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CARLO BO

Università degli Studi di Urbino Carlo Bo

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THE ROLE OF MORPHO-STRUTURAL SETTINGS ON ROCKY COASTS INSTABILITY

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Coordinator: Prof. Alessandro Bogliolo

Supervisor: Prof. Marco Menichetti

Ph.D. student: Davide Torre

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Summary

Rocky coasts are among the environments where various processes act on landscape evolution across different spatial and temporal scales. Over the past few decades, they have garnered growing attention from the scientific community, especially with the ongoing Global Change that exacerbating the evolution of some phenomena endangers both the local communities and tourism. The study of rocky coasts is often challenging due to inaccessibility of some sites, leading to a reliance on remote sensing methods. In the present day, remote sensing techniques play an important role for natural risk assessment, but there is a tendency to overlook the importance of fundamental field data for accurate interpretation and evaluation of active surface processes. This thesis underscores the role of the geomorphological factors in the evolution of rocky coasts and in particular aims at understanding their morpho-structural evolution through the combination of field surveys and remote sensing analyses which are essential for obtaining accurate insights into interactions with vulnerable elements. To achieve this goal, three study areas representative of rocky coasts with different evolutionary scenarios were selected and investigated: Mt. Conero and Mt. San Bartolo along the western coasts of the Adriatic Sea (Italy) and La Herradura section in the coastal sector of the Granada province (Spain). The methodology of this study has allowed for a comprehensive understanding of sea slope evolution and how to mitigate the associated natural risks.

This Ph.D. thesis is organized as follows:

In **Chapter I** the main context and objectives of this work are presented with a general description of the study areas. The state of art on the role of geomorphological and structural factors as well as on the analytical techniques for the purpose of a correct assessment of geohazards is discussed. A general review of the rocky coasts is carried out: their distribution

over the world and Mediterranean coastlines, touristic and socio-cultural importance, classifications implemented to date, and erosional processes acting on the coastal slopes. The following section describes the geodynamic and geological frameworks of the two regions in which the study areas are located. The first, which includes two of the three study areas, is the Peri-Adriatic sector (Italy) characterized by sedimentary rocks and the second is the coast of the Granada Province (Spain), where metamorphic rocks of the Alpujárride Complex crop out.

In **Chapter II**, the tools and methodologies used to collect the data and carry out the analyses are described. Here, the methods, platforms, and software used for all the study areas are illustrated, from data acquisition to processing with photogrammetric software to create 3D point clouds model, resulting in high-resolution orthomosaics and Digital Surface Models (DSMs). In the individual methodological sections of the following chapters dedicated to the single case studies more details on the methodologies used are provided. In addition to bibliographic research, a variety of remote analysis and field survey techniques were used: consultation of Synthetic Aperture Radar Interferometry (InSAR) data, use of low-altitude aerial photos by Unmanned Aerial Vehicles (UAVs), use of digital applications for surveying and data storage, and use of spatial analyses, such as the Land-Surface Quantitative (LSQ) analysis, in Geographic Information System (GIS) environment.

Chapter III presents the Mt. Conero case study, with detailed geological and geomorphological maps. In this case, a combination of field surveys and LSQ analysis, through the use of slope angle and roughness variables, was carried out to determine the evolution of the coastal slope. In the same coastal slope different morphodynamic styles have been detected, as a consequence of the different attitudes of strata and joints. Subsequently, the numerical modelling on Portonovo landslide strengthened the conceptual model of the area and clarified the evolution of the main Conero landslide, which developed through two gravitational phenomena, the first around 56 and the second at 16 ka.

Chapter IV describes the work made on Mt. San Bartolo coastal cliff, focusing on the use of LSQ analysis to detect of the spatial distribution of landslide areas. Using four morphometric indices (slope, elevation standard deviation, roughness, and terrain ruggedness index), it was possible to discriminate landslide areas and different kinematic styles. This was correlated with the morpho-structural settings, identifying a strong litho-structural control on the evolution of the cliff.

In **Chapter V** the case of La Herradura coastal stretch is discussed. Here, due to heavy urbanization, it was not possible to carry out an LSQ analysis, but InSAR data were consulted. Thanks to the analyses carried out, the importance of the geomorphological investigations to understand the on morpho-structural evolution for engineering problem solving, here is emphasised. The geological-evolutionary model of the area was completely redefined, and the landslide areas were remapped, showing that they are five orders of magnitude larger in terms of area, with respect to the previous estimations.

A final **Discussion** and **Conclusion** paragraph is added to summarize the single discussion paragraphs for the three different study areas.

Chapter I

1. Introduction

1.1 Introduction and objectives

Geomorphological processes occurring in an area must be studied to comprehend how the landscape evolves and how these changes impact the territory (Panizza, 1978; Howard, 2013). This is especially important for identifying risks and implementing mitigation strategies, as well as for urban development (Howard, 2013; Sreenivasan and Jha, 2022). Nowadays, geomorphological investigations are playing an increasingly fundamental role in supporting engineering geology (Hearn, 2019; Laimer, 2021). Geomorphological processes typically affect large areas (geomorphic systems), and consequently they are often challenging to identify solely from a field-based perspective. Modern remote sensing methodologies are facilitating the acquisition and analysis of spatio-temporal data. In this frame, Synthetic Aperture Radar Interferometry (InSAR) data (e.g., Cigna et al., 2011; Bianchini et al., 2013; Barra et al., 2022; Reyes-Carmona et al., 2023) and photogrammetric low altitude aerial photos acquired from Unmanned Aerial Vehicles (UAVs) (e.g., Hackney and Clayton, 2015; Tziavou et al., 2018; Giordan et al., 2020) have emerged as useful tools for geological and geomorphological mapping and ground characterization. The growing availability of remote data can induce to base on these data, which are nowadays easily accessible, stability assessments. However, to get a complete picture and an accurate conceptual model of an area, it is necessary to follow standardized procedures. Preliminary planning and remote sensing analysis serve as preparation for field mapping, and ultimately lead to the development of ground modelling (Griffiths, 2019; Hearn, 2019). Field surveys, identification of landforms and surface processes and their impact on the landscape, as well as detailed geological and geomorphological mapping are essential

steps that should be addressed to perform a reliable diagnosis based on remote sensing techniques.

In coastal zones, geomorphological assessment, supported by remote sensing techniques, is widely used (Sreenivasan and Jha, 2022). These zones, with high population density, cultural heritage, valuable ecosystems, and essential freshwater resources are currently highly impacted by a large number of interactions among natural and human processes and by the effects of Global Change, such as sea-level rise, increasing aridity or heavy and sudden rainfall events (López-Fernández et al., 2022). In the present climate, Earth's oceans are growing in volume (and thus in height), with a forecast of global sea level rise of 2-6 m in the next 2,000 years (Vinogradova and Hamlington, 2022; Intergovernmental Panel On Climate Change, 2021), thus posing coastal zones among the most susceptible environments to climate changes. Among coastal areas, rocky coasts, which are affected by diverse processes than low-lying ones, represent half of the Mediterranean shoreline (Furlani et al., 2014), one of the most human-altered areas in the World (Falcucci et al., 2007).

In this regard, three case studies on rocky coasts were selected as they represent the transition environment between land and sea and are affected by the concurrent action of different processes. Furthermore, the challenge in the study of rocky coasts is often the site inaccessibility, which requires both greater efforts for detection, for example with snorkelling approach (Furlani, 2017; Furlani and Antonioli, 2023), and the use of remote analysis techniques to study and better visualize the erosion processes and unstable ground (e.g., Mantovani et al., 2016; Polcari et al., 2018; Devoto et al., 2020; Svigkas et al., 2020; Piacentini et al., 2021; Fullin et al., 2023). A commonly used example of remote sensing data that can be accessed is the InSAR data through the European Ground Motion Service (EGMS), which is an ambitious initiative of the European Space Agency (ESA) that provides near real-time information on ground motion and deformation events occurring in the majority of European

countries. The European Space Agency (ESA), the European Union, and other national organizations and academic institutions are working together on it to identify and track ground motion events including earthquakes, landslides, and subsidence. But the synergy between remotely sensed data and traditional studies based on ground truthing, is not always pursued as demonstrated by the insight derived from the study areas of this work.

For this Ph.D. thesis, it was decided to combine the different techniques of detection and analysis to perform the geomorphological and structural characterization of the selected coastal areas, in particular for coastal instability. Indeed, gravitational processes along rocky coasts are very common in any geological and geographical contexts and in all types of cliffs, resulting from the cliff retreat, marine action, or other types of forcing. In fact, the influence of bedding and structural setting on gravitational phenomena, and particularly on coastal landslides, is well-documented in the scientific literature (Bromhead and Ibsen, 2004; Margielewski, 2006; Grelle et al., 2011; Bromhead, 2013; Santangelo et al., 2015; Schlögel et al., 2016; Francioni et al., 2018; Bevan et al., 2022) and the association with the geomorphological setting led to a complete comprehension of the morpho-evolutive picture. To do this, three study areas different for lithology, tectonic evolution, geographical context, and degree of urbanization were chosen. The first two areas (Mt. Conero and Mt. San Bartolo) are located in Italy, on the western side of the Adriatic coast of Marche region. Although they have a fairly similar geodynamic and geographical context, they present different lithologies and structural settings and therefore diverse landforms and evolutionary styles. The Mt. Conero is made up of Cretaceous calcareous rocks, while the Mt. San Bartolo is mainly composed by intercalation of sandstones and marls; this lithological difference results in a different response to the erosive agents acting on the rocky coast. The third study area (La Herradura coastal sector) is located in Spain, on the Mediterranean coastal area of Granada province. The densely urbanized area is characterized by metamorphic rocks, with a different behaviour than the other two areas.

One of the objectives of this thesis is to provide an integrated and complete approach that underlines the importance of traditional field surveys as an important asset for remote sensing studies. For that, in-depth geological-geomorphological surveys have been conducted in the three coastal sectors, supported by UAV surveys and remote qualitative and quantitative analyses. This contribution includes a wide range analysis of the landforms, as well as comprehensive geological and geomorphological maps, which the subsequent interpretation of the movements detected by the aforementioned techniques are based on. In this frame: (i) for Mt. Conero it was possible, through surveys and a qualitative morphometric analysis to identify the landforms, understand the processes and reconstruct the evolution of the costal slope, all this supported also by a numerical modelling via back-analysis of the Portonovo landslide evolution; (ii) for Mt. San Bartolo, through a remote Land Surface Quantitative Analysis (LSQ) using four morphometric variables (slope angle, elevation standard deviation, roughness, and terrain ruggedness index) and field surveys, landslide areas and different landslide types have been discriminated; (iii) for La Herradura section, through field surveys and comparison of InSAR data, the extent of landslide areas compared to those mapped until now and the determination of the processes of unknown origin have been carried out.

This study emphasizes the importance of geomorphological assessment on morpho-structural setting along coastal slopes, with the combination between the field survey and the remote sensing analysis, in order to get a correct assessment for the purpose of risks mitigation and land planning along rocky coasts.

1.2 Rocky coasts

Rocky coasts are an erosional type of landforms (Kennedy et al., 2014) that includes sea cliffs, bluffs, rocky shore platforms (Del Río and Gracia, 2009) and other types such as arches, stacks and keyhole inlets (Naylor et al., 2010). The global extent of rocky coasts has been estimated to be around 75-80% of the coasts worldwide and are rarely involved in heavy urbanization processes (Emery and Kuhn, 1982; Trenhaile, 1987) with respect to the low-lying ones. More recently, Young and Carilli (2019) have calculated the global extent of rocky coastlines at 52%, with a vector coverage of world's coastlines at 89%. These percentage include not only the hard rocky coasts, but also the soft rocky coasts, the rocky shore platform and the above mentioned other types. The Mediterranean and Black seas have approximately 50,000 km of coastline and about the 50% of it consisting of rocky coasts (Furlani et al., 2014) (Fig. 1); for instance, the Spanish Mediterranean coastline is characterized by ~ 1,800 km and the Italian peninsula by ~ 4,600 km of rocky coasts (Ferretti et al., 2003).

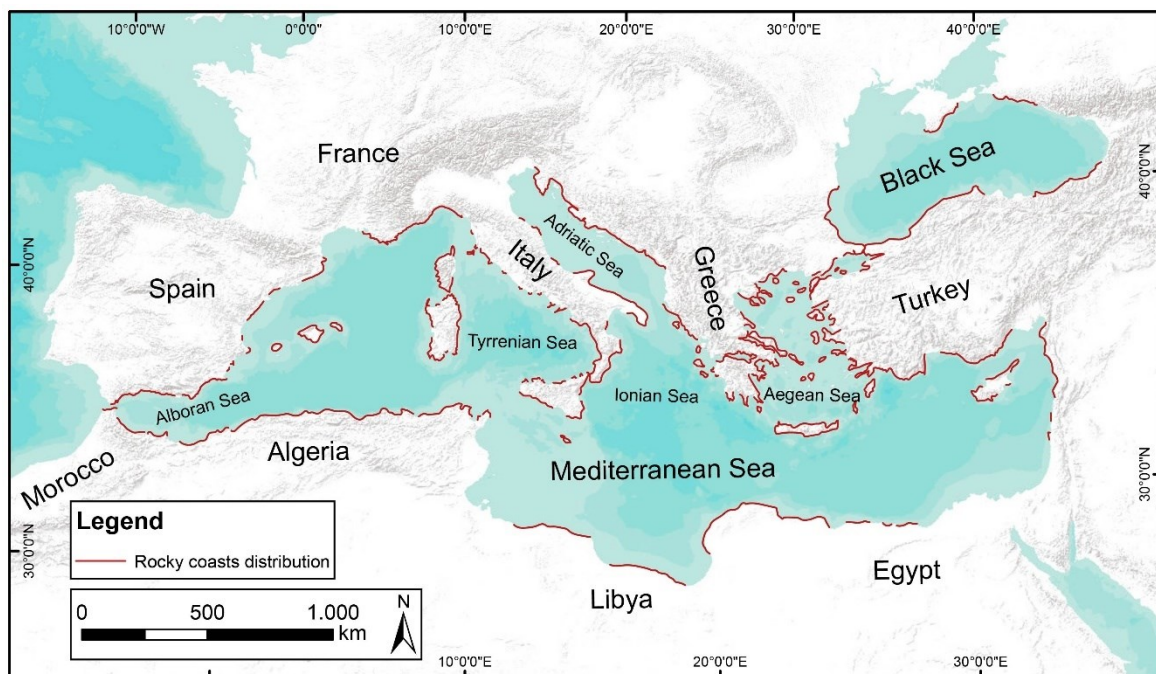


Figure 1: Distribution of rocky coasts (red lines) along the Mediterranean and Black Seas coastlines, which extend for about 25,000 km, comprising half of the total coastline length (modified after Furlani et al., 2014).

Starting from the two seminal books on the rocky coasts (Trenhaile, 1987; Sunamura, 1992) many studies and concept have been developed over the years in relation to the many types of agents and processes that affect the retreat and therefore the evolution of rocky coasts (Naylor et al., 2010; Stephenson et al., 2013; Kennedy et al., 2014) with the advent of more and more advanced new technologies. In particular, they focused on different topics:

- sea waves action (Sunamura, 1977, 2015; Stephenson and Kirk, 2000; Hansom et al., 2008; Kennedy et al., 2011; Naylor and Stephenson, 2010; Beetham and Kench, 2011; Trenhaile, 2011; Poate et al., 2018), which acting constantly or with more intensity in stormy conditions on the rocky coasts. They can erode directly generating a force on the coasts (water hammer) by wave quarrying or pressure in the rock joints, or by abrasion mobilizing sediments against the cliff (Stephenson et al., 2013).
- tides (Marshall and Stephenson, 2011; Trenhaile, 2011; Kennedy and Milkins, 2015), which play a significant role in the evolution of a shore platform and the action of waves (and thus on erosion) at the base of the cliff;
- seismic measurements related to the waves action (Kanyaya and Trenhaile, 2005; Kennedy et al., 2011; Young et al., 2013, 2016; Earlie et al., 2015) that report, through the use of seismometers, the action of the stresses acting on the cliff;
- subaerial processes and weathering (Stephenson and Kirk, 2001; Stephenson et al., 2004; Kanyaya and Trenhaile, 2005; Kennedy et al., 2011) that may be physical or chemical, such as wetting and drying, depending on the intertidal location, solution and salt weathering, in relation to the rock types (Stephenson et al., 2013);
- bioerosion activity (Naylor et al., 2012; Pappalardo et al., 2016, 2018) that although has little influence on coastal erosion, can influence large-scale erosion (Stephenson et al., 2013);

- mass movements (Hampton and Griggs, 2004; Della Seta et al., 2013; Young, 2015; Miccadei et al., 2019; Troiani et al., 2020; Devoto et al., 2020, 2021; Piacentini et al., 2021; Furlani et al., 2022; Fullin et al., 2023; Marmoni et al., 2023) which involve the rocky coasts compared to the low-lying ones, depending on several triggering and predisposing factors particularly climate, hydrology, and geo-structural framework (Stephenson et al., 2013). In some cases, as studied by Troiani et al. (2020) and Marmoni et al. (2023) in the case of Mt. Conero, additional slope-scale gravitational processes such as Mass Rock Creep (MRC) (*sensu* Chigira, 1992) can be added to these factors to comprehend the evolution of a rocky coast. This process is evidenced by the presence of gravity-driven deformations, which reflect the strain effects resulting from the viscous rheology of the rock mass. The culmination of the MRC is the occurrence of large disruptive landslides, caused by an increasing strain rate over time (Vick et al., 2020).

1.2.1 Classifications of rocky coasts

Over the years the need for common terminology has led to numerous proposals for rocky coasts classifications and more in general for coasts. The objective of a classification is to group similar coasts in categories according to morphology, genesis, and geological-evolutionary context, and then provide a universally understandable definition for each coast. However, coasts exhibit various types, and each classification also has its limitations due to the inherent complexity.

Emery and Kuhn (1982) have proposed a classification for the sea cliff based on their profile and accounting for the erodibility and morphology of the rocky coast (Fig. 2). They identified three main stages: (i) active cliffs, where marine and subaerial processes play a fundamental role in the cliff retreat; (ii) inactive cliffs, without marine action because of a covering talus and, in some cases, continental vegetation; (iii) former cliffs, in which only the subaerial

processes, which smooth the rocks, are operating and erosion produces material that accumulates at the base. The marine erosion is due to the waves and storm waves action, while surface running water and flows in fractures characterize the subaerial erosion and landslides.

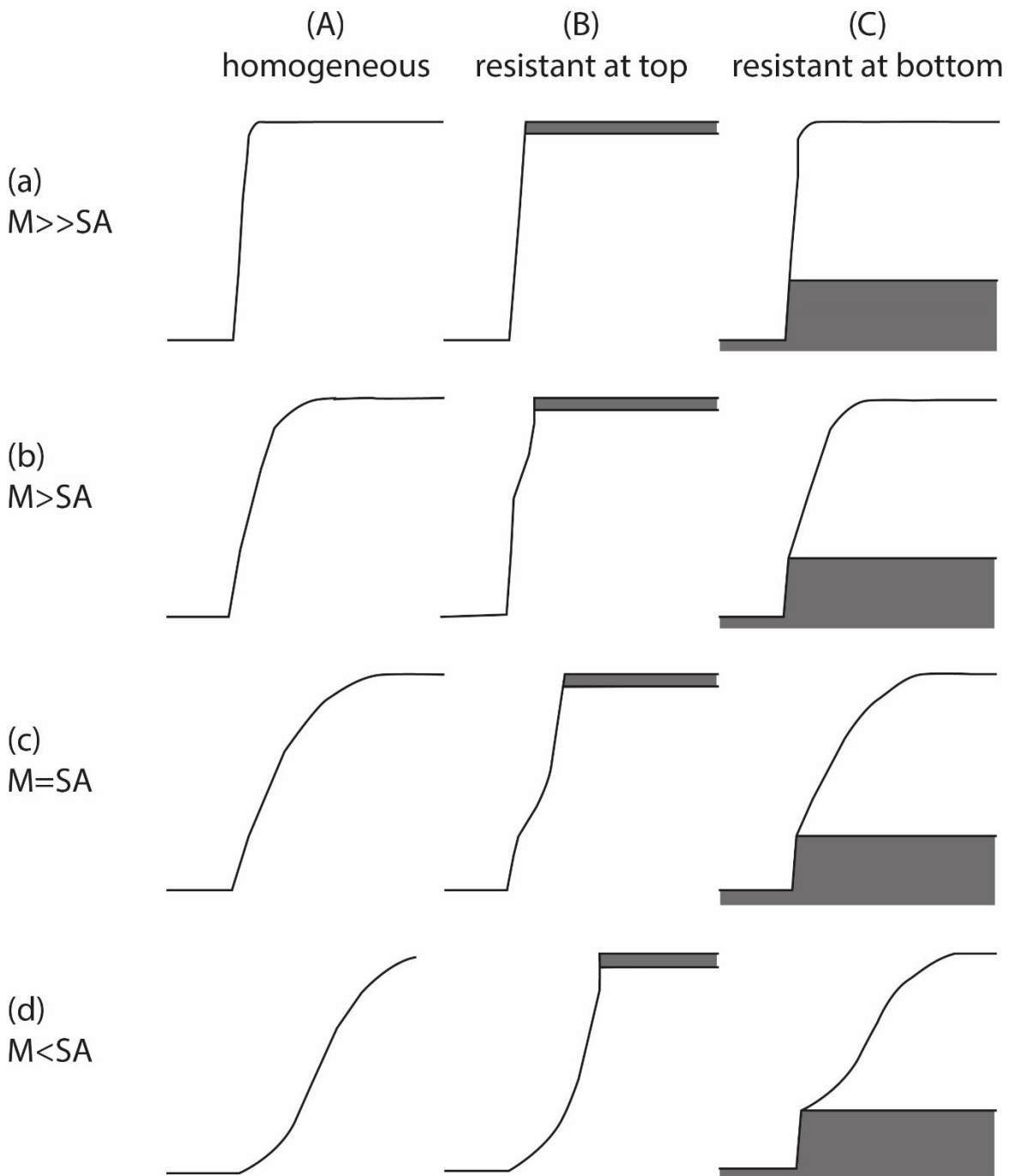
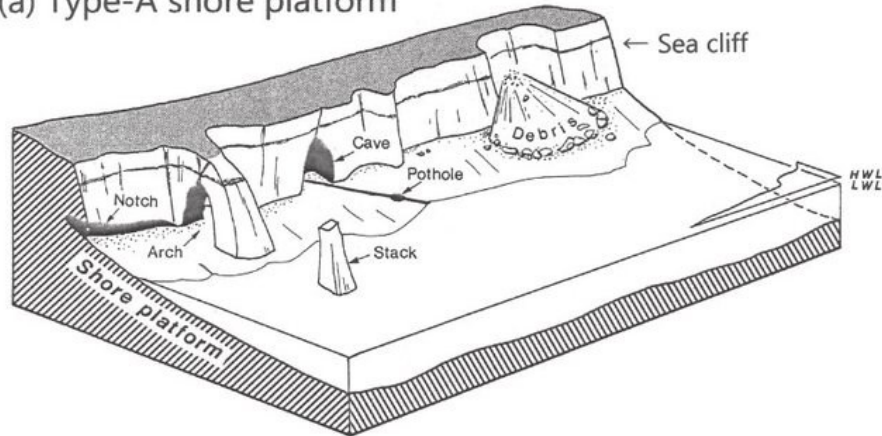


Figure 2. Results of the possible active sea cliff profiles in relation to the action of Marine (M) or Subaerial (SA) processes (modified after Emery and Khun, 1982). It is clear visible how a coastal slope profile can change based on the presence of less erodible rock (grey area) compared to a more erodible rock (white area).

