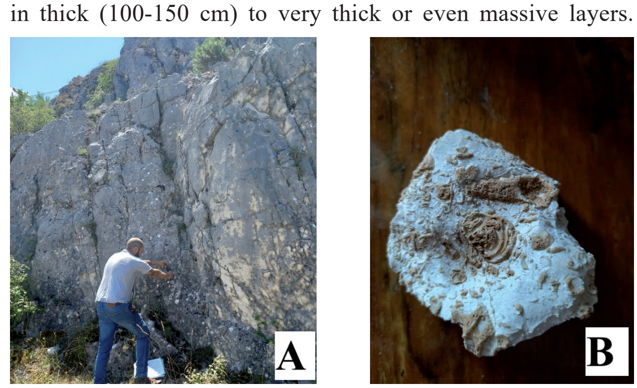

Fig. 5 - A: CCG outcrop showing plurimetric layers. B: Bioclastic level with gastropods

These are interspersed with horizons composed of mudstones-wackestones containing benthic foraminifera, algae, and/or ostracods (Fig. 6A). Massive biodetritical beds have great resistance to weathering and erosion. This results in limestone cliffs, *i.e.*, prominent morphologies compared to the surrounding geological units. The macrofaunal content in the study area mainly includes Requieniidae and Ostreidae (Fig. 6B), and its estimated thickness is approximately 200 metres.
(Age: Late Barremian - Early Aptian *p.p.*).

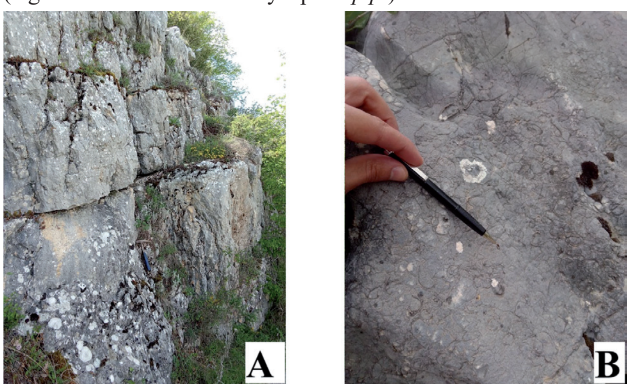

Fig. 6 - A: Outcrop of RCO strata with a metric thickness. B: Layer rich in bioclastic material

- *Limestone and Marls with Salpingoporella dinarica and Charophyta (CMS)*

Lithofacies variability characterise this unit, cropping out in the middle and upper parts of the mountain slope. Three main members were identified. Heterometric and heterogeneous breccias are present at the base of the unit, with clasts ranging from centimetres to decimetres in size and composed of lithotypes from the underlying limestone units. The breccias are followed upwards by well-bedded mudstones interlayered with green marls and marly limestone (Fig. 7A), occasionally containing horizons rich in Charophyta oogonia. The calcareous lithotypes often feature an abundant presence of Dasycladacean algae (Salpingoporella dinarica). The thickness of the lower and middle levels of the CMS formation is highly variable, averaging 3-4 metres, with maximum thicknesses reaching approximately 15 metres.

The depositional sequence ends with about 30 metres of limestone, marly limestone, and marls (Fig. 7B), whose facies reflect sedimentary environments varying from marine to coastal-palustrine areas. The marine facies are predominantly composed of mudstones-wackestones with benthic foraminifera, ostracods, Dasycladacean algae (Salpingoporella dinarica), and peloids. In contrast, the green marls and marly limestones with Charophyta are associated to swamps and coastal lakes. The overall thickness of this unit in the study area is approximately 80-100 metres.
(Age: Early Aptian *p.p.*).

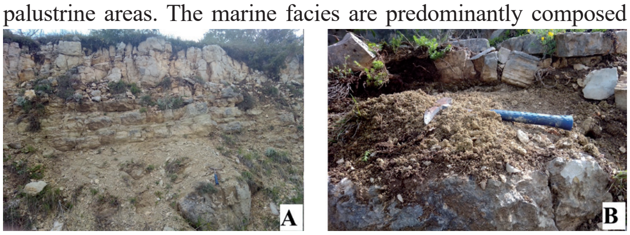

Fig. 7 - A: Outcrop of limestone and marls of the middle member of the CMS formation. B: Marl-rich layer within the uppermost member

- *Cyclothemic Limestone with Requienia (CIR)*

The most recent Lower Cretaceous formation outcrops extensively in the upper part of the Stiffe-San Martino d'Ocre ridge. It is composed mainly of mud-supported limestones, such as mudstones and wackestones, with poor biogenic content. Limestone are well-layered with thicknesses ranging from 60 to 120 cm (Fig. 8A). The lithofacies are typical of peritidal and subtidal cycles (Fig. 8B). The microfauna is often represented by oligotypic faunas (mainly miliolids and ostracods), except for some horizons containing orbitolinids. The macro-paleontological content is limited to two horizons with Requieniidae (Fig. 8C). The estimated thickness of this unit in the study area is approximately 250 metres.
(Age: Upper Aptian - Lower Albian *p.p.*).