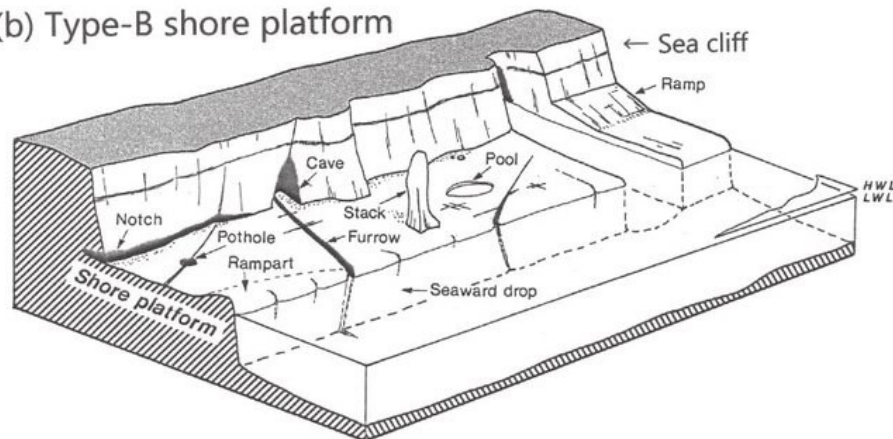
The classification reported by Sunamura (1992) is actually one of the most used to give a morphological characterization of a rocky coast. Sunamura divided the rocky coasts in three major morphologies, two types with and one without shore platforms (Fig. 3). The sloping shore platform (Type-A) is composed by a sea cliff with a low inclined platform that continue to the nearshore seabed below the low tide level (Fig. 3a). The horizontal shore platform (Type-B) is characterized by a sea cliff with an almost horizontal platform with a marked difference in height at their edge towards the sea; often these platform types terminate with a rampart which reaches almost the high tide level (Fig. 3b). The plunging cliff (Type-C) is a sea cliff which continues below sea level, well beyond the depth at which it feels the wave action, without any platform (Fig. 3c).

The genesis of the two platform types occurs by sea cliff recession; in particular, the erosion of the sea cliff, and therefore the development of the platforms, depends on the relationship between the wave strength and the rock resistance. The latter depends on litho-structural factors, biological activity, and chemical alteration (such as aloclastism), which are controlled by tidal amplitude. With the same pre-existing topographical conditions, Type-A platforms occur on more erodible rocks, while Type-B platforms develop on rocks with a rather high degree of resistance. Type-C are formed when the strength of the rock is greater than the strength of the waves. An important limitation of this classification is that Sunamura focuses on the action of waves and the resistance of rocks, not considering the tidal excursion as an important variable for the development of shore platforms, as evidenced by Trenhaile (2000, 2002).

(a) Type-A shore platform



(b) Type-B shore platform



(c) Plunging cliff

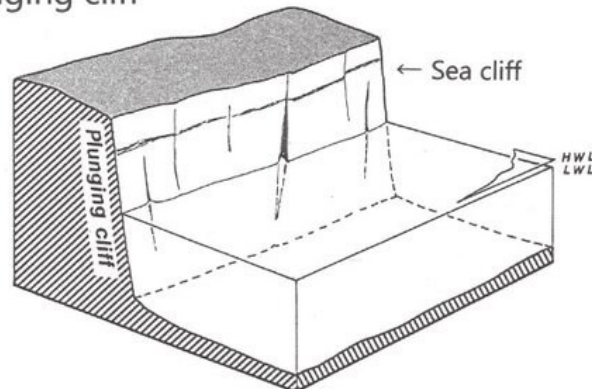


Figure 3. Three major morphologies of rocky coasts of the Sunamura classification (after Sunamura, 1992: (a) sloping shore platform, composed by a cliff with a sub-horizontal seaward platform; (b) horizontal shore platform, characterized by a horizontal shore platform with a net slope at the end of platform; (c) plunging cliff, with a depth beyond the low-tide level and without any shore platform. In relation to the sea-level acronyms: HWL = High Water Level, LWL = Low Water Level.

At this point Bird (2008) recognizing the types of coasts of the Sunamura classification considers also the height of the sea level and so the tidal excursion (Fig. 4a-d). In particular,

Bird distinguishes the Type-B of Sunamura classification in two subcategories: (i) high tide shore platform whose surface is near high tide level and are only slightly submerged (Fig. 4c) and (ii) low tide shore platform, close to the low tide level and therefore always submerged (Fig. 4b). According to Sunamura, both these platforms have a net break (often >3 m) at the seaward edge.

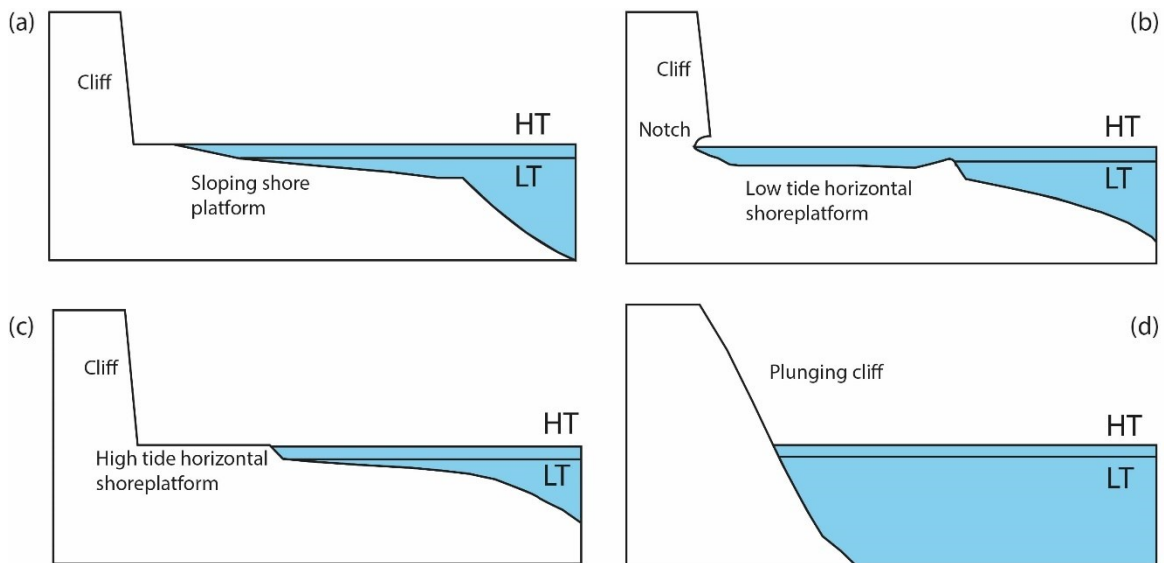


Figure 4. Rocky coasts morphology types of the Bird classification (modified after Bird, 2008): (a) seaward sloping shore platform; (b) low tide horizontal shore platform; (c) high tide horizontal shore platform; (d) plunging cliff, without any shore platform. HT = High tide, LT = Low Tide

More recently, Biolchi et al. (2016) employed a classification for Malta coasts based on the geomorphotypes encountered, which are characterized by distinct topographical, litho-structural and geomorphological features: (i) plunging cliff, as described by Sunamura (1992), vertical or sub-vertical sea cliff that extends well below sea level, beyond the reach of wave action and low-tide level, without any platform or ramp; (ii) a low-lying rocky coast characterized by slope angles ranging from 5° to 45° ; (iii) shore platform, as described by Trenhaile (1987), from 0° to 5° rock surface, formed along a shoreline by the influence of marine processes, in conjunction with the gradual retreat of a cliff in the intertidal zone; (iv) screes, described and called “rdum” in Said and Schembri (2010), defined by the presence of extensive slope-failure deposits

situated between the coastline and karst plateaus, such as rocks spread and rock slides; (v) cliffs, vertical or subvertical slope with a concave ramp; (vi) pocket beach, sand, gravel or pebble beach, in the inner portion of a bay, fed by cliff rock falls; (vii) built-up coast, coastal areas intensely urbanized and modified by the human activities.

1.2.2 Sea-level and Global Changes on rocky coasts

Sea level is the one of the principal factors for coastal evolution, which control cliff retreat and shore platform geometry. Rocky coasts have different modality of response to sea-level changes especially if the rise is as fast as in the Holocene period (blue curve in Fig. 5a) (Bray and Hooke, 1997; Stephenson et al., 2013). Before this latter and actual period (Marine Isotope Stage, MIS 1) there was a glacial period called Last Glacial Maximum (LGM, MIS 2), in which the sea has reached the lowest level at about – 120/130 m compared to the current level (Fig. 5b) (Clark et al., 2009; Lambeck et al., 2014). During deglaciation the sea rose up rapidly over a period of 20 ka, reaching its current level; the rates of sea-level rise also reached peaks of 50 mm/ka (red curve in Fig. 5a) (Benjamin et al., 2017). According to one of the latest IPCC reports, the Global Mean Sea Level (GMSL) rose in the 20th century faster, with an average rate of 2.3 mm/yr (over the 1971-2018 period) increased to 3.7 mm/yr (over the 2006-2018 period). It is virtually certain with different predictions until at least 2100 that it will continue to rise (Fig. 5c) (Fox-Kemper et al., 2021).

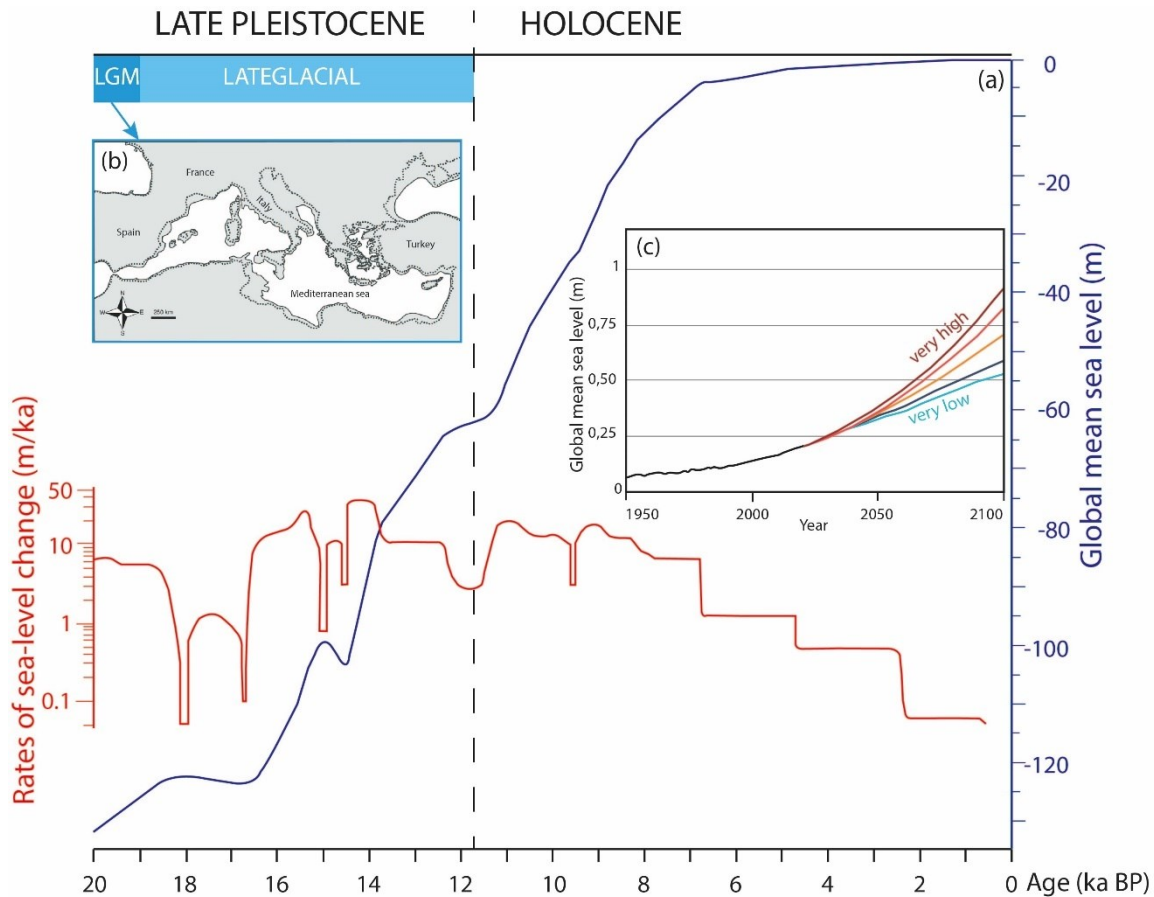


Figure 5. The principal graph (a) shows the trends of the GMSL (blue curve) and rates of sea-level change (red curve) (Lambeck et al., 2014) after the LGM (modified after Benjamin et al., 2017). In the graph (c) GMSL changes and projections are illustrated by IPCC reports. Historical changes (black curve) are observed by tide gauges and altimeters; projections (coloured curves) are evaluated according to observational constraints, relying on emulation of Coupled Model Intercomparison Project (CMIP), icesheet, and glacier models. On the year 2150 the GMSL rise is between 0.37 to 0.86 m under SSP1-1.9 (Shared Socio-economic Pathways, very low scenario) and 0.98 to 1.88 m under SSP5-8.5 (very high emissions scenario) (Calvin et al., 2023). The map of the Mediterranean area conditions in the LGM is visible in figure (b) (after Mazza et al., 2013).

Soft rocky coasts or bluffs will tend to change more rapidly than hard rocky coasts in response to Global Change (shifts in storm frequency, changes in rainfall intensity and many other factors; Naylor et al., 2010; López-Fernández et al., 2022). With the higher Relative Sea Level (Rovere et al., 2016b), greater wave energy will be transferred to at the base of the cliff as a result of reduced wave attenuation rates (Naylor et al., 2010). As already described by (Mörner, 1996), changes in RSL are due to several factors, such as (i) vertical changes in sea level

(eustasy), (ii) vertical changes in land (tectonics), (iii) reshaping of the coastal morphologies and (iii) change in the sea-land interaction processes; these factors act in different space-time scales (Fig. 6) and therefore affect rocky coasts in a differential way. The primary division lies between continuous and regional processes (on the right side of both graphs of Fig. 6) and sudden and local events (on the left side of both graphs of Fig. 6) (Mörner, 1996).

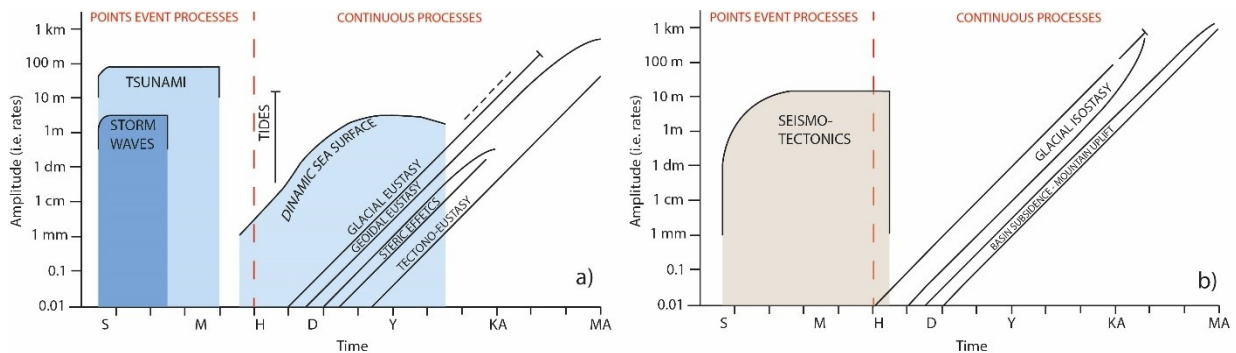


Figure 6. Spatial and temporal relationship between the different factors influencing sea (a) and land (b) levels. Scales are logarithmic with S = second, M = minute, H = hour, D = day, Y = year, KA = kilo year and MA = million year. (modified after Mörner, 1996).

Among many indicators of the RSL (Rovere et al., 2016a), marine notches (Pirazzoli, 1986; Trenhaile, 2015) are commonly used on rocky coasts because they can be very precise sea-level indicators (Kershaw and Guo, 2001; Benjamin et al., 2017). At the same time, however, notches may have difficulty in forming or may not be visible, since they need a relative stability on both the land and sea. The rates of erosion are extremely different for the different types of rocky coasts (Trenhaile, 2015) and it is important to consider also several factors such as tectonic uplift or the presence of landslides, which can limit the notch formation. In the Adriatic sea the development of a notch was estimated in 500 ± 100 years (Furlani et al., 2011), while Antonioli et al. (2004) suggested that it takes up to 400 years to carve a notch into limestones in the Mediterranean area (Trenhaile, 2015).

1.3 Overview and geodynamics of the study areas

1.3.1 Peri-Adriatic sector, northern Marche region

The geological and tectonic evolution of the external domain of Umbria-Marche fold-and-thrust belt has been strongly controlled by the presence of Adria continental plate (Pezzo et al., 2020). The collisional tectonic phase starting since the Miocene, with WSW-directed subduction, developing on the underlying monocline geometry of the Adria plate (Mariotti and Doglioni, 2000; Amadori et al., 2019; Maesano et al., 2023). The sedimentary cover, which pertains to the Umbria-Marche Meso-Cenozoic stratigraphic succession, detached from the underlying basement through a thrusts sequence that affects the Adria foreland. A system of thrusts with stepped geometry propagates from the western deeper inner zone to the shallower outer structures. The resulting NE-verging fold-and-thrust belts migrate since the Upper Miocene in the Umbria reaching the Adriatic foreland in the Pliocene (Menichetti et al., 1991). Subsequently, the outer (offshore) system of the Peri-Adriatic belt is evolving since late Pliocene, involving the foredeep, through folds-and-thrusts (Fig. 5). The main detachment level is rooted within the Triassic evaporites (Anidridi di Burano Fm.), while superficial detachment levels are situated in Late Miocene marls (in the bottom part of the Schlier Fm.) (Maesano et al., 2013; Pezzo et al., 2020, 2023). Multiple thrusts associated with folds are present and are buried under Plio-Pleistocene marine and continental deposits (Maesano et al., 2023). These thrusts are responsible for lifting some sectors of the northern part of Marche coasts such as Mt. Conero and Mt. San Bartolo, which are characterized by folded structures. The consequence of these sectoral lifts of the coast is the absence of the Pleistocene succession, which instead covers large portion of the coast (Fig. 5). The Pliocene succession instead appears to be deformed in many seismic lines (Menichetti et al., 1991; Roveri et al., 2005), indicating a likely erosion of Pliocene formations during the uplift of the coastal ridges. The compressional outer phase is

coeval with the extension tectonic along the Apennine chain (De Nardis et al., 2022; Maesano et al., 2023).