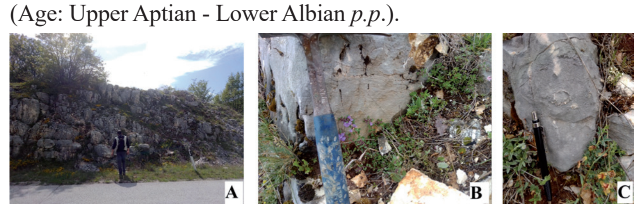

Fig. 8 - A: Outcrop of cyclothemic limestone with Requienia. B: Stromatolitic layer within the CIR formation. C: Requienia

- *Bryozoan and Lithothamnion Limestone (CBZ)*

The unit includes Middle-Upper Miocene carbonate deposits ascribable to an open ramp environment. It is characterised by notable lithofacies variability as annotated in the CARG guidelines, which has led to its division into three members. In this study, only the uppermost member (CBZ3) is exposed, with thicknesses ranging from 50 to 200 metres. This member overlies the Lower Cretaceous limestones of the CIR unit in unconformity, as clearly visible in the Cerri-Terranera locality. Locally, the Miocene carbonate lie directly on the RCO unit. The lithofacies are represented by calcarenites-calcirudites organised in meter-thick layers (Fig. 9A), with abundant bryozoans, amphistegines, lepydocyclines, and fragments of lithothamnids. The macrofossil content consists of abundant bryozoans and lithothamnids, often associated with frequent fragments of bivalves (Fig. 9B). The estimated thickness of this unit is approximately 200 metres.
(Age: Langhian p.p. - Serravallian; locally p.p. Tortonian).

Geomorphological survey and remote sensing

The geomorphological analysis was focused on identifying and characterising the morphological features potentially attributable to a DSGSD process, through both field surveys and remote sensing observations. Aerial-photo interpretation was carried out

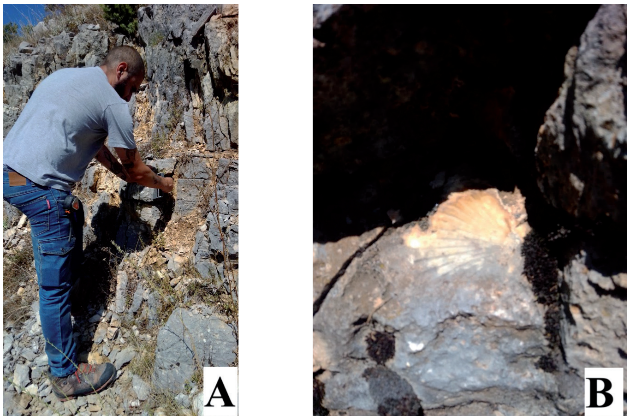

Fig. 9 - A: Outcrop of Limestone with Bryozoans and Lithothamnion. B: Pecten

at the INGV headquarters in Rome using an SD2620W-PLANAR digital stereoscope (Fig. 10A). The instrument operates through two 26-inch monitors polarized at 45° and 135°. These, together with a beam-splitter mirror and glasses (with lenses also polarized at 45° and 135°), enable 3D stereoscopic viewing of digital stereo-pair photographs. Aerial photographs were obtained from the *"Volo Italia"* survey, 1994, at a scale of 1:70,000 (Fig. 10B).

Additional observations were obtained from the analysis of satellite imagery (Google Earth) and the Digital Terrain Model (DTM), with a resolution of 10 meters, obtained through the "*Geoportale Nazionale*".

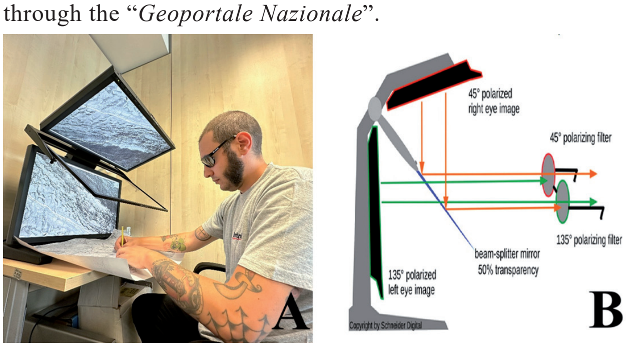

Fig. 10 - A: Photo-interpretation activities performed at INGV. B: Schematic representation of the stereoscope

Geomechanical survey

The geomechanical analysis was performed to characterise rock masses and determine their geomechanical properties. The parameters measured are as follows: 1) uniaxial compressive strength JCS (Joint Wall Compressive Strength), determined using a Schmidt hammer; 2) Jv (Joint volumetric index), *i.e.* the total number of discontinuities for unit volume (1m^3) of rock mass; 3) JRC (Joint Roughness Coefficient) that was acquired using the Barton comb profilometer; 4) RQD (Rock Quality Design), it was estimated through the empirical relationship of Palmström (1982): RQD = 115 − 3.3 * Jv; 5) RMRb (Rock Mass Rating base) by Bieniawski (1993); 6) GSI (Geological Strength Index) for homogeneous rocks by Hoek & Brown (1997).

Eleven measurements sites were characterised, with at least two sites for each formation. Discontinuity sets were represented using stereographic projections, with the freeware software Stereonet. Based on the geomechanical characterisation of the rock masses, a geological-technical map of the area was elaborated, grouping the geological formations into geological-technical units mainly based on the thickness of the layers and the values of JCS.

Geophysical Measurements

Geophysical investigations were carried out to gather information on the thickness of the Quaternary alluvial deposits filling the sector of the Aterno Valley that borders the investigated slope, in order to provide an indicative assessment of the maximum relief energy (Di Giulio *et alii*, 2020; Giannini *et alii*, 2021).

To achieve this goal, four single-station of seismic ambient noise measurements were acquired using sensors (Pasi type: 3DLG-2) with a natural frequency of 2 Hz and analysing traces according to the HVSR technique (Horizontal-to-Vertical Spectral Ratio, Nakamura, 1989). Each measurement was recorded for 1200 seconds following a preliminary 180-second test (Fig. 11A). The measurements were conducted along a "transect" perpendicular to the valley's longitudinal axis; stations location was determined using a "Garmin eTrex 32x" GPS (Fig. 11B) and subsequently plotted onto satellite images (Fig. 11C).

Values and variation trends of the fundamental frequency were identified. This allowed estimating the thickness of the soft

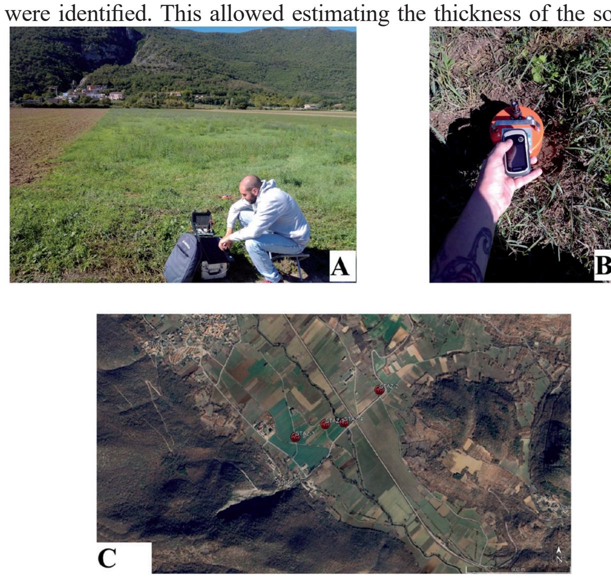

Fig. 11 - A: Acquisition of seismic ambient noise measurements in the Aterno Valley; in the background, the village of Stiffe. B: Recording the positions of noise measurements using GPS. C: Satellite image showing the location of the points where ambient noise measurements were conducted. Image source: Google Earth

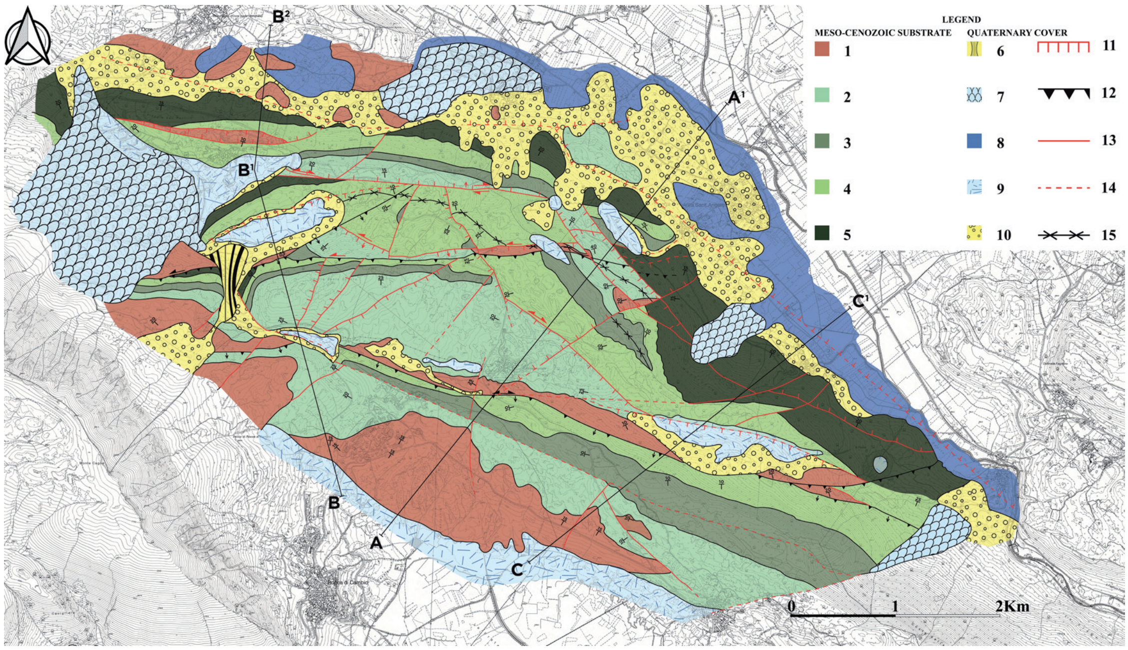

Fig. 12 - Original geological map of the Stiffe-San Martino d'Ocre Ridge. Key to the legend: 1) Bryozoan and Lithothamnion Limestone (CBZ); 2) Cyclothemic Limestone with Requienia (CIR); 3) Limestone and Marls with Salpingoporella dinarica and Charophyta (CMS); 4) Limestone with Requienia, Caprotinae, and Ostreidae (RCO); 5) Cyclothemic Limestone with Gastropods (CCG); 6) Debris Fan deposits; 7) Landslide deposits; 8) Recent alluvial deposits; 9) Eluvio-Colluvial deposits; 10) Slope debris; 11) Normal fault; 12) Reverse fault; 13) Strike-Slip fault; 14) Supposed fault; 15) Syncline axis

sediments resting on the carbonate rigid bedrock. Finally, the obtained data were compared with extensive noise measurements previously conducted by other researchers (Civico *et alii*, 2017).

RESULTS

Geological map

Field surveys produced an original geological map of the Stiffe-San Martino d'Ocre ridge at a 1:10.000 scale (Fig. 12). The carbonate bedrock shows an overall structure of a SW-dipping monocline, complicated by a tight syncline observed in the middle part of the slope, that widens toward the north-western sectors. The carbonate ridge is separated from the Aterno Valley by high to very high-angle, NE to E-dipping faults, with dip values ranging from 60° to 80°. Many of these structures display various kinematic indicators that attest a dip-slip kinematics following strike-slips to oblique movements (Fig. 13A). Along the slope, it was observed that these predominant tectonic features rotate from a preferential NW-SE orientation in the central-southern sectors (Stiffe) to a more pronounced E-W orientation in the central-northern sectors (San Martino d'Ocre).