The two investigated areas correspond to two external ridges of the northern Apennines. The Mt. Conero area consists of Cretaceous carbonate and early Paleogene calcareous marls rocks (from the Maiolica Fm. to the Schlier Fm.) but following the ridge towards Ancona also foredeep Messinian formations are present (from the Schlier Fm. to the Colombacci Fm.). The Mt. San Bartolo area is characterized by the Messinian foredeep succession (from the Schlier Fm. to the Colombacci Fm.). Geological formations will be analysed in detail in the specific chapters of the study areas.

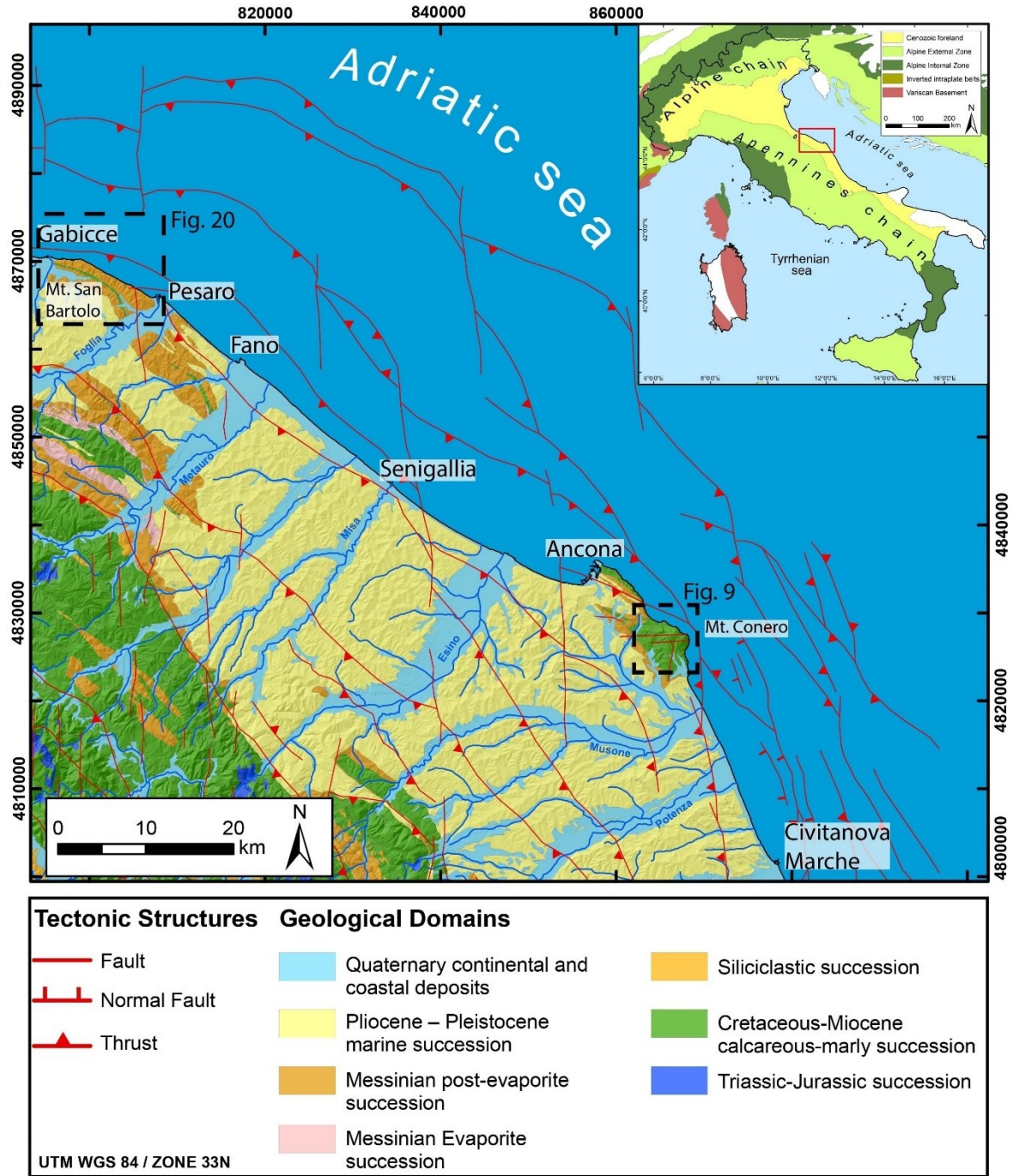


Figure 5. Geological and structural map of the northern coastal sector of Marche region. It is relatively easy to distinguish, based on the colours, the two rocky coastal sectors of Mt. San Bartolo and Mt. Conero, in contrast to the surrounding Plio-Pleistocene deposits. The map of Italy with orogenic domains is modified after Moragues et al. (2021); geological map of the northern Marche region is modified after Conti et al. (2020) and the structural lineaments are modified after Tirincanti (2020). The dashed black rectangles indicate the two study areas.

Moderate to strong earthquakes could be caused by fault planes associated with these structures (Pezzo et al., 2020), which are included in the DISS database (DISS Working Group, 2021). In the coastal area of Marche region seismic catalogues show activity along the compressive fronts, both in the historical seismic records catalogue (Rovida et al., 2020, 2022) and in the instrumental seismic catalogue (<http://terremoti.ingv.it/>). From the year 1000 to mid-September 2023, 22 events above 5 Mw and 76 events above 4 Mw occurred offshore and in the inner coastal sector of Marche region; the large part of these present focal mechanisms are mainly of compressive and transpressive kinematics (Lavecchia et al., 2004; Mazzoli et al., 2014).

Tectonic uplift for the coastal sector has been estimated between 0.13 and 0.18 mm/yr over the last 125 ka (Troiani and Della Seta, 2011 and reference therein). The slow coastal uplift supports the long-term and present-day tectonic regime of this area, characterized by the compressional forces along the front of the Apennines (Ferranti et al., 2006).

1.3.2 Alpujárride Complex, southern Andalusia region

The Alpujárride Complex belongs to the Alborán Domain of the Betic Cordillera fold-and-thrust belt (Azañón et al., 1994; Azañón and Crespo-Blanc, 2000), which is the result of the subduction due to the Cenozoic convergence between Africa and Eurasia plates (Poulaki et al., 2023; Simancas, 2018). The tectonic evolution of this system is highly debated, starting from the nature and timing of the subduction with different scenarios proposed and resumed in Poulaki and Stockli (2022). The Betic Cordillera is divided into an Internal and an External zones: the first one, is composed by Precambrian, Palaeozoic and Triassic rocks of the Nevado-Filábride and Alpujárride complexes and by Palaeozoic, Mesozoic and Tertiary rocks and sediments of the Maláguide complex (Tubía et al., 1992; Benito et al., 2010); the second one, is characterized by Mesozoic and Cenozoic sedimentary rocks of the South Iberian continental paleo-margin (Tubía et al., 1992; Vera et al., 2004; Benito et al., 2010). The contact between Nevado-Filábride and Alpujárride complexes is considered an ancient thrust, subsequently

reactivated as low-angle normal faults that lead the Permian rocks of the Alpujarride above the Triassic rocks of the Nevado-Filábride (Poulaki and Stockli, 2022). Focusing on the tectonic evolution of the Alpujarride Complex, where the case study is located, the sequence of deformational events (D_1 - D_4) has been well described by many authors (Tubía et al., 1992; Simancas and Campos J., 1993; Azañón et al., 1997; Azañón and Crespo-Blanc, 2000; Rossetti et al., 2005; Williams and Platt, 2017; Simancas, 2018). This sequence started with from the High-Pressure/Low-Temperature (HP/LT) metamorphism phase (D_1), followed by D_3 , characterized by regional-scale folds with a predominant E-W trend and NW vergence. Deformation event D_4 is characterized by low-angle faults dipping toward N and finally, since the Serravallian to the present day, top-to-the SW low-angle normal faults and other structures have been affecting the Alpujarride Complex and the entire Internal Zone.

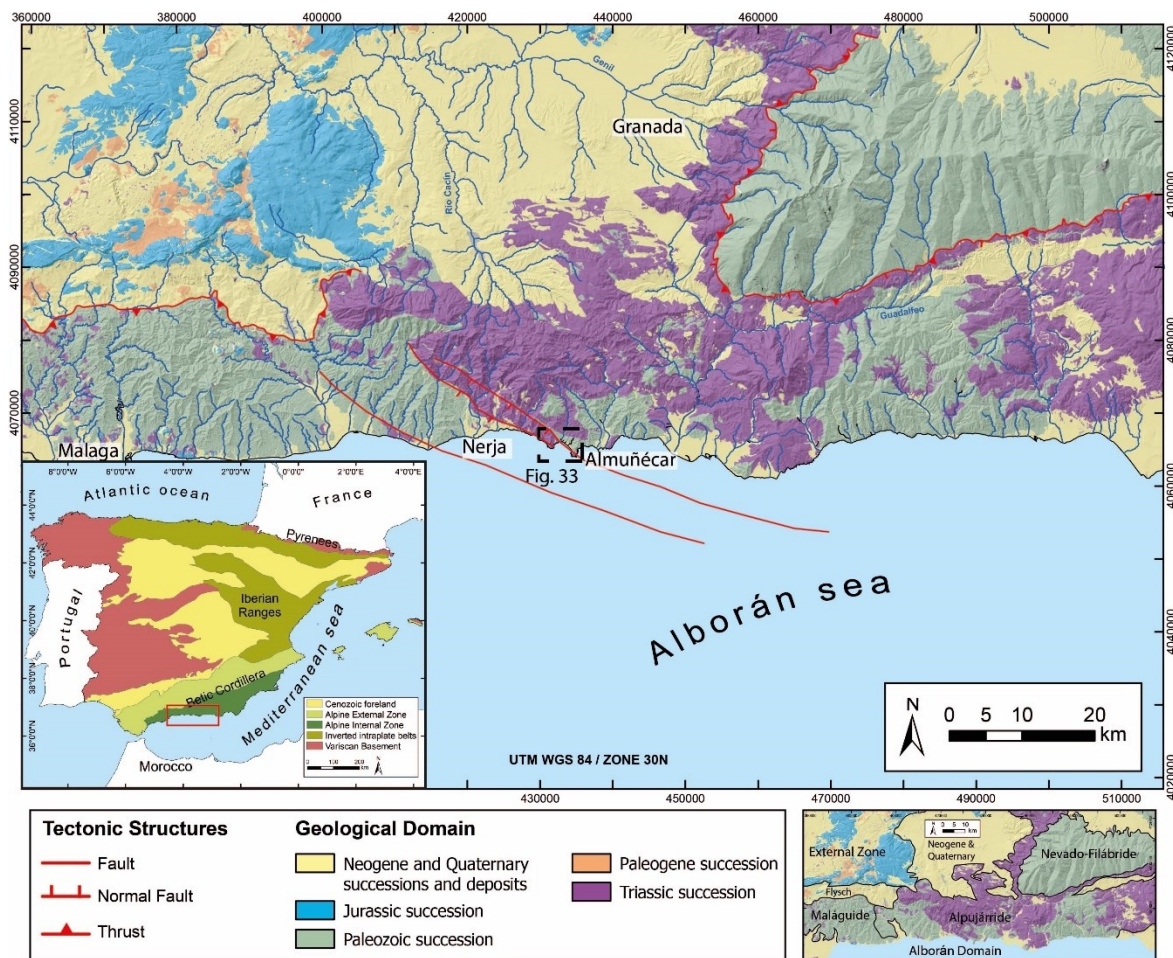


Figure 6. Geological and structural map of the southern coastal sector of the Andalusia region. The map of Spain with zones of Betic-Rif orogen is after Moragues et al. (2021); The geological map is after Marín Lechado et al. (2009) and faults is after Ruano (2003), Ruano et al. (2004), Benito et al. (2010). The map of the geological complexes is after Rossetti et al. (2005).

Because of the collision between Africa and Eurasia the Andalusia region is characterized by a moderate seismic activity with also a significant number of earthquakes at a depth between 40 and 150 km (Benito et al., 2010). Historical earthquake catalogue of the National Geographic Institute (IGN, <https://www.ign.es/web/en/ign/portal/sis-catalogo-terremotos>) reports from the year 1370 to mid-September 2023, 7 events above 5 Mw and 100 events between 4 and 5 Mw, occurred in the area of Fig. 6.

Chapter II

2. Investigation methods

The used investigation method is common to all three study areas and is composed in general of four steps to get a complete picture and accurate ground models (Griffiths, 2019; Hearn, 2019):

- (i) desk study;
- (ii) remote sensing analysis;
- (iii) field mapping;
- (iv) ground investigation and modelling.

Following these steps is essential, even if in some cases it may not be possible to use certain techniques due to the territory configuration.

The desk study is the first step and consists of the consultation of existing data. This includes bibliographic research, examination of historical documentations, and review of technical documentations. In some cases, historical aerial images through the use of stereoscopy, can assist in identifying landforms and deposits without the presence of the urban development.

The remote sensing analysis consists of all those techniques that can be performed without the need for direct field visits. Among many remote sensing techniques are included: (i) the consultation of historical and more recent optical aerial and satellite images (e.g., Google Earth) which enables a multitemporal analysis of an area; (ii) the use of InSAR data, such as those made available for Europe countries by the EGMS (<https://egms.land.copernicus.eu/>) to map and monitor surface deformation with millimetric accuracy; (iii) LSQ analysis that involve the calculation of morphometric variables, previously documented in scientific literature (Wilson and Gallant, 2000; Hengl and Reuter, 2008; Florinsky, 2017; Amatulli et al., 2020) to provide a

quantitative description of the terrain topography, through the topographic signature of the different surface processes and landforms (Florinsky, 2017).

Field mapping represents the traditional method for collecting data but often cannot be carried out, thus being replaced by the use of remote sensing data. In this step, geological, structural, and geomorphological surveys are carried out in order to better characterize the study areas. The fieldwork was conducted through digital survey techniques (e.g., using tablet PC with the software FieldMove), based on mobile devices that allowed for collecting field data in digital form, and its direct storage through remote cloud-uploading and real-time updating. The detection and mapping of the processes and landforms were based on the approach proposed by the new Italian Geomorphological Mapping guidelines (Campobasso et al., 2018), which suggest mapping each landform based on its genesis, evolution, and present dynamics.

Field surveys were supported by UAV flights to visualize hard-to-reach spots such as the rocky cliffs along the coast. The use of UAVs is considered an intermediate approach between the remote sensing techniques and fieldwork, but, in this context, it is categorized as a part of field survey because reaching the area is necessary to fly the drone. The drone model, for these works, was a DJI Mavic 2 PRO equipped with a 20 MP Hasselblad camera with a 1" CMOS sensor size; the camera is fastened on a 3-axis gimbal for image stabilization and a 28 mm lens, with a FOV of ca. 77° and an aperture of f/2.8-f/11, allowing a 20 Mpixel photo resolution. Furthermore, this drone is equipped with a GPS/Glonass system for image georeferencing.

Ground models and site investigations are fundamental components to better understand and visualize the geology, geomorphology, structures, and characteristics of an area. As described in Griffiths (2019) ground models can be conceptual, observational, and analytical. The data collected from the field surveys were stored, organized, and processed in ArcGIS 10.8.2 (ESRI®, 2022/2023-licensed "DISPEA University of Urbino") software. From here, geological, and geomorphological maps are generated, and geological cross-sections and conceptual

sketches are subsequently performed, to provide a conceptual and observational overview of the study areas. A further tool that has been used to obtain 3D models was the Agisoft Metashape 1.8.0 (Agisoft, licensed “DISPEA University of Urbino”) software. For the generation of point clouds and, consequently, 3D models, the first step is to acquire images through Structure-from-Motion (SfM) photogrammetric technique (Westoby et al., 2012). To achieve this, in addition to manual UAV flights in areas with more complex features and steep slopes, the UgCS EXPERT (SPH Engineering, 2023-licensed University of Urbino "Carlo Bo") software was used. Among its various applications, it allows the planning and the automation of photogrammetric flights of a predefined area, starting with the setting of the desired ground resolution (cm), through the Ground Sampling Distance (GSD) parameter. Additionally, the photogrammetric survey routes follow a DEM (by default Shuttle Radar Topography Mission, SRTM), which can be user-inserted, such as a DEM derived from Light Detection And Ranging (LiDAR) survey; this ensure that the drone maintains a consistent distance (height) above the ground (Fig. 7).

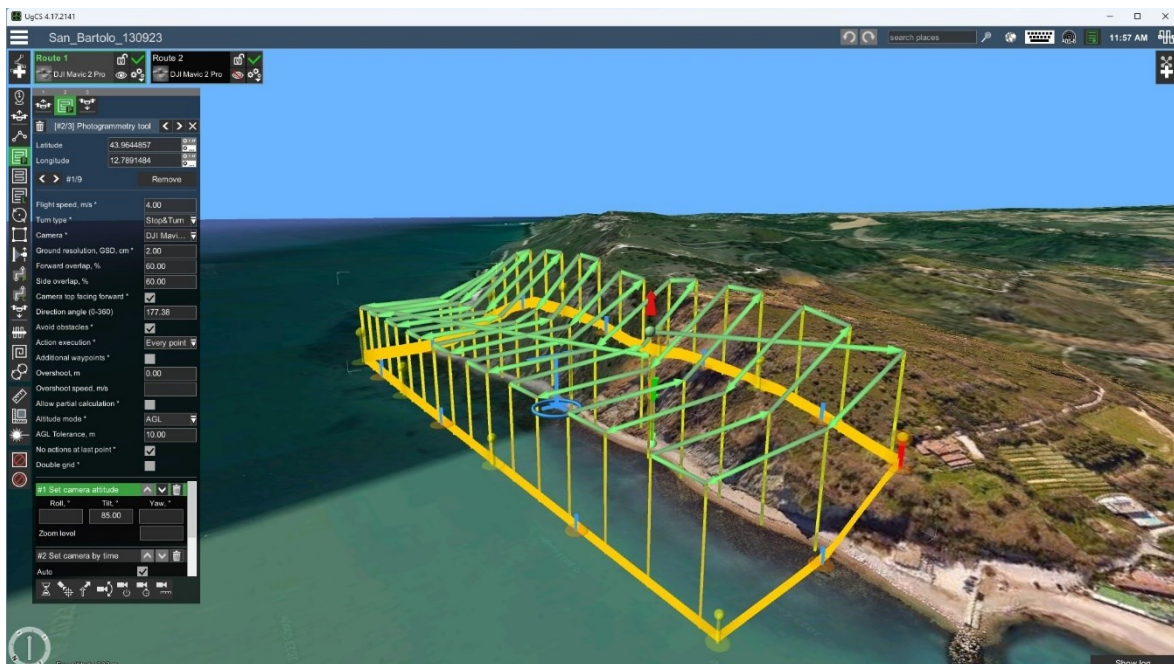


Figure 7. Planning and photogrammetric survey using the UgCS software. It can be observed that the flight paths vary in altitude, utilizing a DEM derived from LiDAR data as a reference, and follow the morphology of the coastal slope of Mt. San Bartolo.

Once the images have been captured, they are imported into the Metashape software, in which several steps are carried out:

- Images alignment to create a sparse point cloud, achieved by identifying tie points between the images.
- Insertion and control of the Ground Control Points (GCP), which are points located within the study area (identified by markers), and for which geographic coordinates (Latitude and Longitude) and elevation (m above sea level, a.s.l.) are measured. The coordinates and altitudes have been taken using a multi-band Real-Time Kinematics (RTK) Global Navigation Satellite System (GNSS) receiver; the GNSS model is the EMLID Reach RS2+ with a centimetre precision.
- Generation of the dense point cloud by densifying the points from the sparse cloud with additional points that occupy the space (Fig. 8).