Within the carbonate ridge and nearby the Fonteavignone-Terranera main scarp (Fig. 2), faults with a WNW-ESE orientation and SSW-dipping were identified, showing a sub-vertical attitude. The kinematics of these tectonic elements was inferred by analysing both indicators on fault planes and the geometric relationships between different formations. It was found that some faults exhibit a reverse kinematics, resulting in Cretaceous limestones tectonically overthrusting the Miocene ramp deposits (Fig. 13B) along two main alignments (Fig. 12). In addition to the tight syncline, the heritage of compressional

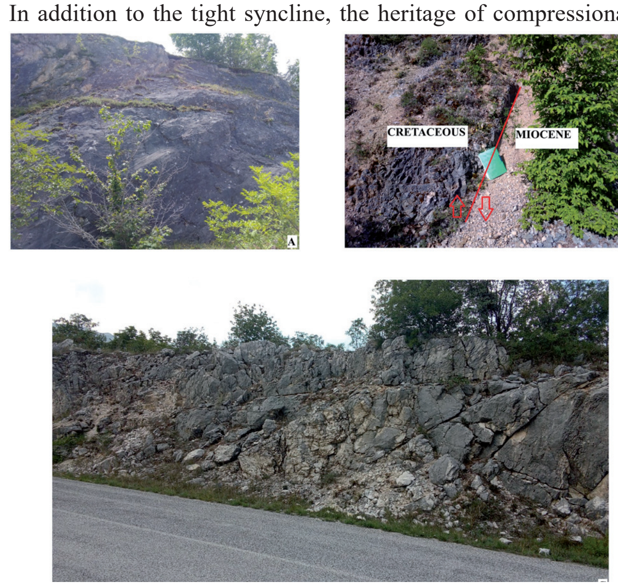

Fig. 13 - A: Fault surfaces within the CIR unit, with multiple kinematic indicators suggesting both right-lateral and left-lateral transtensional dislocations, and normal fault movements. B: High-angle reverse fault bringing the Lower Cretaceous RCO unit over the Miocene carbonate (Fonteavignone). C: Duplex-like structure exposed within the RCO formation (San Martino d'Ocre)

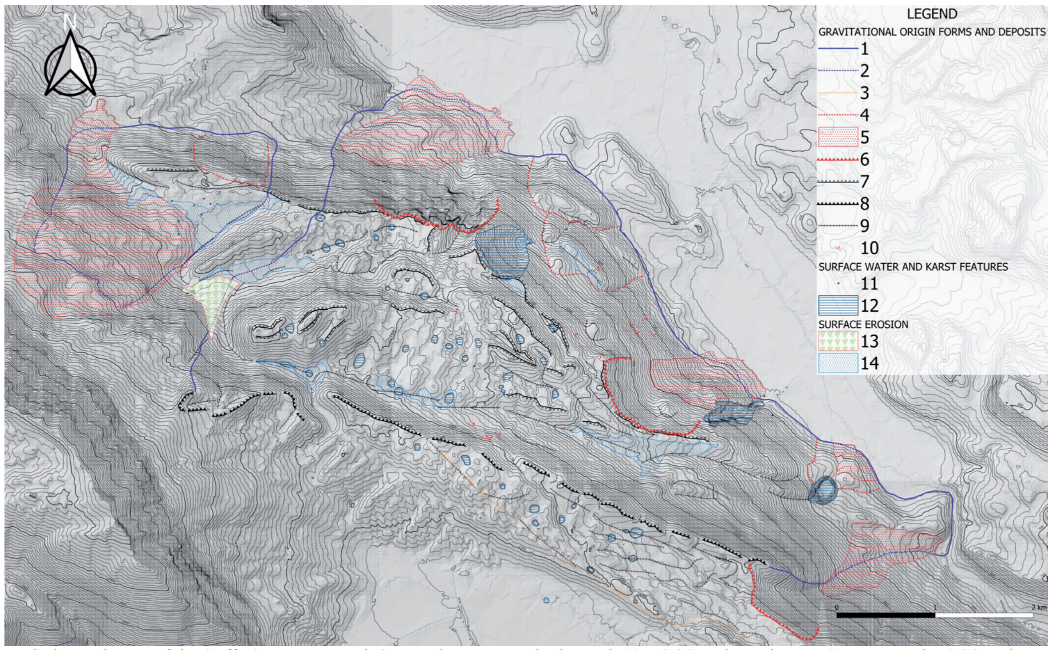

Fig. 14 - Geomorphological map of the Stiffe-San Martino d'Ocre ridge. Key to the legend: 1) DSGSDs boundaries; 2) presumed DSGSDs boundaries; 3) limit of the detensioned zone; 4) minor DSGSDs; 5) landslide accumulation area; 6) landslide scarp; 7) scarps and counterscarps; 8) main scarps; 9) trench; 10) newly- formed shear surfaces; 11) springs; 12) karst morphologies; 13) debris fan; 14) eluvial and colluvial deposits

tectonics in the study area includes also mesoscale, thrust-related structures (Fig. 13C). However, strike-slip kinematics was also evidenced on the afore-mentioned reverse faults, thus suggesting an intermediate tectonic phase occurred between pure thrusting and late normal faulting in the study area.

Geomorphological map

The data collected from the geomorphological survey and remote sensing activities resulted in a geomorphological map at a 1:10.000 scale. This map covers the same area as the geological map but extends several hundred metres further to the NW and SE to better highlight significant features related to gravitational deformations (Fig. 14).

Geological-technical map and rock mass characterisation

The geomechanical characterization of rock masses resulted in a geological-technical map at a 1:10.000 scale (Fig. 15). Four geological-technical units have been identified:
1) massive limestone; 2) stratified limestone; 3) heterogeneous limestone; 4) Quaternary covers. As previously mentioned, grouping the geological formations into geological-technical units was mainly based on the beds thickness and JCS values.

Geophysical measurements

The reduced number of ambient noise measurements acquired and elaborated using the HVSR technique and the lack of information on the Vs of the infilling deposits in the Aterno Valley, disabled a reliable thickness estimation. However, data collected in this work were framed into the extensive noise measurements taken by Civico *et alii*, (2017) in the same area.

In this context, *F0* values ranging between 0.7 and 1.8 Hz were determined at station 1-4. Then, the relationship $F0 = Vs / 4H$, where *F0* is the fundamental frequency, *Vs* and *H* are the shear-wave velocity and the thickness of resonant layer, was adopted. This allowed the estimation of the soft sediment thickness within a 70-190 metres interval (Baoqing *et alii*, 2019; Thabet, 2019; Giannini *et alii*, 2021), assuming a Vs value of approximately 550 m/s, based on bibliographic references (Civico *et alii*, 2017).

Finally, Civico *et alii* (2017) measured frequencies of about 0.4 Hz in the immediate vicinity of the measurements sites 1-4. Leaving out significant Vs variation, this would implied a soft sediment thickness of 460 metres suggesting a complex geometric setting of the carbonate bedrock, likely due to tectonic fragmentation.

DISCUSSION

Based on the multidisciplinary studies conducted in the area, the Stiffe-San Martino d'Ocre ridge shows evidence of a Deep Seated Gravitational Slope Deformation (DSGSD). The geomorphological survey, supported by remote observations, highlights the presence of morphologies typically associated with DSGSDs. Specifically, the following features were identified and mapped in the upper and middle part of the slope: trenches with meter-wide openings (Figs. 16A, 16B, 16E), alignments of scarps and counter-scarps (Figs. 16A, 16B), double ridges (Fig. 16C), and

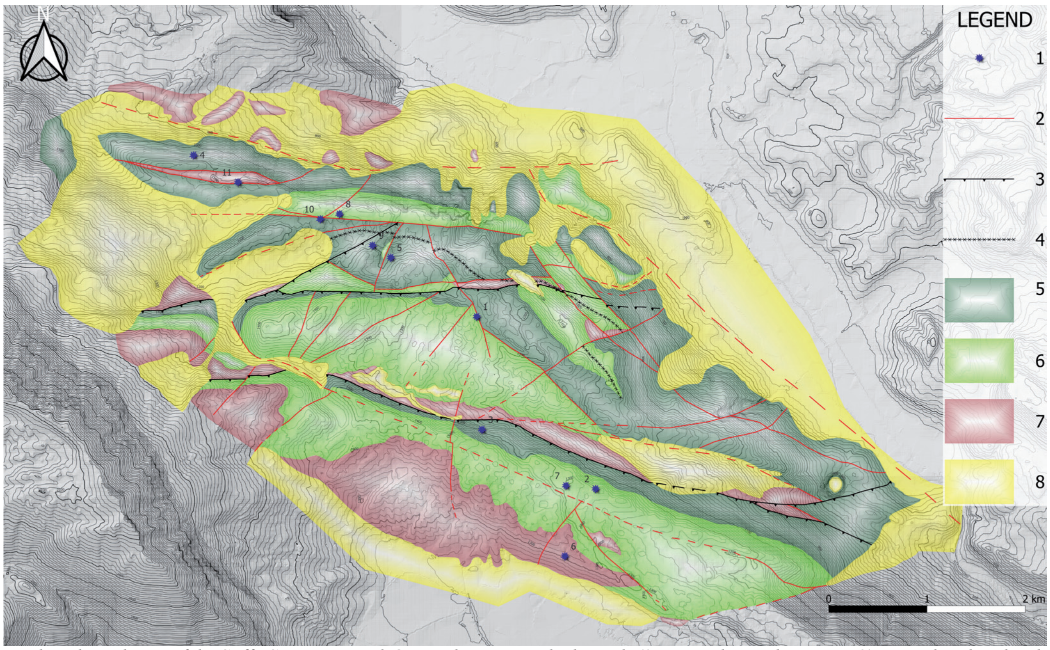

Fig. 15 - Geological-Technical map of the Stiffe-San Martino d'Ocre ridge. Key to the legend: 1) geomechanical stations; 2) normal and strike-slip fault; 3) reverse fault; 4) synclinal axis; 5) Massive Limestone Unit; 6) Stratified Limestone Unit; 7) Heterogeneous Limestone Unit; 8) Quaternary Cover Unit

detensioned tectonic discontinuities (Figs. 16F, 16G). In addition, an increase in rock mass fracturing and several large landslide deposits (Fig. 12) were recognized along the slope edge.

Gravitational processes can be distinguished into two distinct areas (DSGSD 1 and DSGSD2 in Fig. 17) based on the distribution of geomorphological elements and the presence of an interposed sector lacking diagnostic morphologies and coinciding with the western sectors of the mid-slope syncline. As pointed out by some authors (*e.g.*, Agliardi *et alii*, 2001; Discenza & Esposito, 2021), the boundaries of gravitational deformations at the slope scale are difficult to recognise and define with certainty, and the study area in question is no exception.

The north-eastern limit of DSGSD1, the widest area under deformation, follows the boundary between the carbonate slope and the Aterno Valley, and is partially masked by a wide landslide deposit north of the Stiffe cave. To the south, the main limit is identified along the Fonteavignone-Terranera morphological scarp; to the west, the same limit is poorly defined, being hidden by a Quaternary debris cone and landslide deposits; finally, to the north-west, the DGSD boundary coincides with the valley floor and the limit of the alluvial deposits of the Aterno Valley.