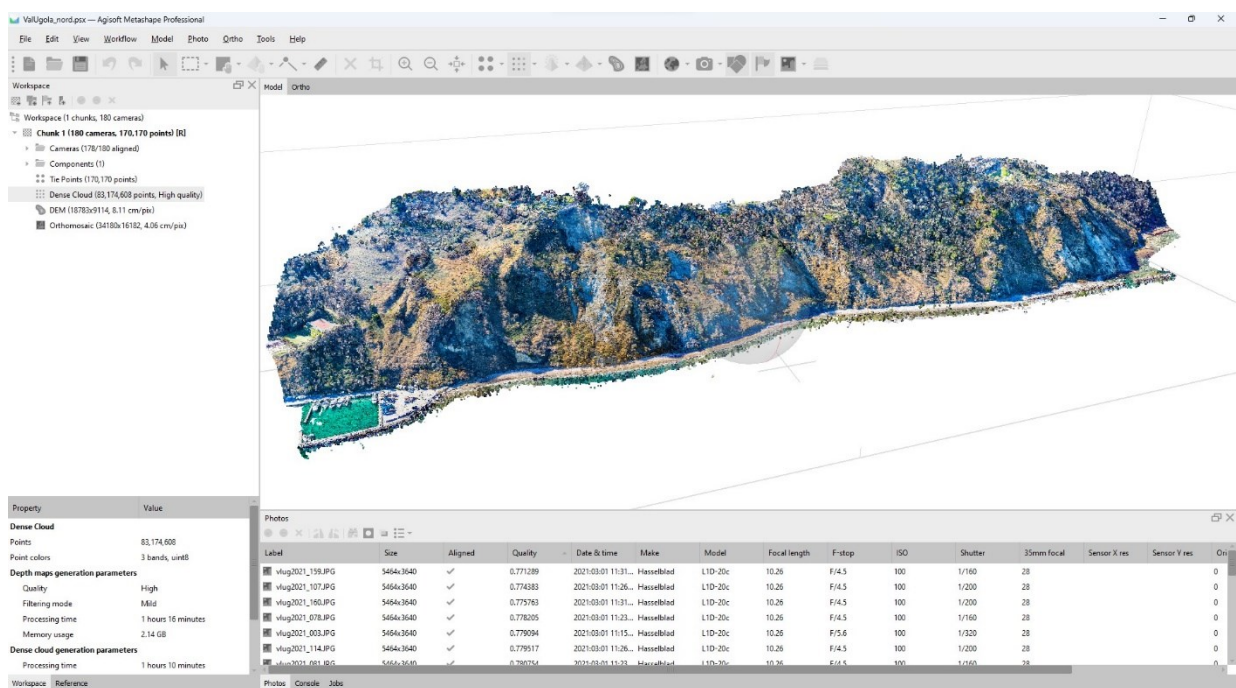


Figure 8. An example of dense point cloud generated by the Metashape software. In the workspace on the left side, it is possible to note all the steps listed, starting from the photographs, going through the image alignment (Tie points), dense cloud generation, and culminating in the creation of a Digital Surface Model (DSM) and an orthomosaic.

These are the main steps from which various products can be developed, such as: (i) the 3D mesh, which is a 3D surface generated from the dense points cloud, with its points becoming vertices of triangles and performing a 3D triangulation to develop a surface; (i) Digital Surface Model (DSM), with a centimetric resolution and with the altitude (m a.s.l.) value for each pixel; (iii) orthomosaic, which is a mosaic of the images with the application of orthorectification. Regarding classification systems, in this study, rocky coasts will be designated using the terms listed in the classification of Sunamura (1992) and Bird (2008), while landslide mechanisms were classified according to Cruden and Varnes (1996) and Hungr et al. (2014).

Chapter III

3. Morpho-structural assessment on carbonate rocky coast: the case of the Mt. Conero study area

Arguments developed in the three years of PhD and in the following publications:

- Troiani F, Martino S, Marmoni GM, Menichetti M, Torre D, Iacobucci G, Piacentini D (2020) Integrated Field Surveying and Land Surface Quantitative Analysis to Assess Landslide Proneness in the Conero Promontory Rocky Coast (Italy). *Applied Sciences* 10:4793. <https://doi.org/10.3390/app10144793>
- Marmoni GM, Martino S, Censi M, Menichetti M, Piacentini D, Scarascia Mugnozza G, Torre D, Troiani F (2023) Transition from rock mass creep to progressive failure for rockslide initiation at Mt. Conero (Italy). *Geomorphology* 437:108750. <https://doi.org/10.1016/j.geomorph.2023.108750>

Personal contribution to the above-mentioned publications: (i) Field investigation and data collection, (ii) laboratory analysis and data storage in GIS environments; (iii) redaction of geological and geomorphological maps.

3.1 General setting

The Conero coastal sector is located in the Marche region (Central Italy) about 10 km SE of Ancona city (43°37'2" N, 13°30'56" E) and is formed by a promontory (Mt. Conero ca. 572 m a.s.l.) representing the highest relief along the western side of the Adriatic coast. The 5 km rocky coastline has a NW-SE main orientation in the northern part and a N-S orientation in the southern part. The vegetation is mainly of Mediterranean type with woods of holm oak, hornbeam, and neapolitan maple, but also olive groves, vineyards, and fruit trees (Roccato,

2004a). There are some villages in the inner part (i.e., Poggio and Massignano) and on the coastline (i.e., Portonovo and Sirolo). These villages as well as the coast of the Mt. Conero are national and international summer tourists destination and therefore experience intensive tourism exploitation (Roccato, 2004a). The Natural Regional park of Mt. Conero was established in 1987 (L.R.23.04.1987, n°21) to safeguard this coastal area; this is the first regional park established in the Marche region, with an area of about 6000 ha. Within the park area there are different zones with levels of protection including an integral reserve in the sea slope from Portonovo to the Due Sorelle sea stacks (Roccato, 2004a).

The area is characterized by a Mediterranean climate, Csa according to Köppen-Geiger classification (Fратиanni and Acquaotta, 2017; Rubel et al., 2017; Beck et al., 2018), with dry summers and very humid winters (Fig. 9); the mean annual precipitation ranges from 780 to 790 mm and the mean annual temperature from 14 to 15 °C (Savelli et al., 2017; Furlani et al., 2018). Dominant winds approach from NNE (Savelli et al., 2017), but prevailing winds are from SSE (Mastronuzzi et al., 2017) generating a SE main wave direction (Furlani et al., 2018) and a local longshore current from S to N (Mastronuzzi et al., 2017). In the occurrence of Bora dominant wind, storm waves up to 3.5-4 m approach from NNE especially in winter seasons; the tidal excursion is about 0.5 m (Furlani et al., 2018).

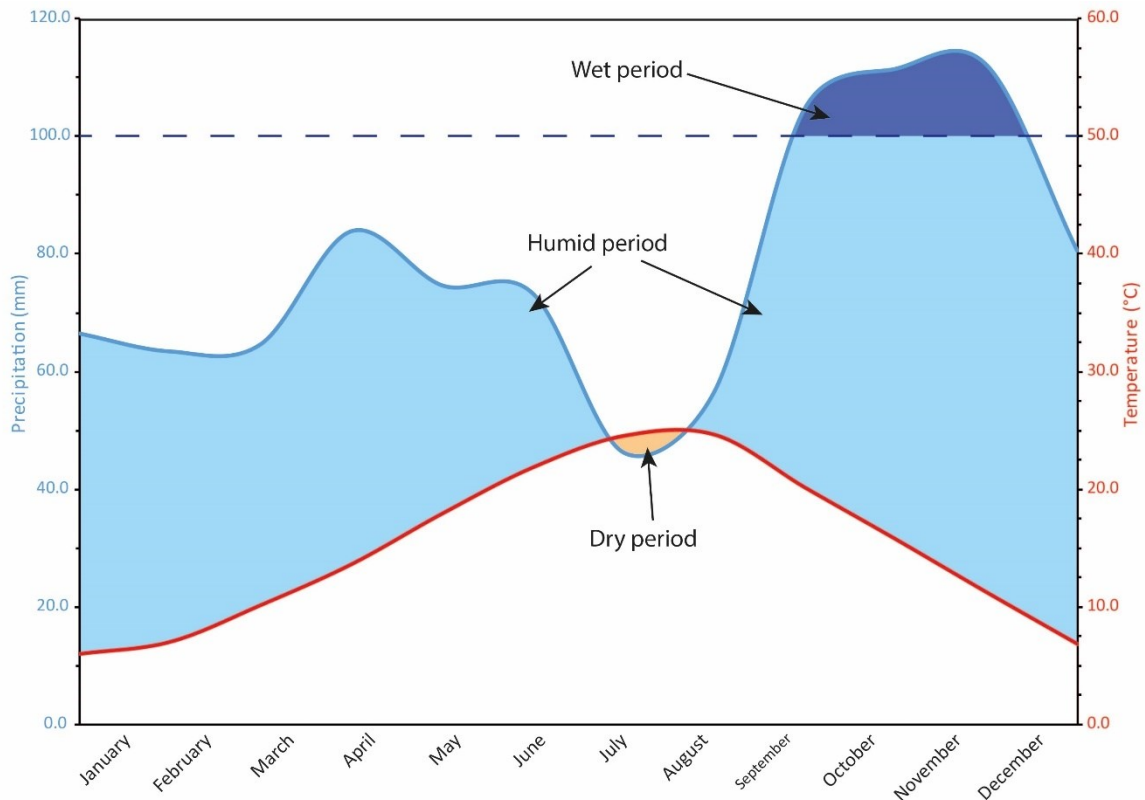


Figure 9. Climatograph (Walter and Lieth, 1967) for the Mt. Conero area, depicting the relationship between monthly average temperature (°C) and monthly average precipitation (mm) from 1990 to 2020. Data are downloaded from <https://climatecharts.net/> (Zepner et al., 2021)

3.1.1 Geological and geomorphological setting

The Conero promontory represents the easternmost outcropping part of the Umbria-Marche fold-and-thrust belt and consists of a NE-verging asymmetric anticline in the northern sector and E-verging in the southern part (Cello and Coppola, 1984; Montanari et al., 2016). The outcropping rocks belong to the Umbria-Marche stratigraphic succession (Fig. 10) consisting of the following formations, from bottom to top (Sarti and Coltorti, 2011; Montanari et al., 2016; Coccioni et al., 1993): (i) Maiolica Formation (Fm.) (Lower Cretaceous), prevalently composed of decimetre-scale well-stratified limestones with chert and black shales and with a thickness of about 300 m; (ii) Marne a Fucoidi Fm. (Lower Cretaceous), characterized by a thickness of approximately 15 m and comprising centimetric marls and marly calcareous layers with black shales; (iii) Scaglia Rossa Fm. (Upper Cretaceous) with a thickness of about 200 m, consisting

of alternating and well-stratified centimetric to metric limestones, calcarenites, biocalcarenites and marly calcareous layers. In the eastern (inland) and northern part (beyond the Portonovo bay) of the Conero ridge the Neogene succession outcrops ending with the Schlier Fm. The about 15 m thickness of the Marne a Fucoidi Fm. is far from the regional thickness up to 80 m (Coccioni et al., 1989; Furlani et al., 2018) and the contact between Marne a Fucoidi and Scaglia Rossa Fms. is likely due to syn-sedimentary slumps (Coltorti et al., 1987), with the almost total absence of the Scaglia Bianca Fm. and of the basal part of the Scaglia Rossa Fm. Due to the anticline axis orientation, in the western limb (inland) the bedding dips up to 25° to the WSW and in the eastern limb (coastal cliff) towards ENE dipping up to 80° (Cello and Coppola, 1989). Only in the northern part the Scaglia Rossa Fm. is characterized by NW dipping strata with angles up to 30° . The structure is affected by top-to-the-N left-transpressive faults clearly visible in the coastal cliff (Fig. 10).

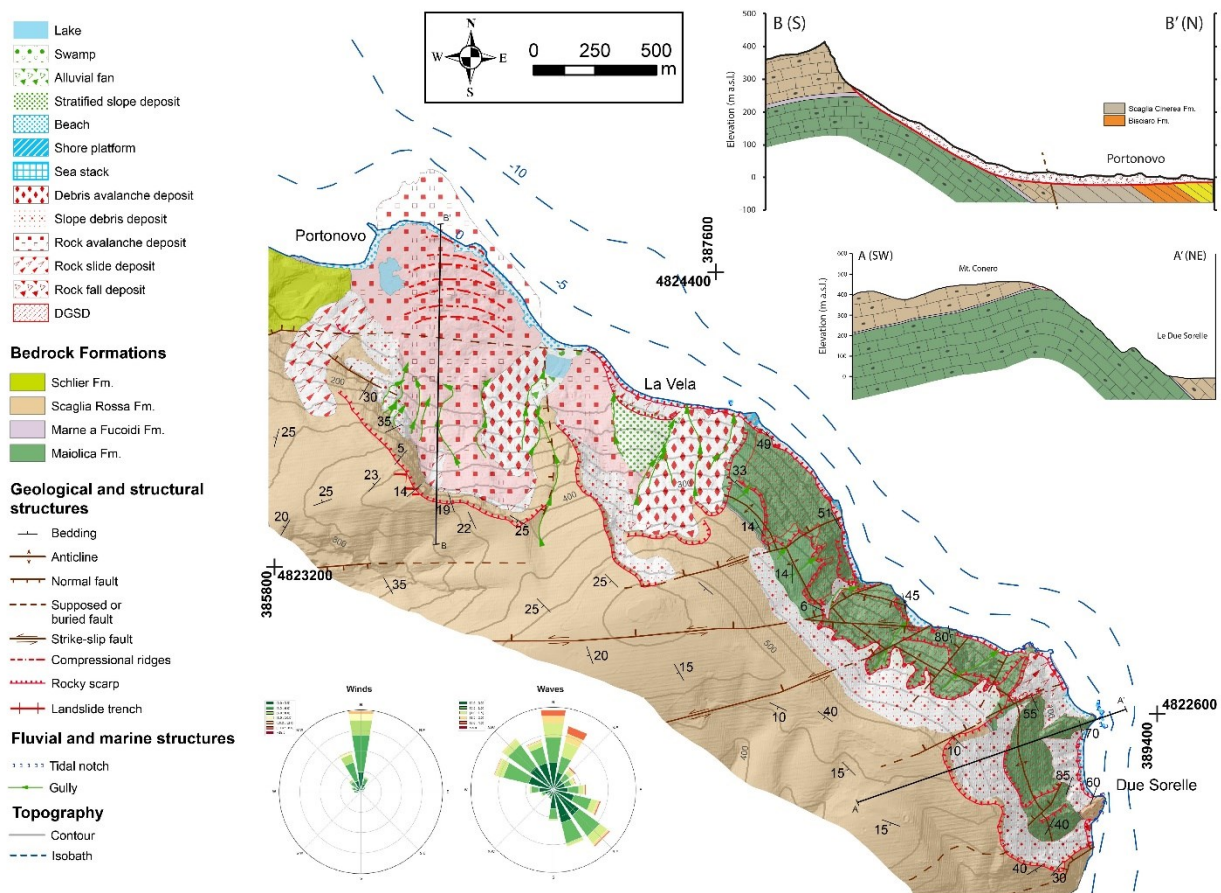


Figure 10. Geomorphological map of the Mt. Conero coastal area. Landslide types and areas have been mapped with field surveys and remote analysis. The two polar diagrams show the direction and intensity of the winds and the direction and heights of the waves; data of winds and waves are downloaded from the Rete Ondametrica Nazionale (RON, <https://www.mareografico.it/>), and take into consideration the Ancona wave buoy (43°49'26'' N, 13°43'10'' E) for the period 01/01/2021-15/10/2023.

The landforms and deposits that have been found are mainly due to gravitational and marine processes acting on the coastal slopes. Landslides of different typologies, size, and state of activity occur in the area and principally characterize the entire coastal slope morphodynamics. In the northern coastal sector, in the Portonovo and La Vela areas are located the largest landslides (Aringoli et al., 2014; Montanari et al., 2016). Towards the S, beaches, pocket beaches, made of rocky blocks and gravels, and plunging cliffs (Type-C of Sunamura classification) characterize the coastline, alternating to the landslide deposits. In some cases, gently dipping sloping shore platforms (Type-A of Sunamura classification, sloping shore platform of Bird classification) are also observable. In a few limited areas, a more horizontal shore platform (Type-B of Sunamura classification, low-tide horizontal shore platform of Bird classification) is visible. Current tidal notch is present in La Vela and Le Due Sorelle sea stacks (Furlani et al., 2018), located at short distances from the coastline; active and intensive morphodynamic is evidenced by the absence of Tyrrhenian marine deposits and uplifted tidal notches (Furlani et al., 2018). Anthropic structures, such as local harbour and touristic buildings appear especially in the Portonovo landslide deposit.

3.2 Specific investigation methods

A series of field geological, geomorphological, and structural surveys were performed by subsequently associating remote LSQ analysis. The surveys were carried out at a scale of 1:10,000 using the topographic dataset (downloadable at <https://www.regione.marche.it>) in vector format, to identify deposits and landforms as well as to redefine the mapping of bedrock lithology and structures along the entire coastal slope between the Portonovo and Due Sorelle

sites. Field surveys were supported by low-altitude aerial photos taken from a UAV platform, then processed with Metashape to obtain DSM and orthomosaics. One of the final aims was to unravel the connection between the frequency and distribution of joints in the local bedrock and the rock slope deformation and instability. To achieve this, on the Gabbiani plates (southern part of the Mt. Conero), which constitute the sliding surface of the Due Sorelle landslide, a quantification of the fracture pattern was performed using the FacPaQ software (Healy et al., 2017). FracPaQ is a set of MatLab routines that allows obtaining parameters such as length, orientation, connectivity, and permeability of a fracture pattern from a digital dataset (an image, a file with node coordinates, etc.). A preliminar analysis has been made through the interpretation of 1988-1989 and 1994-1998 panchromatic aerial orthophotos at www.pcn.minambiente.it as a Web Map Service (WMS); furthermore panchromatic aerial photos available at the scale of 1:33,000 (year 1954) and 1:75,000 (year 1989) were consulted. Historical aerial images were used to visualize pre-urbanization areas and to map recent landslide activity, and a stereoscope was also used for a 3D interpretation of landforms. In combination with the latter, a multi-temporal analysis was also carried out with the most recent optical satellite images in Google Earth Pro. The peculiar amount of landslide phenomena affecting the coastal slopes imposed special attention on the detection and mapping of the gravity-induced processes and landforms, and their complex evolutionary scenarios.

The 2 m cell-sized DEM, on which the LSQ analysis was performed, was derived from the LiDAR dataset available for the Italian coastline at www.pcn.minambiente.it. ESRI-ArcGIS desktop software was used for this purpose and for the storage of geological, geomorphological, and structural data derived from the surveys. Two main morphometric parameters were selected and calculated starting from the available 2 m cell-sized DEM. The first parameter is the Slope Angle (SA), derived by means of the surface slope algorithm running in the Spatial Analyst extension of the ESRI-ArcMap software. For each DEM cell, this algorithm computes the first

derivative of the elevation surface, or the maximum change in elevation between a cell and its eight neighbours (i.e., the steepest downhill descent from the cell) (Borrough and McDonell, 1998). The second parameter is the surface Roughness (R) that is useful to define different landslide features and to examine the landslide activity (McKean and Roering, 2004; Berti et al., 2013). Among the numerous studies that have performed a method for calculating the R (e.g., Hobson, 1972; Shepard et al., 2001; Guth, 2003), in this work, the R was calculated as the standard deviation of the elevation values within a 4 x 4 moving window, which is a useful method for evidencing the topographic signature of large landslides (Berti et al., 2013). In order to obtain the R values, the focal statistics tool running in the ESRI-ArcMap software was adopted. The number of pixels per bin (i.e., pixels in each parameter class) was reported for both parameters through histograms for the southern and northern coastal sectors.

Furthermore, altimetric profiles, that provide elevation distribution for progressive distance, were performed, based on the 2m cell-sized DEM. The three tracks (up-slope, mid-slope, and foot-slope) allow an accurate description of coastal morphology, in association with both S and R variables only for the mid-slope and foot-slope. This type of visualization enhances the evidence of parameter value variations attributed to the presence of landslides with different types, sizes, and state of activity.

Subsequently, a stress-strain numerical modelling, via back-analysis using FLAC 2D 8.0 (Itasca, 2011 - licensed “Sapienza”), was also performed only for the Portonovo landslide. To achieve this, the pre-event slope morphology was reconstructed through the linearization of the contour lines, and the geomechanical parameters of the rock mass were calculated based on the condition of joints and intact rock.

3.3 Results

Different landslide typologies are present in the entire costal slope, leading to numerous landslide deposits in the middle and lower slope areas and vertical scarps in the upper slope.

The most significant mass movements identified in the Mt. Conero coastal area are located in the northern part between Portonovo village and La Vela sea stack, which exhibit evident landslide bodies and extensive detachment areas. The southern sector, in locality of Due Sorelle beach, is characterized by a plunging cliff, with escarpment and the slide surface clearly visible. The first two landslides, called Portonovo and La Vela, can be attributed to a rock avalanche while the third, called Due Sorelle landslide, is caused by active rock wedge slides and falls (Hung et al., 2014).

3.3.1 Gravity-driven processes

The Portonovo landslide exhibits a runout of approximately 500 m seaward, modifying the profile of the ancient coastline and generating the bay where Portonovo village is situated (Fig. 11a). The foot of the landslide body shows a hummocky morphology with small hills (up to 10 m) and small depressions, forming a series of typical arched compressional ridges. In contrast, La Vela landslide shows a truncated toe; however, the nearshore seabed morphology up to the contour line -10 m below sea level (b.s.l.) indicates that a terminal landslide lobe can still be present (Fig. 11a). Small and altered outcrops of stratified slope waste deposits (Fig. 11b) can be observed along the base of the cliff, overlaying unconformably the La Vela landslide deposit. Stratified slope deposits are quite common within the Umbria-Marche Apennines, even along the coastline (Coltorti and Dramis, 1995); they are especially abundant in areas where bedrock, such as Maiolica or Scaglia Rossa Fms., is particularly susceptible to freeze-thaw processes. These deposits are characteristic of cold, periglacial environments (Van Steijn, 2011) and represent the termination of the last glacial slope-fluvial sedimentation cycle in the Apennine region (Nesci and Savelli, 1986), with a chronological association at the end of Late Pleistocene (Savelli et al., 2013). At the foot-slope of both the landslide bodies, there is a distinctive wave-cut scarp, which exposes typical rock avalanche/slide deposits, with Scaglia Rossa and subordinately Marne a Fucoidi rock blocks (from 1 to 5 m³) and calcareous debris

with sandy clay. Shallow debris avalanche reactivation of the main Portonovo landslide body occurred, overlying the rock avalanche deposit. In the up-slope zone, a 150 m high scar area characterize the escarpment of the Portonovo landslide; here are exposed the R2 and R3 members of the Scaglia Rossa Fm with a sub-horizontal bedding (Montanari et al., 2016). Trenches and depressions in the backscarp area have been found, delineating the releasing zone (Fig. 11c).