Within DSGSD1, in addition to deformation features located outside of the slope, in the proximity of the Aterno Valley, a more internal detensioned zone is developed south of the Fonteavignone-Terranera main scarp (Figs. 14, 17). This zone is characterised by swarms of trenches with meter-wide opening and decametric extension but reduced depth and infilling, often accompanied by

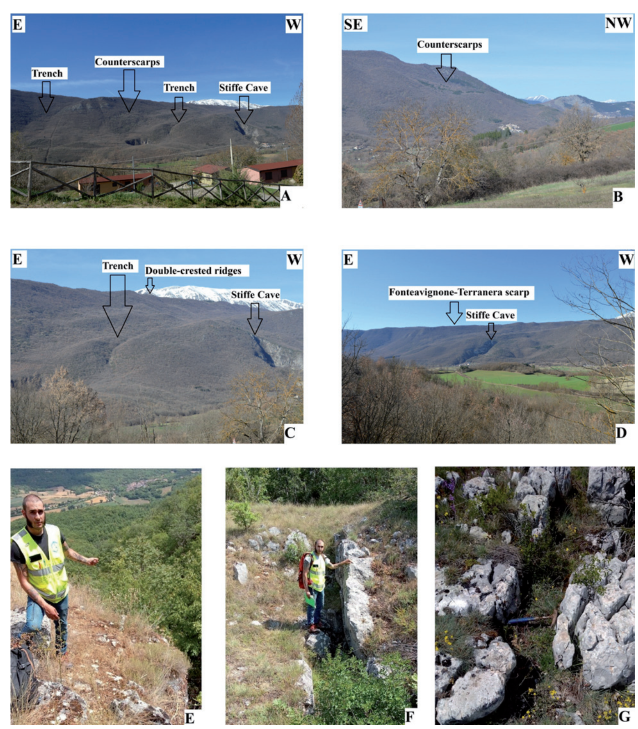

Fig. 16 - A: Panoramic view of the study area showing both gravity-driven and karst morphologies including the Stiffe Caves; B: Counterscarp observed southwest of the Villa Sant'Angelo village. C: Large trench and double ridges documented southwest of the Stiffe village. D: Fonteavignone-Terranera main scarp, the Stiffe Cave appears in the foreground. E: one of the main trenches with meter-wide openings and extension. F,G: detensioned tectonic lineaments

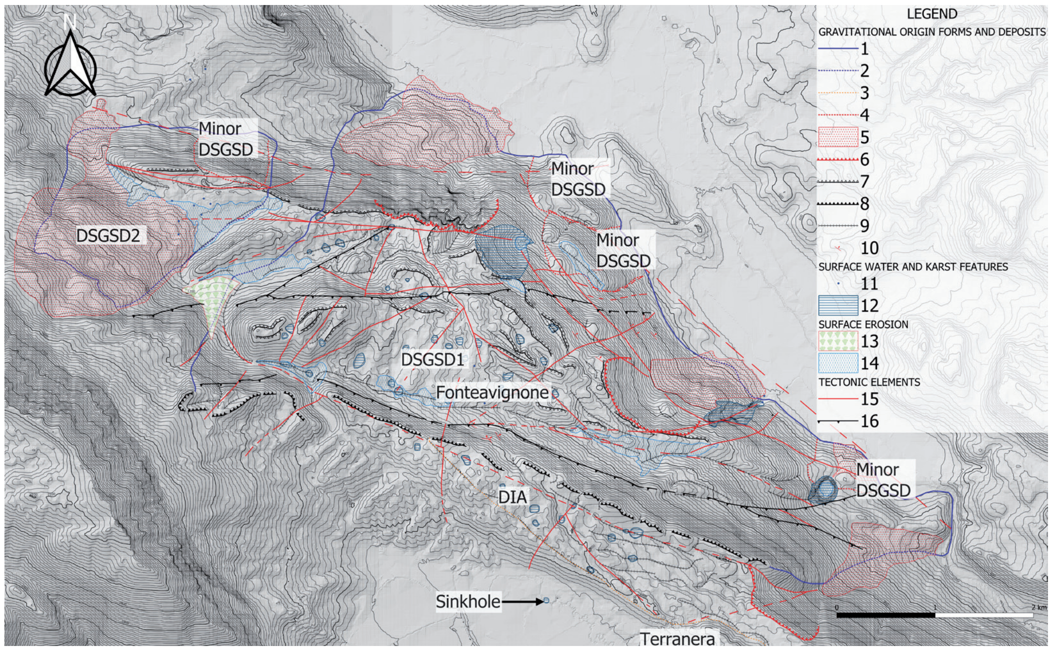

Fig. 17 - Geomorphological map with tectonic elements. DIA = Detensioned Internal Area. Key to the legend: 1) DSGSDs boundary; 2) supposed DSGSDs boundary; 3) limit of the Detensioned Internal Area; 4) minor DSGSDs; 5) landslide accumulation area; 6) landslide scarp; 7) scarp and counterscarp; 8) main scarp; 9) trench; 10) newly-formed shear surface; 11) spring; 12) karst morphologies; 13) debris fan; 14) eluvial-colluvial deposits; 15) normal and strike-slip fault; 16) reverse fault

karst morphologies. This tensile stress-relief zone extends to the east of Terranera, suggesting a possible evolution of DSGSD1 toward the southeast (Figs. 14, 17).

Similarly to DSGSD1, also the less extended DSGSD2 has boundaries that are only partially recognisable. In the foothill area, to the north, the limit coincides with the base of the rocky slope facing the Aterno Valley. To the south, in the upper part of the slope, the deformation area includes a large rotational landslide affecting flysch deposits, in their turn covered by a wide carbonate debris mantle. The detritic rock material plays a role in water transfer, leading to several water springs in the San Martino d'Ocre area (Fig. 17).