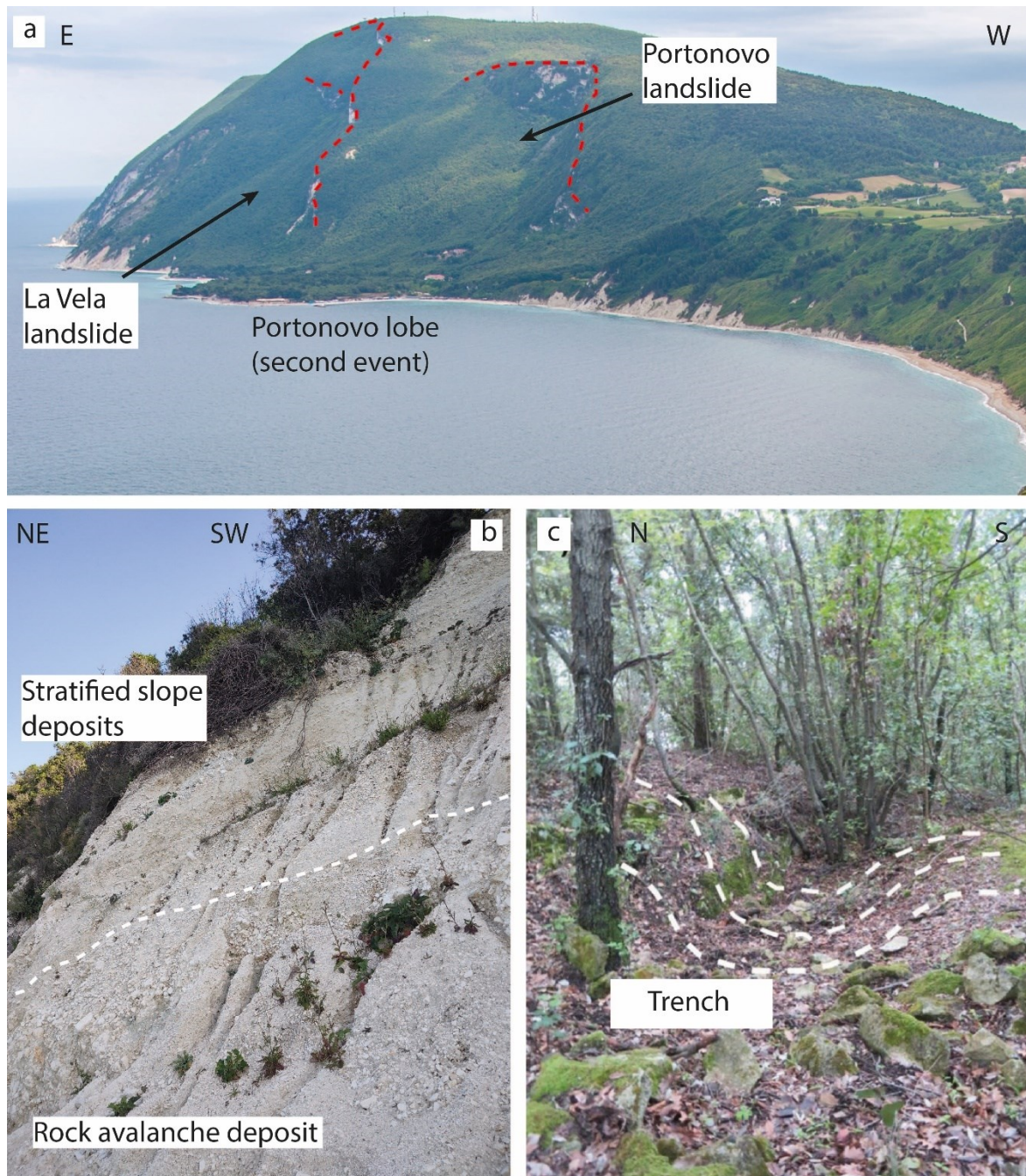


Figure 11. (a) Panoramic view of the Portonovo and La Vela landslides from Mt. dei Corvi. Both landslide bodies and the lobe that modified the coastline, on which the Portonovo village was built, are clearly visible. (b) The La Vela rock avalanche deposit overlayed by the altered stratified slope deposits. (c) Trenches in the backscarp area of Portonovo landslide associated with the MRC process.

In the southern sector, the Due Sorelle landslide (Fig. 12a) particularly stands out characterized by a limited presence of the landslide body, often consisting mainly of an active talus deposit at the foot-slope. Just below the 30 meters landslide escarpment, composed by Scaglia Rossa Fm., a rockfall deposit is present. What distinguishes this landslide from the previous ones is the sliding surface, which is clearly visible on the slope consisting of two plates of Maiolica Fm., called Placche dei Gabbiani (Fig. 12a). In front of the left flank of the landslide there are two sea stacks called Due Sorelle (Fig. 12b, c), cut by an active tidal notch (Fig. 12c) (Furlani et al., 2018). This tidal notch is important because offers a valuable insight into the historical stability of the areas where it is found, providing information spanning the last 500 years or more. The notches can also serve as evidence of RSL changes, especially on sturdy and resilient rocks.

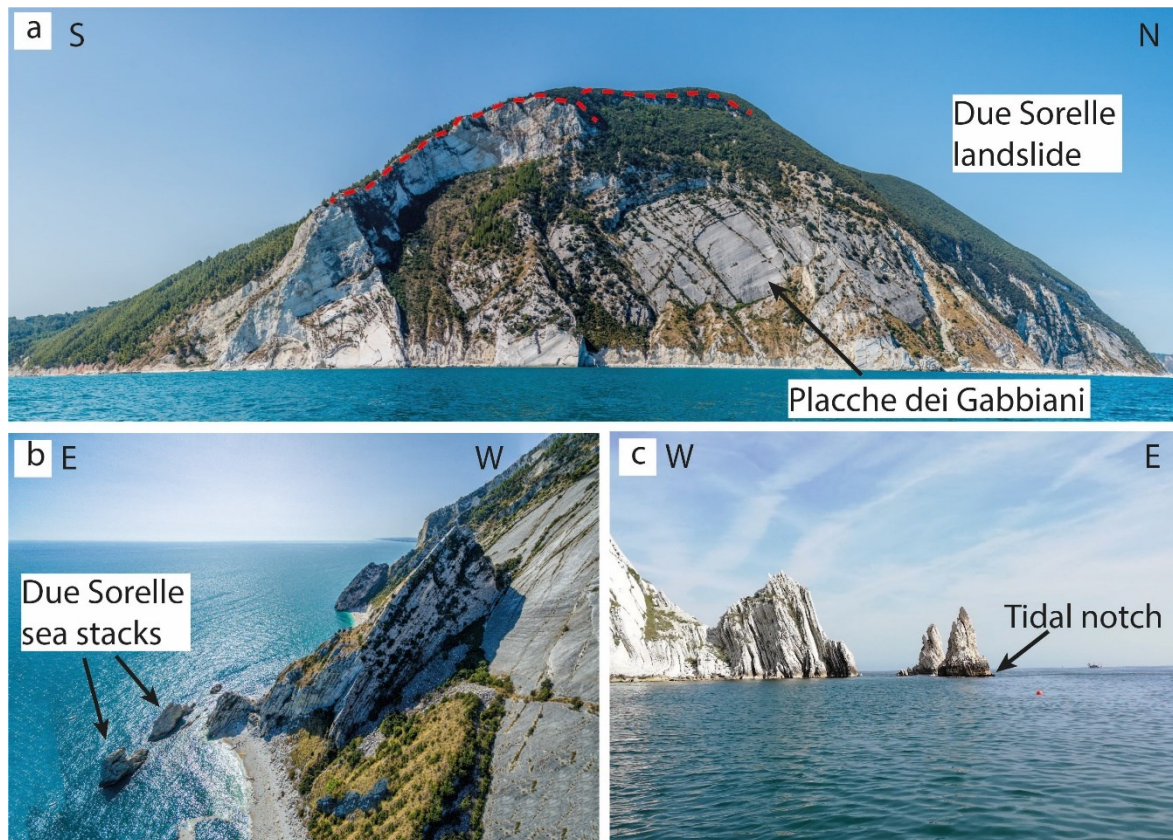


Figure 12. (a) Panoramic view of the Due Sorelle coastal slope from boat; The slide surface and detachment area are clearly visible. (b) A view that highlights the high dip angle of the strata in this area, caused by the presence of the asymmetric anticline axis near the coastline. Additionally, the Due Sorelle sea stacks (c) stand out, formed by Scaglia Rossa Fm., that are detached from the slope (Maiolica Fm.) due to the erosion of the Marne a Fucoidi Fm., which can be observed on the right flank of the landslide.

In the area between La Vela and Due Sorelle landslides features of general slope instabilities have been found, with evidence of slope-scale gravity-driven processes related to MRC. Flexural toppling (Fig. 13a, b) along a steeply dipping and closely spaced primary set of discontinuities was evidenced, despite the presence of horizontal cross joints which serve as breakout surface, driving the rotation of the blocks (McAffee and Cruden, 1996; Nichol et al., 2002). Block toppling leads to the development of surfaces subparallel to the slope, which in conjunction with the bending of strata, act as release surface (red line in Fig. 13a) contributing to the potential failure (Pánek and Klimeš, 2016). Additionally, the presence of buckling folds (Fig. 13c, d) leading to tension and shearing fractures can further contribute to the occurrence of rockfalls and attests to the process of Mass Rock Creep acting at slope-scale.

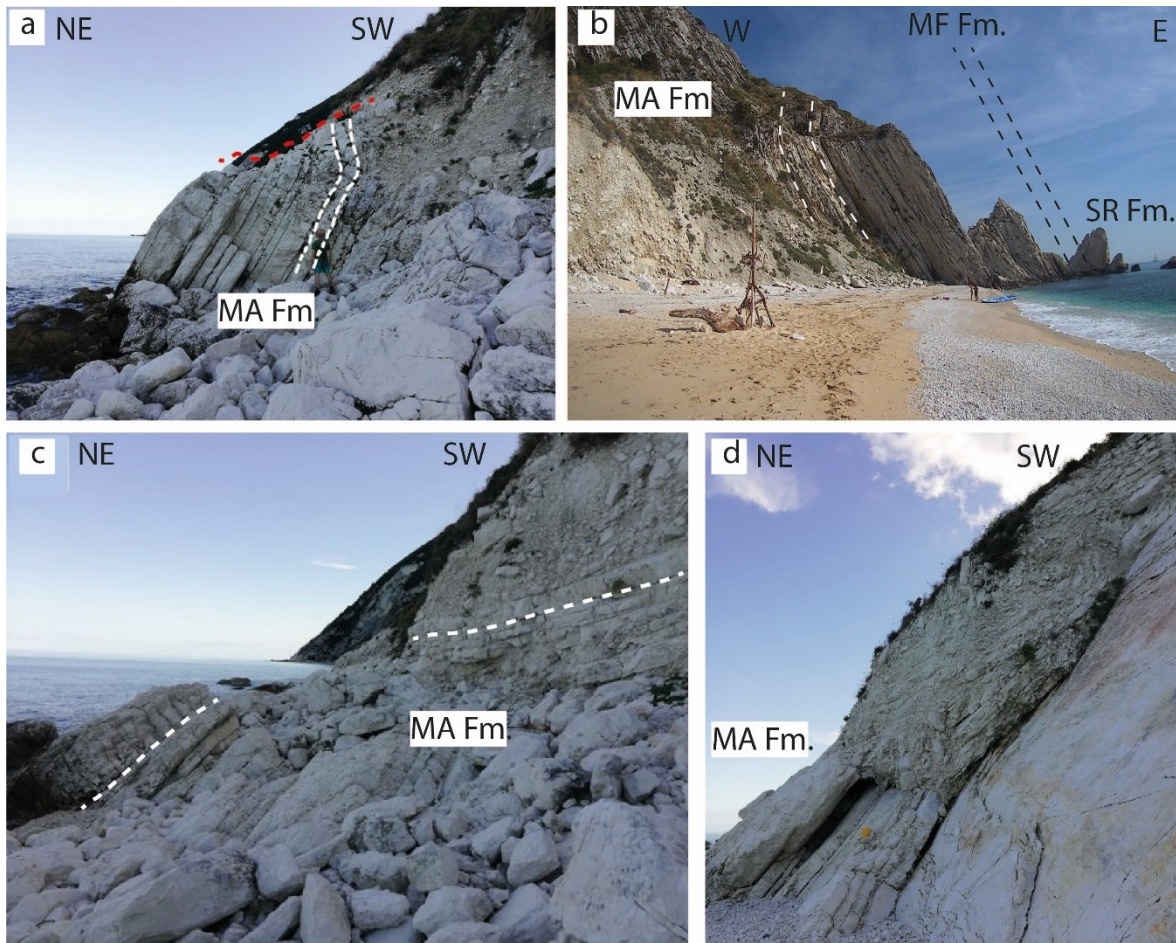


Figure 13. Evidence of gravity-induced deformations driven by MRC process. a) and b) flexural toppling, respectively near La Vela sea stack and on the left flank of Due Sorelle beach; this process evolving through formation of breakout planes (red line in a)). c) and d) folds due to buckling process along the coastal slope after La Vela sea stack.

3.3.2 Land Surface Quantitative analysis

Along the analysed coastal slope, SA and R have been calculated in order to determine the spatial variation of these two morphometric variables.

The SA displays extremely variable values and it is a useful variable to have good evidence of the subvertical geometry of the cliff. Specifically, the SA map (Fig 14) provides compelling evidence of a close correspondence between the highest slope angle values and the main rock-block detachment zones. Statistical analyses (Fig. 14a, b) reveals that the highest slope values

are predominantly concentrated in the southern sector, while in the northern sector the distribution is more heterogeneous due to the presence of the landslide bodies.

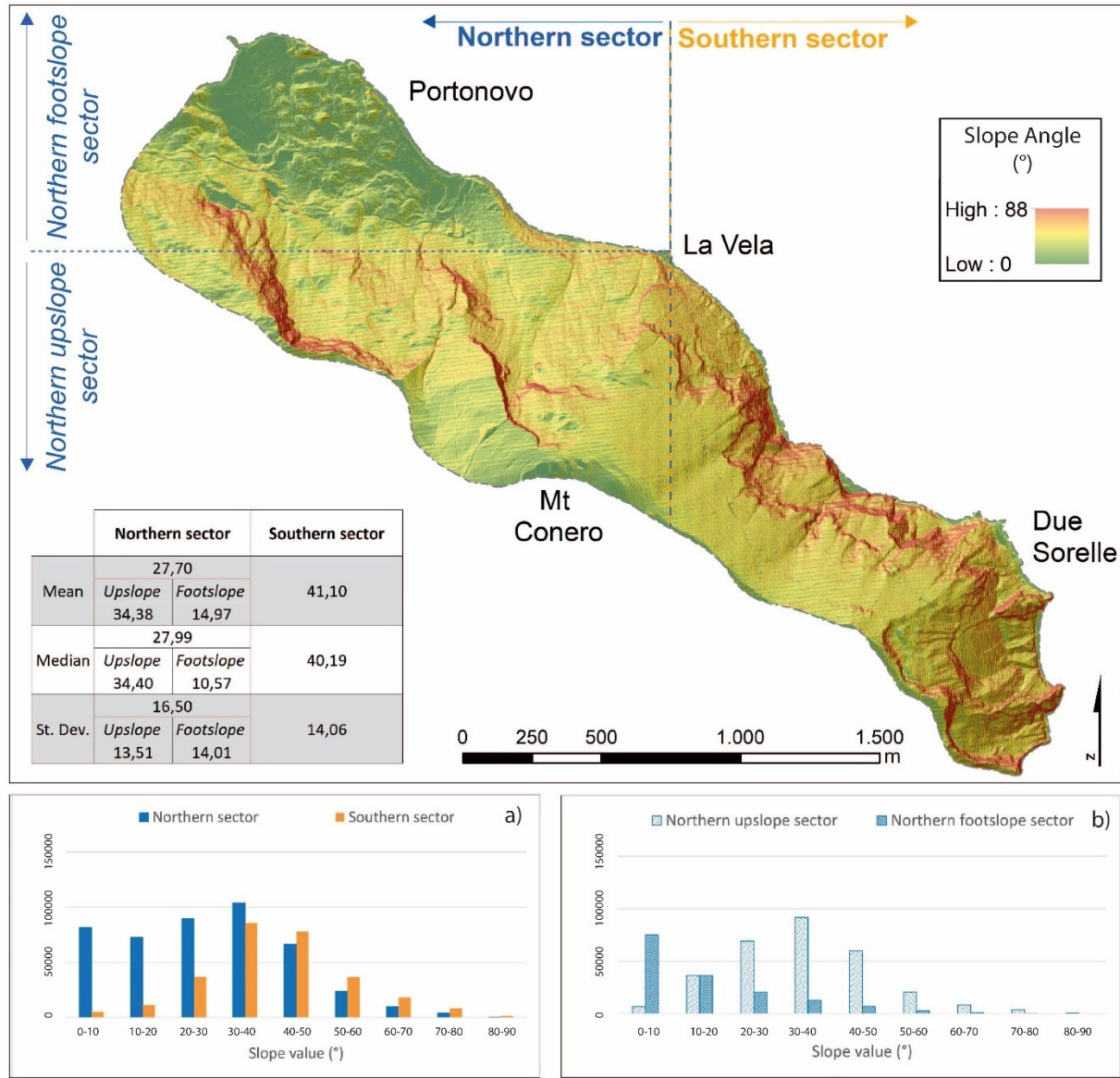


Figure 14. Spatial distribution of the SA values in the study area, based on LiDAR derived DEM. a) histogram depicting the distribution of slope values in both the southern and the northern sectors of the study area (the y-axis represents the number of pixel per bin); b) histogram illustrating the distribution of SA values in both the foot-slope and up-slope sections of the northern sector of the study area (the y-axis represents the number of pixels per bin).

The spatial distribution of the R parameter (Fig. 15) coincides fairly with that of the SA, but with maximum values up to 33 m. Highest values are predominantly found along the main escarpments, while lowest values are present in more flat or smoothed areas. The southern

sector exhibits highest average values, while in the northern sector it is possible to identify two distinct zones (Fig. 15a, b). The first one encompasses the entire extent of the La Vela landslide body and the upper portion of the Portonovo landslide deposit, with higher values, and the second one characterizes the Portonovo landslide lobe, with values between 3 and 6 m.

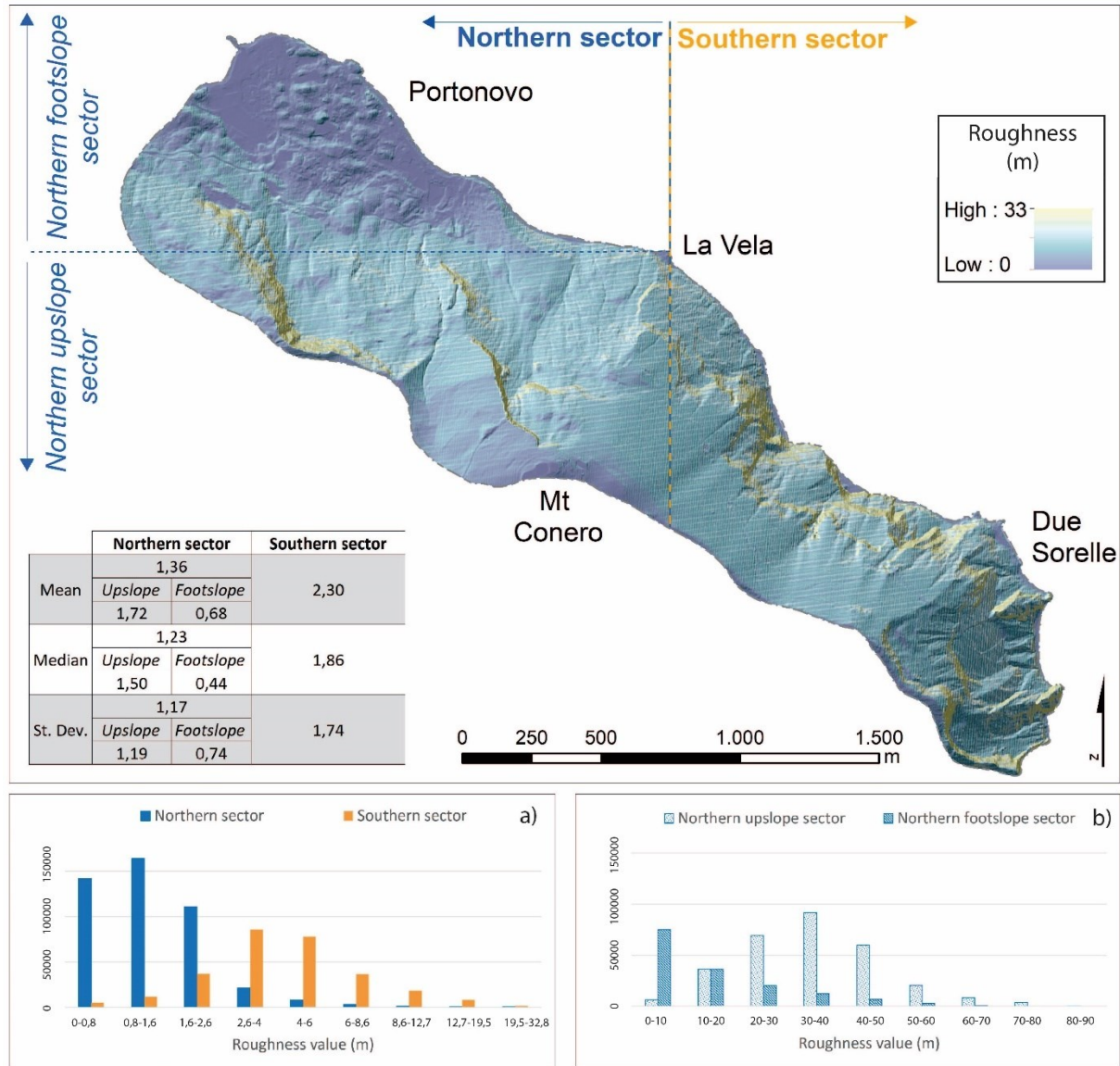


Figure 15. Spatial distribution of the R values in the study area, based on LiDAR derived DEM. In a) histogram depicting the distribution of R values in both the southern and the northern sectors of the study area (the y-axis represents the number of pixels per bin); b) histogram illustrating the distribution of R values in both the foot-slope and up-slope sections of the northern sector of the study area (the y-axis represents the number of pixels per bin).

To enhance the understanding of the LSQ analysis described above, it was associated with altimetric profiles oriented along the coastal slope direction and with the litho-structural conditions (Fig. 16). Three profiles have been made: (i) on the ridge, to depict the general slope profile, (ii) at +200 m (a.s.l.), to capture landslide deposits in the mid-slope and (iii) located at about 50 m from the current shoreline, to record either the base of the rocky slope or the talus deposits at the foot-slope.

Along the transect at +200 m (a.s.l.), it is evident that both Portonovo and La Vela landslides exhibit the same R values in contrast with the values of the same landslides along the profile at +20 m (a.s.l.). The active retreating cliff is prominently highlighted by highest R values along the +20 m (a.s.l.) transect.

The SA variable shows fairly uniform values up to 40-45° on the transect at +200 m (a.s.l.) with exception at the Due Sorelle cliff and at the right flank of Porotnovno sector. Similar to the R parameter, the +20 m (a.s.l.) profile also highlights the presence of the subvertical active wave-cut cliff, characterized by significant higher values; in the other sectors the average SA values are >40-45°, except for the Portonovo landslide lobe, which exhibits values below 20°.

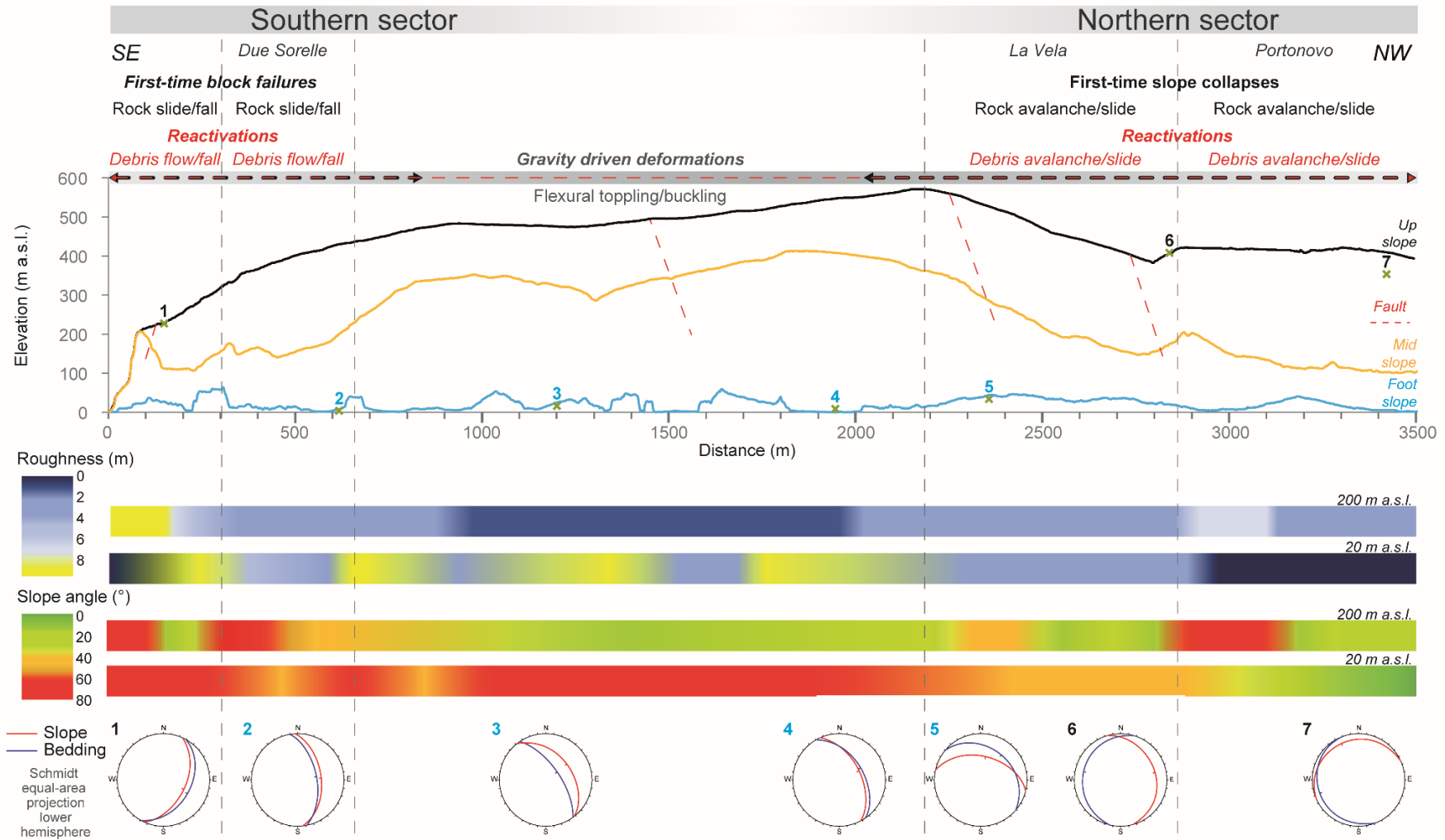


Figure 16. Altimetric profiles along the entire Mt. Conero coastal slope. The three profiles show the morphology of the up-slope (black line), mid-slope (yellow line) and foot-slope (blue line). In the foot-slope profile the landslide deposits are distinguished very well with a convex line. Variations of R and SA parameters are represented in two distinct transect with a continuous gradient of colours. Stereo plots illustrate the bedding attitude in relation to the slope attitude.

3.3.3 Litho-structural factors

The instability of the coastal cliff is primarily ruled by litho-structural factors. In particular, the Due Sorelle coastal slope is conditioned by the presence of the anticline axis, leading bedding dip to the NE at high angle (up to 70°), facilitating the planar and wedge sliding. The volume of the blocks ranges from ten to hundreds of cubic meters. The Marne a Fucoidi Fm. have played a fundamental role, acting as a detachment surface between the Scaglia Rossa Fm., that characterize the vertical scar area, and the Maiolica Fm., outcropping in the Placche dei Gabbiani. The analysis of fractures in the Placche dei Gabbiani (Fig. 17) clearly outlines how the rock wedge is delimited by fractures oriented in the 50°N and 140°N directions, which also seem to be the most common. In contrast, in the northern sector the bedding dips toward E-ENE more gently than the previous one (up to 25°), as a consequence of the fold-axis plunging and periclinal folding. Here too, the Marne a Fucoidi Fm. have played a key role in slope stability, but with a different evolution that will then be discussed later. High angle pre-orogenic transtensional faults (Cello and Coppola, 1984) have dissected the anticline forelimb, establishing the structural framework within which slope-scale deformation has evolved (Di Luzio et al., 2004; Alfaro et al., 2019). Some of the present discontinuities show a correlation with the main tectonic elements and in particular with ENE-WSW transtensional faults.

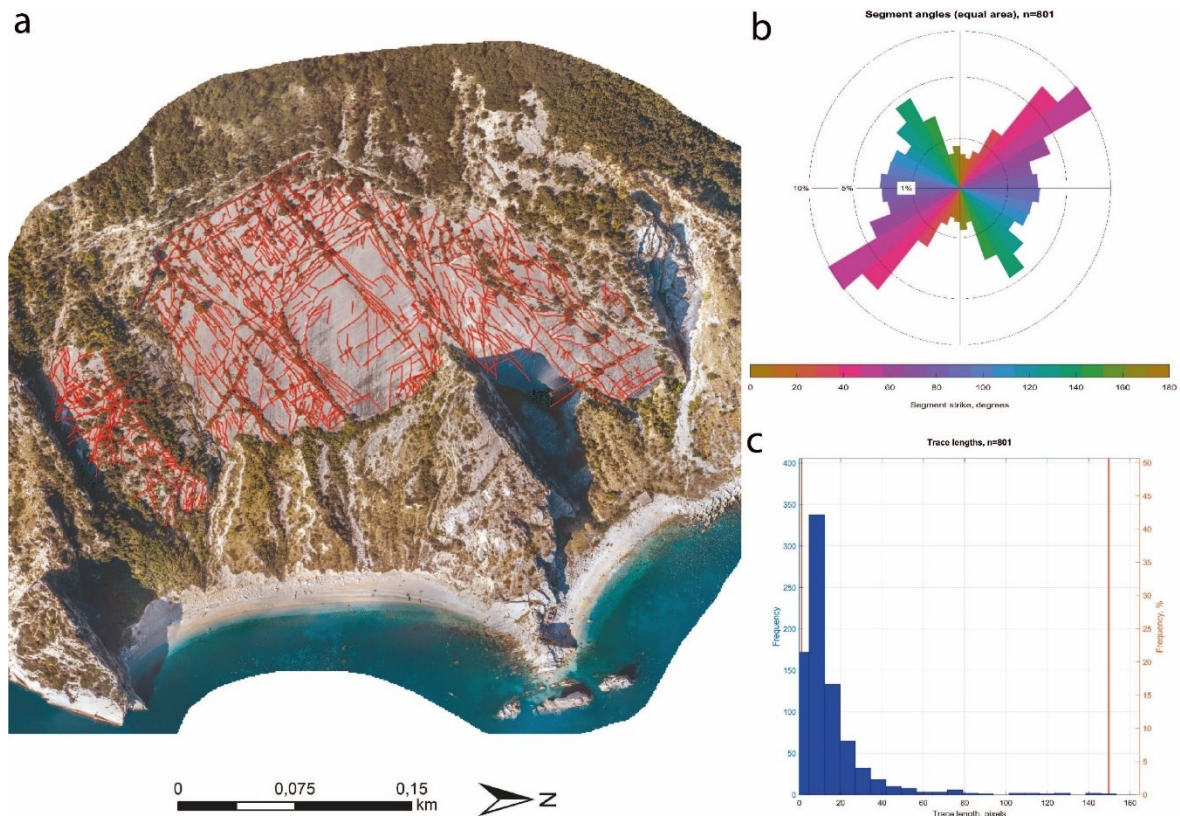


Figure 17. Quantification of fracture pattern made with FraQPaQ software. a) fracture traces on Placche dei Gabbiani slope; b) polar diagram with the segment strike directions (the N is equal to 0°); c) histogram with length and frequency of the fractures. The length is in pixel (each pixel is 3 cm).

The importance of litho-structural factors in the slope evolution is also highlighted by the numerical back-analysis modelling, carried out by Marmoni et al. (2023), and conducted for the Portonovo landslide (Fig. 18). A pre-event engineering-geological cross section was reconstructed on the same Portonovo section (B-B') of Fig. 10, which took into consideration the pre-failure morphology. The reconstruction of the pre-landslide morphology was conducted through the linearization of the elevation contour lines on the DEM, from the ment area up to the accumulation zone (topography visible in the Fig. 18a). The engineering-geological model was developed through on-site geomechanical characterization of the rock mass. The strain softening hypothesis applied to the Marne a Fucoidi Fm. could provide an explanation for the overall slope collapse, which occurred in two distinct events at approximately 56 and 16 ka, with an estimated volume of 20 Mm³ for both events.

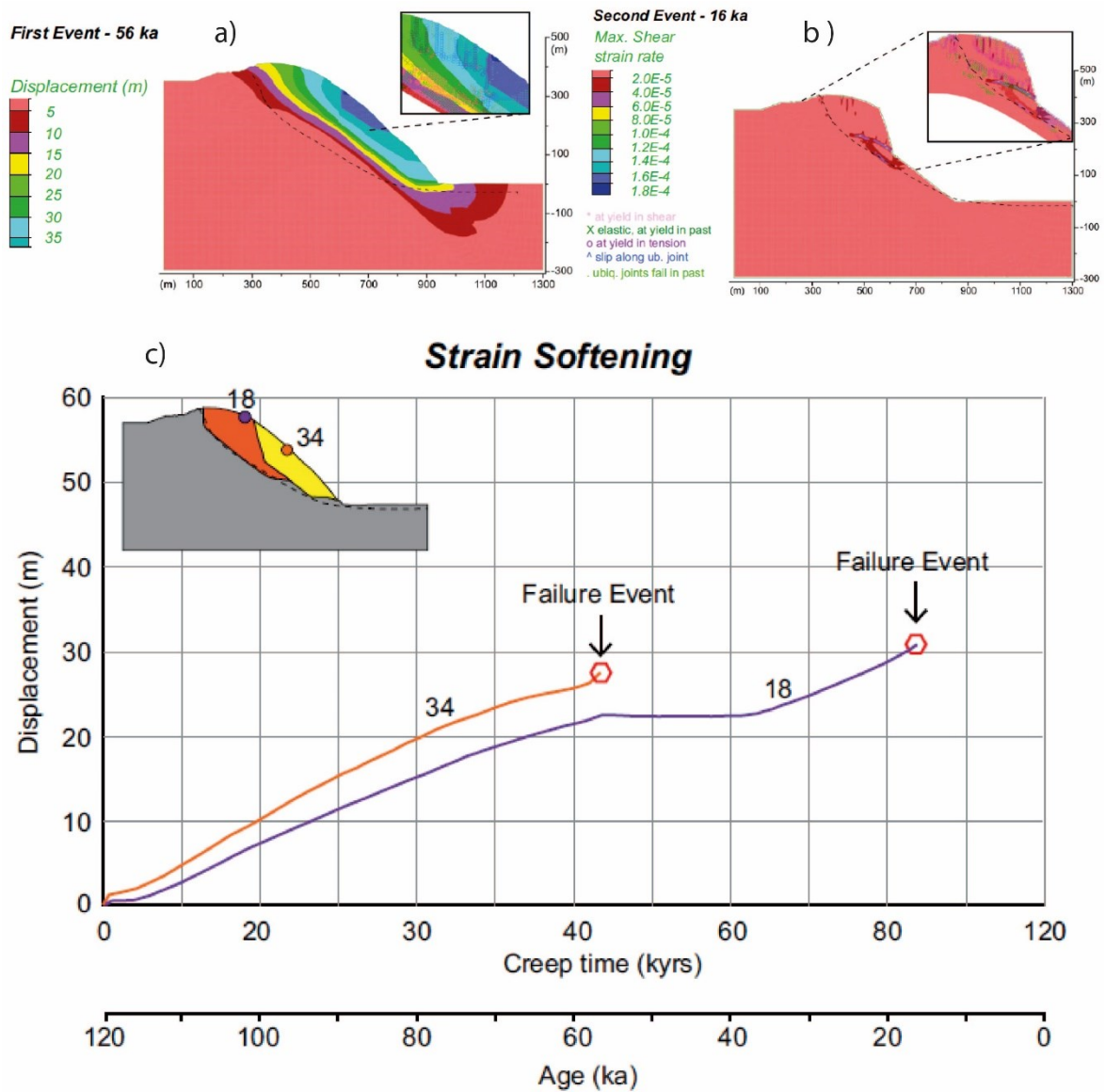


Figure 18. a) and b) numerical modelling of the Portonovo, highlighting the first (56 ka) and the second event (16 ka); dashed line along the section represents the present topographic profile. In c) is reported the double-step failure in a displacement-time series.

3.4 Discussion

The Mt. Conero coastal slope can be divided into two distinct sectors characterized by convex dip-slopes (Scarascia Mugnozza et al., 2006): the first sector is composed by Portonovo and La Vela zones and the second correspond to the Due Sorelle slope. Despite sharing the same geological formations, topographic and structural assessments show some differences, that lead

to two different morpho-evolutive styles due to gravity-induced processes acting at different spatial and temporal scales (Fig. 19).

In the northern part, the landscape of the coastal slope is characterized by slope-scale massive landslide and their associated detachment areas, while cliff scale rock fall and rock wedge slide occur in the southern sector. A first-time massive rock slope failure as a consequence of the final stage of the MRC process occurs along the entire slope, covering both the Portonovo and La Vela area, that evolved in two steps: the first one encompasses the entire coastal sector, while the second one pertains exclusively to the Portonovo area. The estimated volume for this latter landslide is of about $40 \times 10^6 \text{ m}^3$. The absence of marine terraces, which are one of the geomorphological markers for the Middle Pleistocene high stand (Furlani et al., 2018) and the existence of periglacial deposits overlaying the main landslide body provide the assumption that both events occurred in the period between ~ 125 and ~ 11 ka. Additionally, the relatively recent appearance of the landslide erosional and depositional landforms rules out the possibility of these mass movements occurring during earlier glacial cycles.

The numerical modelling has confirmed what was identified through field surveys and LSQ analysis. In fact, two events are evident for the Portonovo landslide, the first predating the LGM and the second occurring in the post-glacial period, subsequently filled by slope-stratified deposits. The volumes of the landslides themselves also appear to be comparable to the previously estimated ones.

The spatial distribution of R values in the northern sector appears to validate that there were two distinct massive rock slope failure events: the first one includes both Portonovo and La Vela landslides and the second one took place only in Portonovo area. Specifically, the La Vela landslide body exhibits R values nearly identical to the along slope landslide deposit of Portonovo landslide (Fig. 15), suggesting a similar post-event reshaping and, therefore, a similar failure time. Recent debris avalanche and slide reactivations occurred in both landslide

bodies, confirmed by field observations; for instance, a catastrophic landslide took place during the Middle Age, destroying the local harbour and an ancient Benedictine Abbey (Montanari et al., 2016). The Mt. Conero coastal slope can be regarded as a classical palimpsest landscape (*sensu* Bloom, 2002), where processes evolved at various spatial-time scales and currently demonstrate dissimilar dynamics. In fact, the nested landslide system that characterize the Portonovo and La Vela coastal sector started its development during the early stages of the last glacial period, with a relative low sea level.

The prevailing influence of distinct morpho-evolutionary styles on the Mt. Conero coastal slope is attributed to the different structural settings (Fig. 16) with the same fundamental MRC process on the entire slope scale. According to these observations, a double scale morphodynamic conceptual model is proposed: smaller-scale landslide events are the results of transition from gravity-driven processes to force-driven processes (green arrow in Fig. 19), which can be triggered by local, time-independent factors and forces, such as sea storms and earthquakes; in contrast, larger rock mass failure, such as rock avalanches, are predominantly induced by inertial forces, due to the progressive viscous deformation of MRC (red arrow in Fig. 19).