As afore-mentioned, both DSGSD1 and DSGSD2 areas include smaller gravitational deformations (minor DSGSD in Fig. 17), which have developed in the basal and external sectors of the Stiffe-San Martino d'Ocre ridge. It is documented that these gravity-driven processes developed near pre-existing tectonic elements. The large trenches behind these minor DSGSDs are aligned or located near the faults with NW-SE and E-W orientations and displaying complex kinematics, both normal and strike-slip. Due to hanging-wall blocks downthrown these inherited tectonic elements, generally NE-dipping, caused a significant slope unconfinement towards the Aterno Valley. Moreover, they constituted rock damage zones along which gravity-driven deformations have developed through detaching of rock masses toward the Aterno Valley (Figs. 17, 18, 19, 20). Trenches behind the detached masses are wide open and fulfilled with colluvial and detrital deposits, thus testifying to a mature process. Finally, the extension of these external, minor DSGSD, was influenced at least for the DSGSD1 are by the geometry of the tight syncline characterized by a high-dipping western limb and a highly-tectonized core, including the lower most of the afore-mentioned reverse faults (Fig. 17).

From the geological cross sections (Figs. 18, 19, 20), it is evident that the high-angle reverse faults located in the middle and higher sectors of the slope, characterised by a SW dipping attitude, are not favourable for the development of gravity-driven deformation with a polarity towards the northeastern sectors and the Aterno valley. Therefore, contrarily to the development of the smaller, external DSGSDs, both DSGSDs, inherited tectonics did not play a decisive role in more internal slope areas. Consequently, the origin and development of trenches, scarps, and counter-scarps in the stress-relieved zone behind the Fonte Avignone-Terranera main scarp - and perhaps in the middle part of the slope, south of the syncline area, might be attributed to other factors. It is possible that the karst dissolution of the carbonate mass has contributed to the development of deformations across the entire ridge. To support such a hypothesis, it can be noted how the morphological scarp of Fonteavignone-Terranera, which in some areas reaches elevations of up to 500 metres, does not coincide with any tectonic elements. It follows that the topographic depression ahead, clearly visible in profiles A-A' and C-C' (but also present along trace B-B'), could have been originated from karst processes.

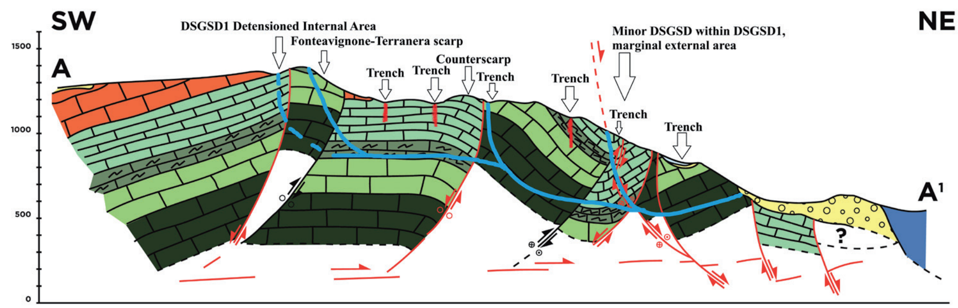

Fig. 18 - Geological Profile A-A[1] passing through the DSGSD1 area (see trace in Fig. 12) and showing geomorphological elements. The minor DSGSD is superimposed on the boundary faults dipping to the NE. The geometry of the basal deformation surfaces/zones (BDZ) is hypothesised in blue, while the deformation/damage zones are shaded in red

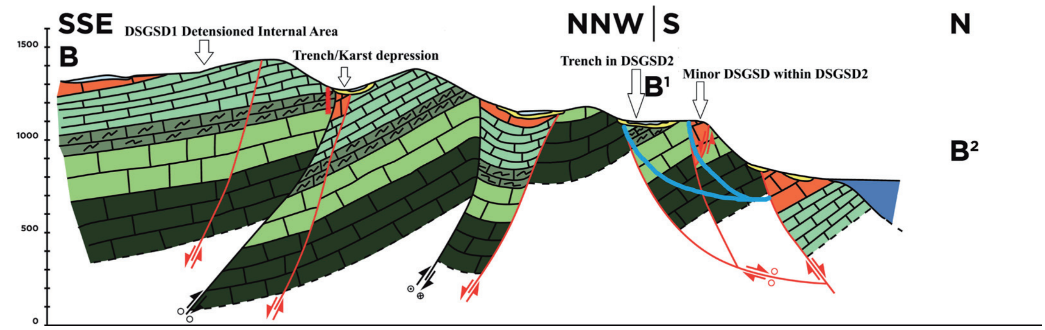

Fig. 19 - Geological Profile B-B[1]-B[2] (see trace in Fig. 12): The minor DSGSD within DSGSD2 is superimposed on the faults dipping to the N and NE. The geometry of the basal deformation surfaces/zones (BDZ) is hypothesised in blue, while the deformation/damage zones are shaded in red

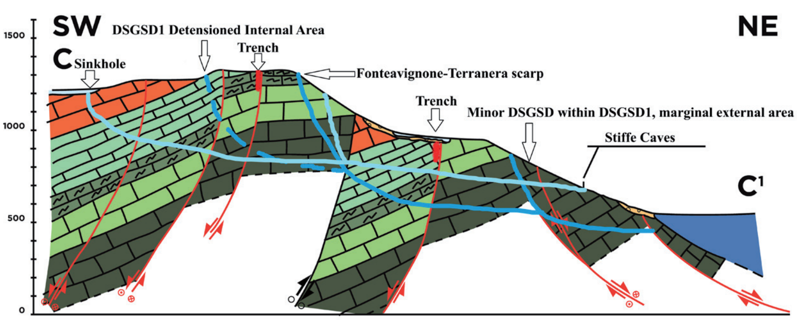

Fig. 20 - The geological profile C-C[1] (see trace in Fig. 12) passes through the Fonteavignone-Terranera morphological scarp and the Stiffe Caves. The profile shows the hypothesised geometry of the basal deformation surface or zone (represented in blue), the damaged zones (shaded in red), and the karstic path (highlighted in light blue)

CONCLUSION

While the role of tectonics in the onset of immature gravitational deformations appears limited in the upper part of the Stiffe-San Martino d'Ocre ridge, the development of the more external gravitational slope deformations, near the margins of the slope, has been facilitated by the presence of high-angle border faults dipping toward the east and northeast. These faults have influenced the location and geometry of rear scarp and trench zones, as these morphological features formed along weakness zones (rock damage zones). Besides, and their dip-slip kinematics contributed to the creation of a significant relief, now reflected in the approximately 800-metres topographic displacement between the slope and valley floor.