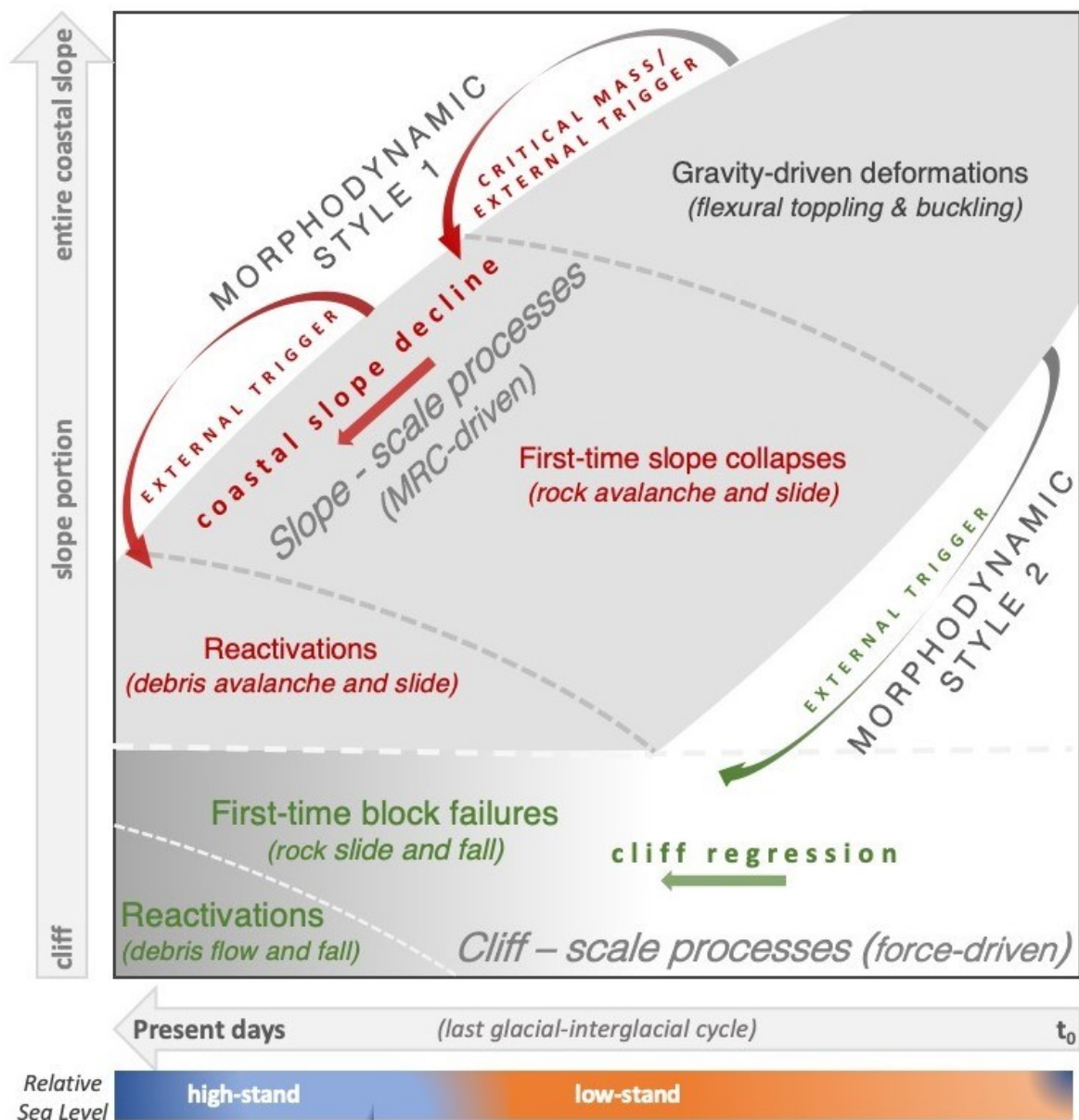


Figure 19. Conceptual space-time evolutive model, which illustrates the dynamic evolution of the Mt. Conero coastal slope. It outlines two different morpho-evolutive scenarios with the same underlying MRC process that affect the entire coastal slope. The first scenario, characteristic of the northern sector, pertains to slope-processes, which are time-dependent; the second scenario, typical of the southern sector, involve cliff-scale processes, which are time-independent or force-driven.

With the same underlying process acting along the entire slope and the same lithologies, this difference in morpho-evolutionary style can be attributed to different structural factors. In fact, for steeper dip strata the MRC deformation does not encompass the critical mass susceptible to failure (Esposito et al., 2007) and the morpho-evolution results in numerous smaller-scale slides

and falls, which have a short recurrence time. This style type is visible in the southern sector on the active Due Sorelle landslide, where reactivations are also possible after a trigger like earthquake or heavy rains. The cliff-scale processes are the most hazardous in comparison to the gravity-driven MRC failures that require more time to reach a general collapse. The coexistence of large-scale MRC process and small-scale processes is evident in the Due Sorelle sector. Here, the observations of flexural toppling and buckling (Fig. 13b) indicates that the progressive MRC deformation rapidly evolved towards slides or falls, avoiding the development of critical mass which is necessary for the achievement of collapse. The LSQ analysis, by various visualizations, has proven to be an efficient mapping methodology; it offers a faster alternative to the time-consuming traditional techniques to refine the survey and mapping of slope processes and gravity-induced landforms. The results emphasize the significance of assessing the long-term morpho-evolution of the entire slope. This comprehensive understanding is crucial for gaining insight into the current behaviour and future evolution of coastal landslides.

Chapter IV

4. Land-Surface Quantitative analysis in addition to the geomorphological assessment: example in the Mt. San Bartolo rocky coast

Arguments developed in the three years of PhD and in the following publication:

- Piacentini D, Troiani F, Torre D, Menichetti M (2021) Land-Surface Quantitative Analysis to Investigate the Spatial Distribution of Gravitational Landforms along Rocky Coasts. Remote Sensing 13:5012. <https://doi.org/10.3390/rs13245012>

Personal contribution to the above-mentioned publication: (i) Field investigation and data collection, (ii) data storage in GIS environments; (iii) statistical analysis; (iv) redaction of geological and geomorphological maps.

4.1 General setting

The Mt. San Bartolo rocky coast is situated in the northern part of the Marche region (Central Italy) on the border with the Emilia Romagna region and between the localities of Gabicce and Pesaro (43°54'33" N, 12°54'59" E). The approximately 10 km of rocky coastline reaches a maximum altitude of about 222 m (a.s.l.) with a main NW-SE orientation. The landscape is rural and scarcely anthropized, with steep slopes covered by Mediterranean type vegetation (i.e., grass, turkey oaks and spanish broom); there are also olive groves, vineyards, and fruit trees. On the ridge of the rocky coasts, there are some villages (i.e., Castel di Mezzo, Fiorenzuola di Focara, and Santa Marina), which, during the last few decades, have resorted to mitigation works for the retreat of the ridge, due to gravitational instability (Coccioni, 2003).

Because of the coastal erosion, block barriers have been inserted in the areas of Castel di Mezzo, Fiorenzuola di Focara and Pesaro, and in the Vallugola locality there is a small harbour, with part of armoured coasts (Elmi and Gori, 1987). Mesothermic climate of Mediterranean type, Cfa according to Köppen-Geiger classification (Fратиanni and Acquaotta, 2017; Rubel et al., 2017; Beck et al., 2018), characterizes this coastal area (Fig. 20). Mean annual temperature reaches values of 14.6 °C and mean precipitation value of about 712 mm. Daily temperature is 23 °C in July, while is 6 °C in January; Monthly rainfall values range from 30 mm in July to 90 mm in November. Winds and waves of grater intensity approach mainly from NNE and subordinately from SE, generating a main longshore current towards N (Colantoni et al., 2004). Storm waves can reach 1.80–2 m, based on the data obtained from the National Sea-Wave Measurement Network (RON, <https://www.mareografico.it/>), while the average tidal range is about 50 cm measured in the harbour at Pesaro (Nesci, 2003; Colantoni et al., 2004).

In 1994 with the L.R.28.04.94 n° 15 was established the Natural Regional Park of Mt. San Bartolo with and area of about 1600 ha and consisting of several areas depending on the anthropization and land use (Roccato, 2004b).

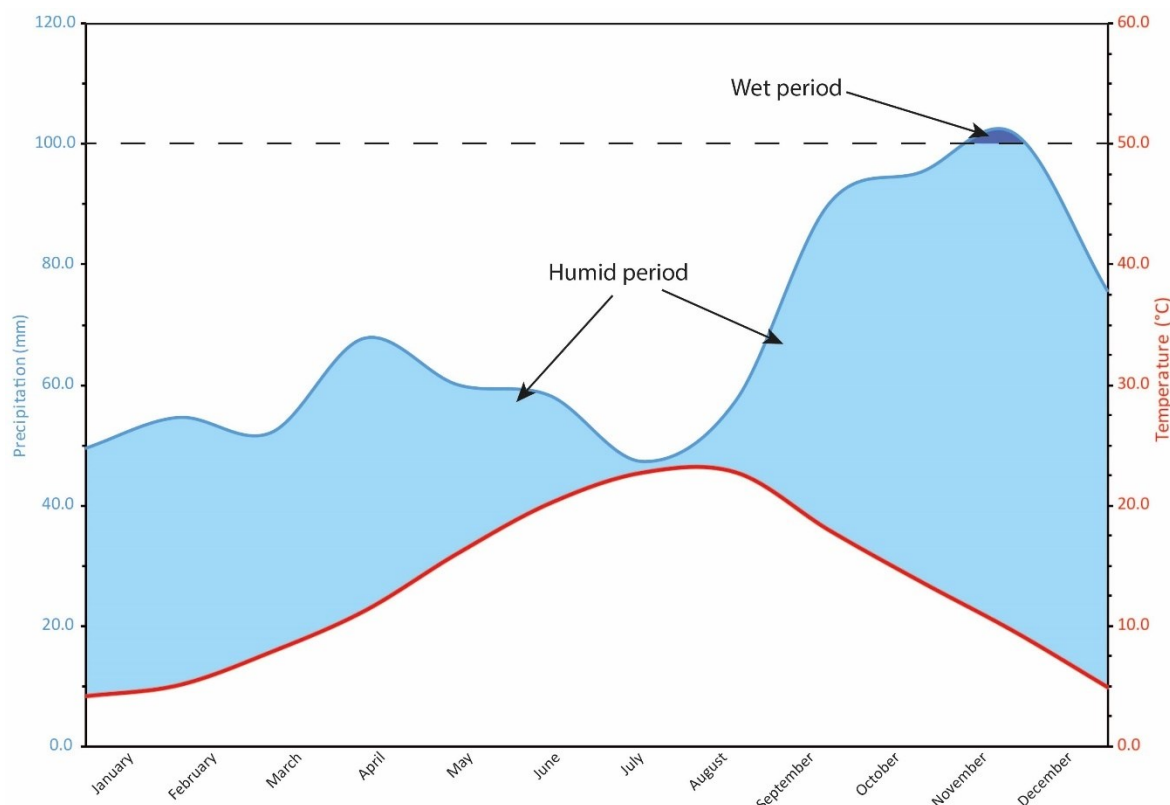


Figure 20. Climatograph (Walter and Lieth, 1967) for the Mt. San Bartolo area, depicting the relationship between monthly average temperature (°C) and monthly average precipitation (mm) from 1990 to 2020. Data are downloaded from <https://climatecharts.net/> (Zepner et al., 2021).

4.1.1. Geological and geomorphological setting

The Mt. San Bartolo coastal ridge represents the first rocky coast after the Veneto and Emilia Romagna low-lying coasts in the western side of the Adriatic sea. From a structural viewpoint the ridge consists of a NE verging syncline-anticline pair. Intercalations of marl and sandstone and other formations, belonging to the Marche-Romagna Apennines foredeep succession (Fig. 21) are present in this area, already described by Capuano and D’Antonio (1992), Colantoni et al. (2004), and Tramontana and Guerrera (2011): (i) Schlier Fm. (Upper Tortonian), composed of prototorbiditic grey-blue marls and white limestones and divided into two lithofacies: a lower one more calcareous with a thickness of 20 m and an upper one more clayey with an outcropping thickness of about 30 m; (ii) Gessoso Solfifera Fm. (Messinian), consisting of evaporites and euxinic grey-blackish shales with grey calcareous layers (Roveri et al., 2005);

(iii) San Donato Fm. (Upper Messinian), alternations of turbiditic sandstones and grey-bluish silty marls with an outcropping thickness of about 180 m and two lithofacies: a lower head of marl intercalations and a higher head of sandstone banks; (iv) Colombacci Fm. (Upper Messinian), alternations similar to the San Donato Fm. with thickness of about 150 m, but with larger arenaceous layers, that reaches also 1 m in thickness; there are evaporitic-carbonate levels (called “Colombacci”) that give the name at the formation and have thickness between 30 and 220 cm. A few tens meters of Schlier Fm. outcrop at the base of the sea cliff at Castel di Mezzo and Mt. Castellaro, with the Gessoso Solfifera Fm. that overlies the Schlier Fm. with two unconformities. In these layers is located one of the main regional shallow thrust detachments.

Because of the syncline structure the bedding attitude on the coastal slope dips with a range between 30° and 50° to the SW; in the southeastern part near Pesaro, the bedding attitude change the direction, dipping up to 30 ° to the ENE, due to the anticline structure which continues into the sea at Punta degli Schiavi. The anticline, with its axis-oriented NW–SE (N130°), is thrust towards the NE a few kilometres and the basal detachment crops out offshore, while a shallow and low-angle thrust shear zone crops out at the base of the cliff, in correspondence to the Schlier and Gessoso Solfifera Fms (Fig. 21). N-S right lateral strike-slip faults affect all the coastal ridge, with offset of few hundred meters and with shear zones of few decimetres in thickness. The geometry of all of the Mt. San Bartolo structures is defined by seismic reflection images and verified by a deep borehole that crosses the basal sole thrust (Menichetti et al., 1991). The sandstone layers of the Colombacci and San Donato Fms. are affected by NW-SE and NE-SW subvertical extensional joints, related to the Late-Miocene-Pliocene compressional tectonic phase (Mayer et al., 2003). The most recent joint system, oriented NE–SW, runs parallel to the cliff face. Marl layers have a refracted fracturing also related to the Plio-Pleistocene exhumation process.

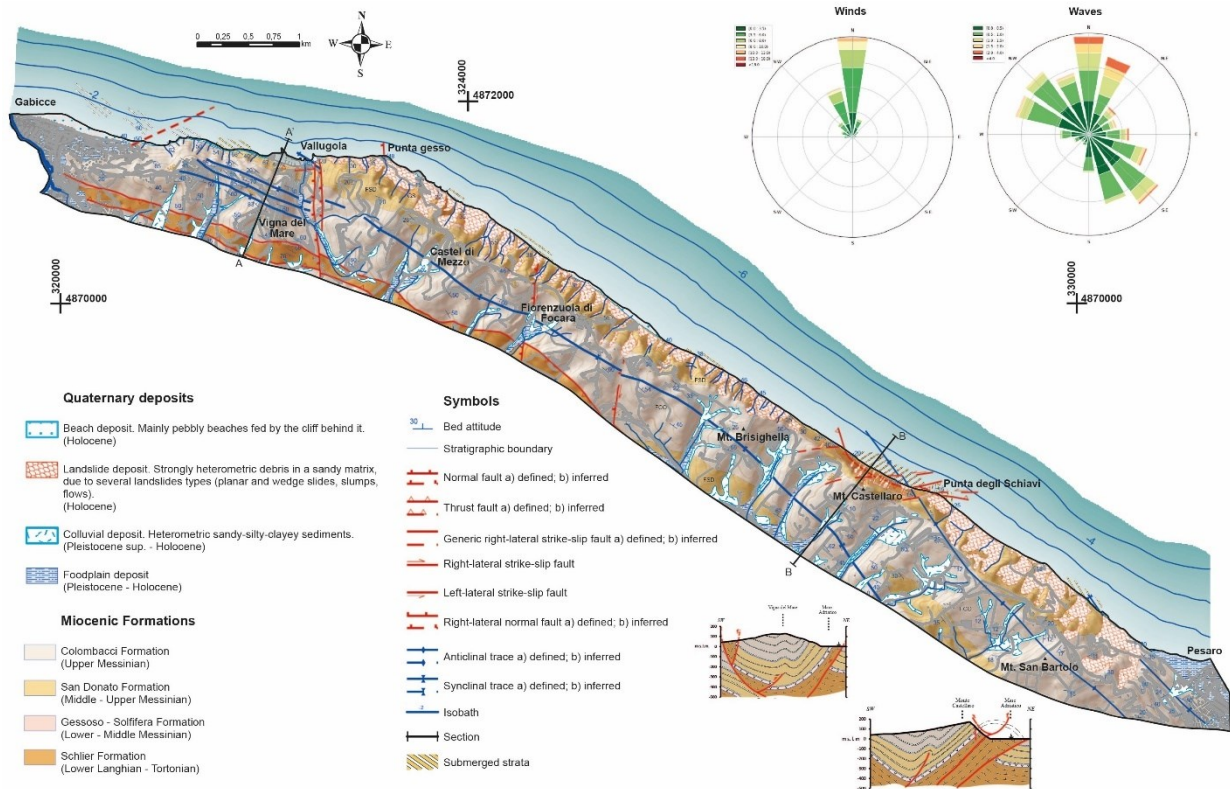


Figure 21. Geological and geomorphological map of the Mt. San Bartolo coastal area. Landslide types and areas are mapped with field surveys and remote analysis. The two polar diagrams show the direction and intensity of the winds and the direction and heights of the waves; data of winds and waves are downloaded from the RON (<https://www.mareografico.it/>), take into consideration the Ancona wave buoy (43°49'26" N, 13°43'10" E) for the period 01/01/2021-15/10/2023.

The morphogenesis of the Mt. San Bartolo coastal slope is mainly conditioned by marine, and gravity driven processes. Different landslide types with different state of activity (Elmi and Nesci, 1990; Nesci, 2003), such as slides, slumps, and flows, affect the sea slope, generating a generalized retreating trend of the coastal cliff. The retreat of the shoreline reached values of about 300 m in Castel di Mezzo area since 6000 years BP (Veggiani, 1988; Colantoni et al., 2004). The retreating process is witnessed by an extended rocky shore platform (Type-A of Sunamura classification), dipping seaward with a gradient of few degrees up to 5 km offshore (sloping shore platform of the Bird classification). Landslide deposits at the base of the cliff are eroded by the storm wave action, generating marine erosion scarps and facets. Shallow landslides or superficial reactivations occur in connection with exceptional rainy periods, as

reported in historical information (Gori and Luzi, 1978; Colantoni et al., 2004). Along the coastline at the base of the coastal slope, discontinuous sandy and gravel beaches are present.

4.2 Specific investigation methods

The main focus is the use of the LSQ analysis, starting from a LiDAR DTM with a ground resolution of 2 m and altimetric accuracy of ± 15 cm, available for entire Italian coastal area from the Ministry of Environment and Protection of Territory and Sea (MATTM, www.pcn.minambiente.it). Geomorphological and structural surveys preceded remote analysis in the years 2021-2022, with also the use of low-altitude vertical and oblique aerial photos, acquired with a UAV. The captured photos are also used for the generation of dense clouds, DSM and orthomosaics to compare with multitemporal panchromatic (years 1988–1989, 1994–1998), and colour orthophotos (years 2000, 2006, 2012), available at www.pcn.minambiente.it as a WMS. The LSQ analysis was performed in ESRI-ArcGIS and QGIS software, where the surveys data are also inserted, using a topographic base map available in vector format at the scale of 1:10,000.

4.2.1 Morphometric variables

Four variables have been chosen for the purpose of the quantitative categorization of different Earth surface processes and landforms: (i) the Slope Angle (SA), (ii) Elevation Standard Deviation (ESD), (iii) Roughness (R) and (iv) Terrain Ruggedness Index (TRI). The SA is a geometric parameter, obtained running the surface slope algorithm in the Spatial Analyst extension of ESRI-ArcMap software, that computes the first derivate of the elevation surface or the maximum change in elevation on a cell-by-cell basis (i.e., the steepest downhill descent from the cell) (Borrough and McDonell, 1998). This is one of the most basic parameters for defining the signature of several processes, in particular for gravitational processes (Lee et al., 2004; Süzen and Kaya, 2012; Budimir et al., 2015; Piacentini et al., 2015), that can be distinguished in different kinematic types by variations of the SA (Pachauri and Pant, 1992;

Piacentini et al., 2012; Tasoglu et al., 2016; Hong et al., 2017; Pawluszek and Borkowski, 2017). The ESD is a statistic parameter, performed through a 3x3 moving window on DEM cells with standard deviation values output (Amatulli et al., 2020). This parameter was computed using the focal statistics in Spatial Analyst extension of ESRI-ArcGIS software and later applying the subtraction on the Equation (1); the result indicates a measure of the amount of variation in heights. The R also is a statistical parameter and is largely used to quantify the topographic complexity. Here it is expressed as the largest absolute difference in elevation between a focal cell and its surroundings (Wilson et al., 2007) in this case in a 3x3 moving window (Amatulli et al., 2020) and it is defined by the Equation (1):

$$R = E_{max} - E_{min}$$

where Emax and Emin are the maximum and the minimum elevations in the neighbourhood considered. The last parameter the TRI was performed using the equation proposed by Riley et al. (1999) and, as the R parameter, define the terrain complexity but expressing the mean absolute difference in elevation between a focal cell and its surroundings in this case in a 3x3 moving window (Amatulli et al., 2020) and it is defined by the Equation (2):

$$TRI = \frac{\left(|z_{(-1;1)} - z_{(0;0)}| + |z_{(0;1)} - z_{(0;0)}| + |z_{(1;1)} - z_{(0;0)}| + |z_{(-1;0)} - z_{(0;0)}| + |z_{(1;0)} - z_{(0;0)}| + |z_{(-1;-1)} - z_{(0;0)}| + |z_{(0;-1)} - z_{(0;0)}| + |z_{(1;-1)} - z_{(0;0)}| \right)}{8}$$

where the focal cell is indicated with (0; 0) and the eight surrounding cells, starting from the cell in the top right and proceeding clockwise, are, respectively, (-1; 1), (0; 1), (1; 1), (1; 0), (1; -1), (0; -1), (-1; -1), and (-1; 0). The TRI was calculated using the GDAL tool available in QGIS software.