If a complete erosion of the Aterno alluvial valley is imaged before the accumulation of the 450 metres-thick alluvial deposits (a thickness estimated from geophysical measurements), it is possible to envision a topographic relief even greater than the present condition, up to 1200-1300 metres of elevation difference between the top of the slope and the valley floor. The progressive infilling of the Aterno Valley could, therefore, have been determined the apparent quiescence of the deformational process, which would have been partially confined in its movement with a north-eastward polarity. This deactivation is also suggested by the

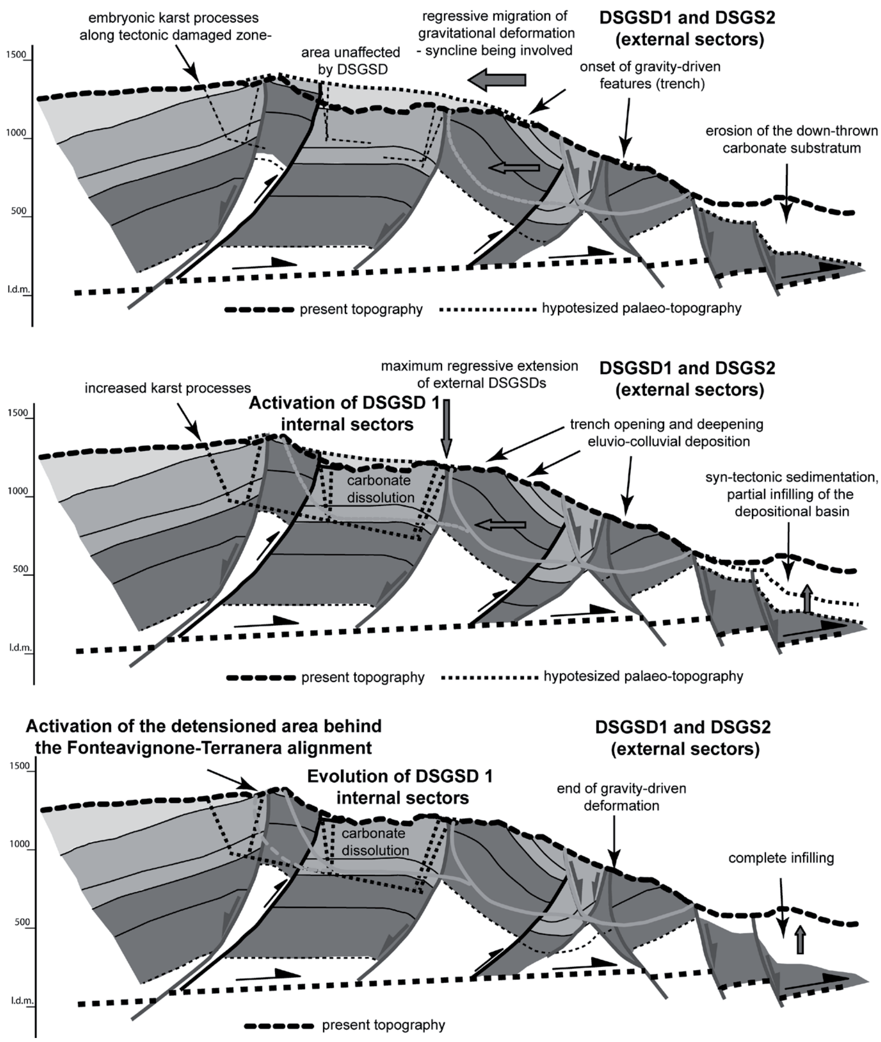

Fig. 21 - Proposed morpho-evolutionary model of the Stiffe-San Martino d'Ocre ridge

presence of abundant eluvio-colluvial material in the trenches behind the minor DSGSD and by a preliminary analysis of interferometric data. However, further investigation dedicated to the reconstruction of the Quaternary tectono-sedimentary evolution of the Aterno Valley are necessary to validate such this hypothesis.

In conclusion, based on the integrated geologic model presented in this paper, the Stiffe-San Martino d'Ocre ridge is affected by a complex gravitational slope deformation, which can be divided into two main sectors with internal differences in related geomorphological features and their distribution. The morpho-evolutionary frame of the ridge can be summarised in three main phases (Fig. 21):

1. First phase: gravity-driven deformation acts on the tectonic discontinuities, and the pre-filling relief energy of the Aterno Valley favours the development of (minor) DSGSDs in the marginal sectors of the ridge.
2. Second phase: karst processes developed in the middle part of the slope, favoured by sub-vertical discontinuities creating preferential infiltration zones (especially within the present DSGSD1 area). Enhanced dissolution eroded large volumes of carbonate rock and local slope unconfinements, causing the gravitational process to extend south of the Fonteavignone-Terranera main scarp.
3. Third phase: the progressive infilling of the Aterno Valley redefines the ridge morphology, bringing the deformational process to the present state of apparent quiescence, as indicated by geomorphological markers and preliminary interferometric analysis.

These hypotheses, although requiring further investigations and more detailed reconstructions including a numerical modelling for validation, are compatible with the morpho-structural framework outlined in this work.

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