4.3 Results

The main focus is the evaluation and interpretation of the spatial distribution of the morphometric variable values in relation to the gravitational landforms and to the geo-structural

setting. The approach used has included geomorphological and geological field data in support of the LSQ analysis.

4.3.1 Geomorphological and Geological Field Data

Data and observations collected in the field surveys, associated with a multitemporal image analysis allow to produce a geological-geomorphological map with special detail on gravitational landforms. The total landslide area on the coastal slope is about 40% of the total area, with a sliding kinematic head, and it is divided in erosional landforms in the up-slope and depositional landforms in the foot-slope. The landslides with slide kinematic represent the largest mass movement observable in the coastal slope with extent reaching 0.15 km² and mainly occur in the southeastern sector between Pesaro and Punta degli Schiavi (Sector 1) (Fig. 22a-c). Here the concordant dip between slope and strata of the Colombacci and San Donato Fms. favors translational sliding events.

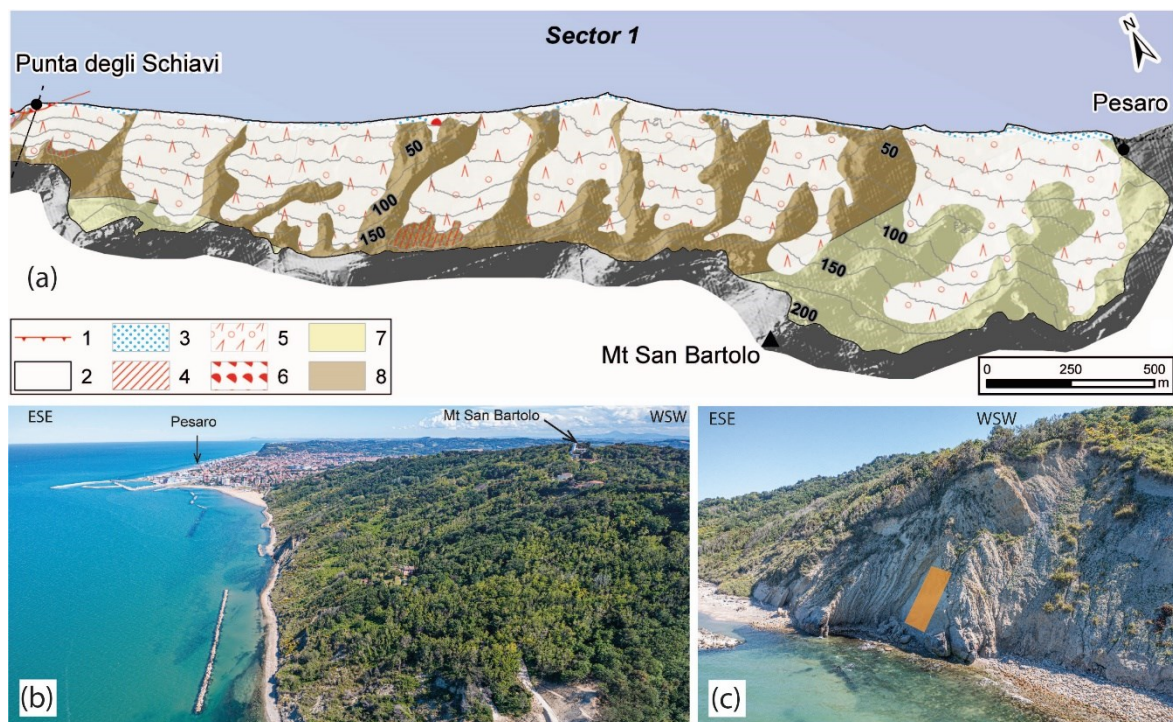


Figure 22. (a) Geological and geomorphological map of the Sector 1: 1, thrust fault; 2, sector border; 3, beach; 4, landslide scarp area; 5, slide; 6, flow; 7, Colombacci Fm.; 8, San Donato Fm. (b) Panoramic view towards the Sector 1; noteworthy is the relatively low slope of the cliff (compared to the other sectors) with

the presence of large landslides with a sliding kinematics. (c) Outcrops of Colombacci Fm. with the high dip angle of the strata, likely exacerbated by landslide phenomena.

In the sector between Punta degli Schiavi and Mt. Brisighella (Sector 2) (Fig. 23a) diffuse instability has been found, due to the high slope angle values (Fig. 23b). Landforms in this area consist of incised hanging gullies, formed by the action of surface concentrated running water, and earth-debris flows of limited extent. Bedding planes here dip towards the SW, marking the transition from the anticlinal eastern flank to the main synclinal eastern side. Clearly this fact is reflected in the landslide kinematics, not finding the slides favoured by bedding direction. At the base of the cliff, NE verging thrust shear zones, cut by subsequent N-S right lateral strike-slip faults, have been found affecting the Schlier and Gessoso Solfifera Fms (Fig. 23a, c).

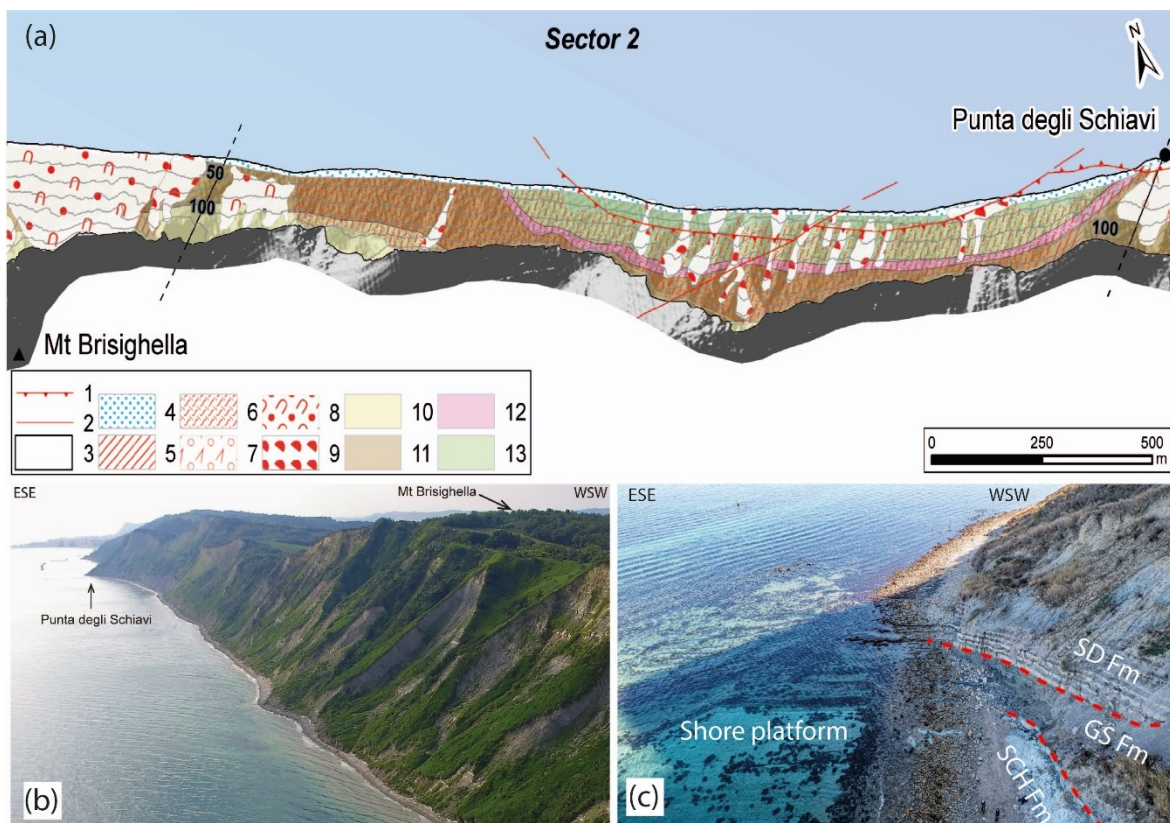


Figure 23. (a) Geological and geomorphological map of the Sector 1: 1, thrust fault; 2, strike-slip fault; 3, sector border; 4, beach; 5, landslide scarp area; 6, diffuse instability; 7, slide; 8, slump; 9, flow; 10, Colombacci Fm.; 11, San Donato Fm.; 12, Gessoso Solfifera Fm.; 13, Schlier Fm. (b) Panoramic view of the Sector 2; the greater slope of this sector is clearly visible. (c) Outcropping rocks in Punta degli Schiavi,

where there is the transition from the Schlier Fm. to the Gessoso Solfifera and San Donato Fms. A sloping shore platform, which is partially visible with the low tide is present.

In the sector between Mt. Brisighella and Vallugola (Sector 3), slumps and flows affect the coastal slope. The first ones occur mainly in the southeastern zone between Mt. Brisighella and Castel di Mezzo (Sector 3a) (Fig 24a) involving the San Donato and Colombacci (only in the up-slope zone) Fms., while the second ones characterize the area between Castel di Mezzo and Vallugola (Sector 3b) (Fig. 24d), including also the Gessoso Solfifera and Schlier Fms. Bedding attitude dips to the SW (Fig. 24f) and top-to-the ENE right lateral strike-slip fault have been found in the two sectors.

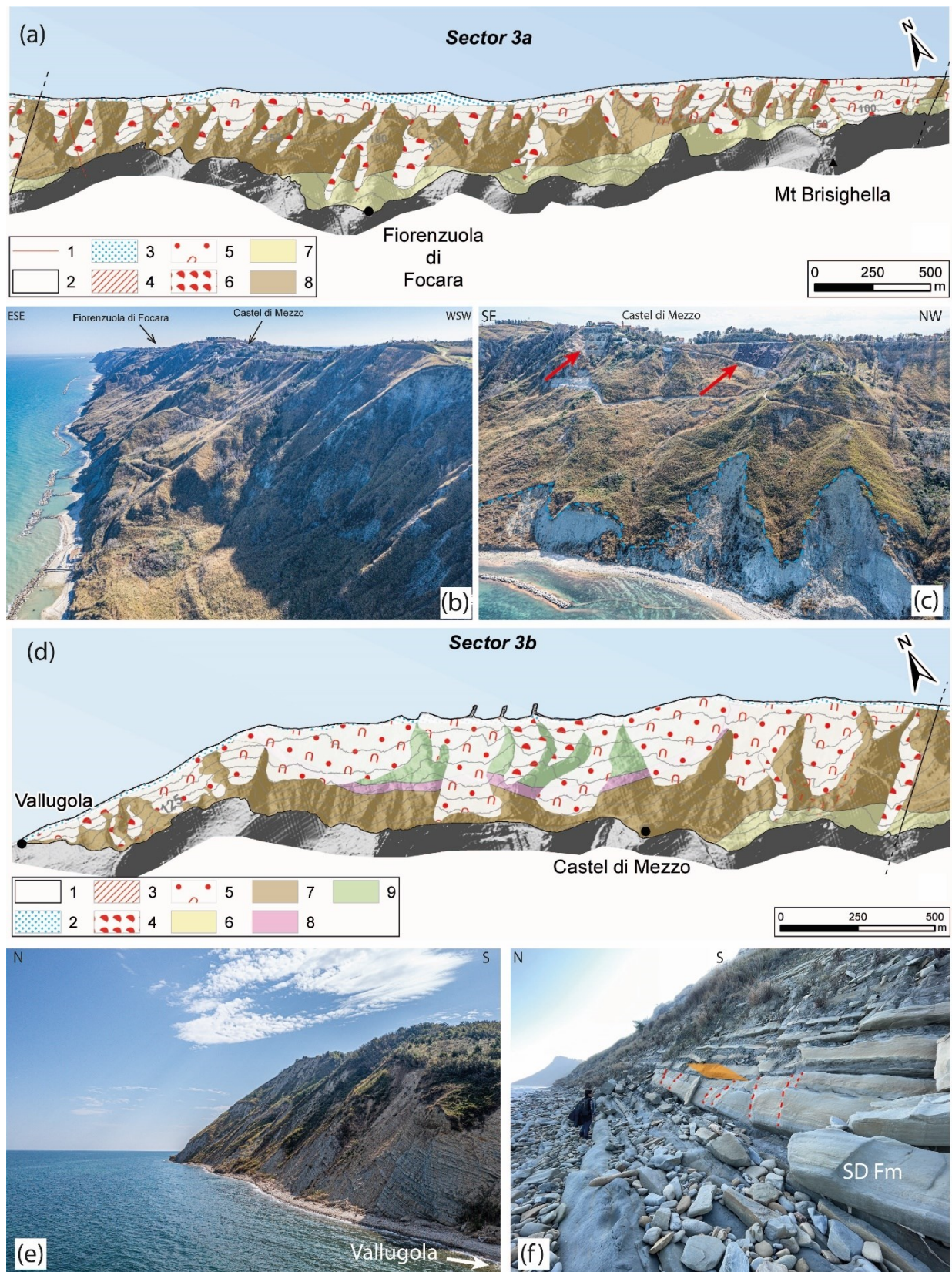


Figure 24. (a) Geological and geomorphological map of the Sector 3a: 1, strike-slip fault; 2, sector border; 3, beach; 4, landslide scarp area; 5, slump; 6, flow; 7, Colombacci Fm.; 8, San Donato Fm. (b) Panoramic view of the Sector 2; deposits of the slumps are visible at the base of the slope. (c) Cliff below Castel di Mezzo,

with landslides mitigation structures (highlighted by red arrows) to counteract the retreat of the upper slope; in the foot-slope, the blue line shows the active wave sea cliff. (d) Geological and geomorphological map of the Sector 3b: 1, sector border; 2, beach; 3, landslide scarp area; 4, flow; 5, slump; 6, Colombacci Fm.; 7, San Donato Fm.; 8, Gessoso Solfifera Fm.; 9, Schlier Fm. (e) Panoramic view of the northern part of the Sector 3b, near Vallugola bay. (f) San Donato Fm. near Vallugola, with the SW dipping bedding; vertical fractures present in the sandstone layers of the San Donato Fm. favors the formation of small local rock falls.

The northernmost part of the Sector 3b has been the subject of several field and UAV surveys, as it shows evidence of recent activity after winter storms or after localized extreme events. It is noteworthy that this stretch of the Mt. San Bartolo coastal ridge changes at an approximately E-W direction, resulting in an average N-facing aspect, which is where dominant winds and the highest waves originate. From the year 2021 to 2023, the entire coastal Sector 3b experienced widespread erosion, particularly after the winter months. However, in 2023, there was an exceptionally rainy May, during which disasters such as flooding in the Emilia-Romagna region occurred. Many landslides interested the Mt. San Bartolo ridge, and the coastline was affected by storm surges. By consulting the data from the Ancona wave buoy (RON, <https://www.mareografico.it/>), several anomalous peaks of wave height are noticeable in the period from April to May 2023. On May 16, 2023, in particular, a significant wave height (Hs) of 3.50 m was recorded, and until reaching the coastline, it likely increased in height (red arrow in Fig. 25). Furthermore, it can be observed that from January to mid-May, there have been consistent peaks of 3 meters in wave height, significantly contributing to potential enhanced erosion of the slope and reactivation of landslide deposits.

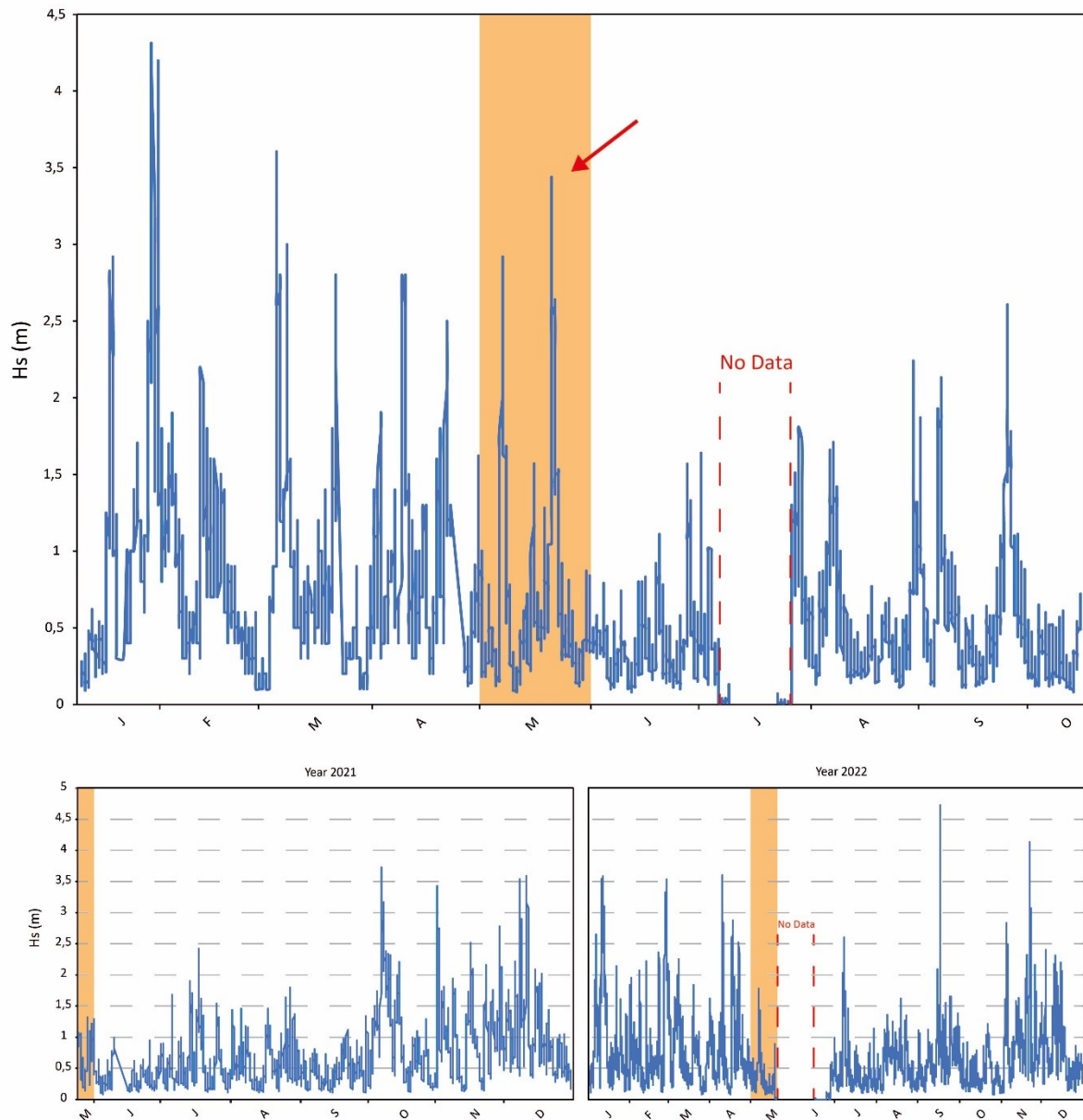


Figure 25. Data of the significative wave height (Hs), measured by the Ancona wave buoy (43°49'26" N, 13°43'10" E) for the period 01/01/2023-15/10/2023 (principal graph above). The peaks of the May storm surges particularly stand out, comparable with the peaks of winter months. Furthermore, graphs with data of the Hs for the years 2021 (period between 24/05/2021 and 31/12/2021) and 2022 (period between 01/01/2022 and 31/12/2022) are represented below. It can be observed that in the months of May (highlighted by the orange rectangles) of the years 2021 and 2022, no extraordinary storm surges events are reported, as those that occurred in May 2023.

Both from accounts provided by Vallugola restaurant owners and numerous regional newspaper articles, the May storm surges was remarkably intense and unusual; it was likely one of the triggering factors with heavy rainfall, for some reactivations along this stretch of coastline.

According to what some restaurant owners in the Vallugola bay have mentioned, beach nourishment activities had to be carried out at the end of May and at the beginning of June to prepare for the tourist season. The evidence of the exceptional event is also partly visible in the records of significant wave height at the Ancona wave buoy, which shows an increase in storm surge events in the spring months of 2023 compared to the previous years.

By dividing the Vallugola area in two sub-sectors, changes that have occurred from 2021 to 2023 can be observed through the use of orthomosaics derived from UAV surveys. It was chosen to directly compare the photos from 2021 with those from 2023 because in the year 2022, there were no significant changes, only a general erosion of the slope caused by surface runoff water. In the southern sector (Fig. 26), there are occasional reactivations of the wave erosion scarps (red circle in the Fig. 26a, b and Fig. 26c, d), although they do not reach the sea and are limited to the gravel and pebble beach. The sea slope, in general, appears more stripped of vegetation, indicating a significant impact of rainfall and surface runoff waters.

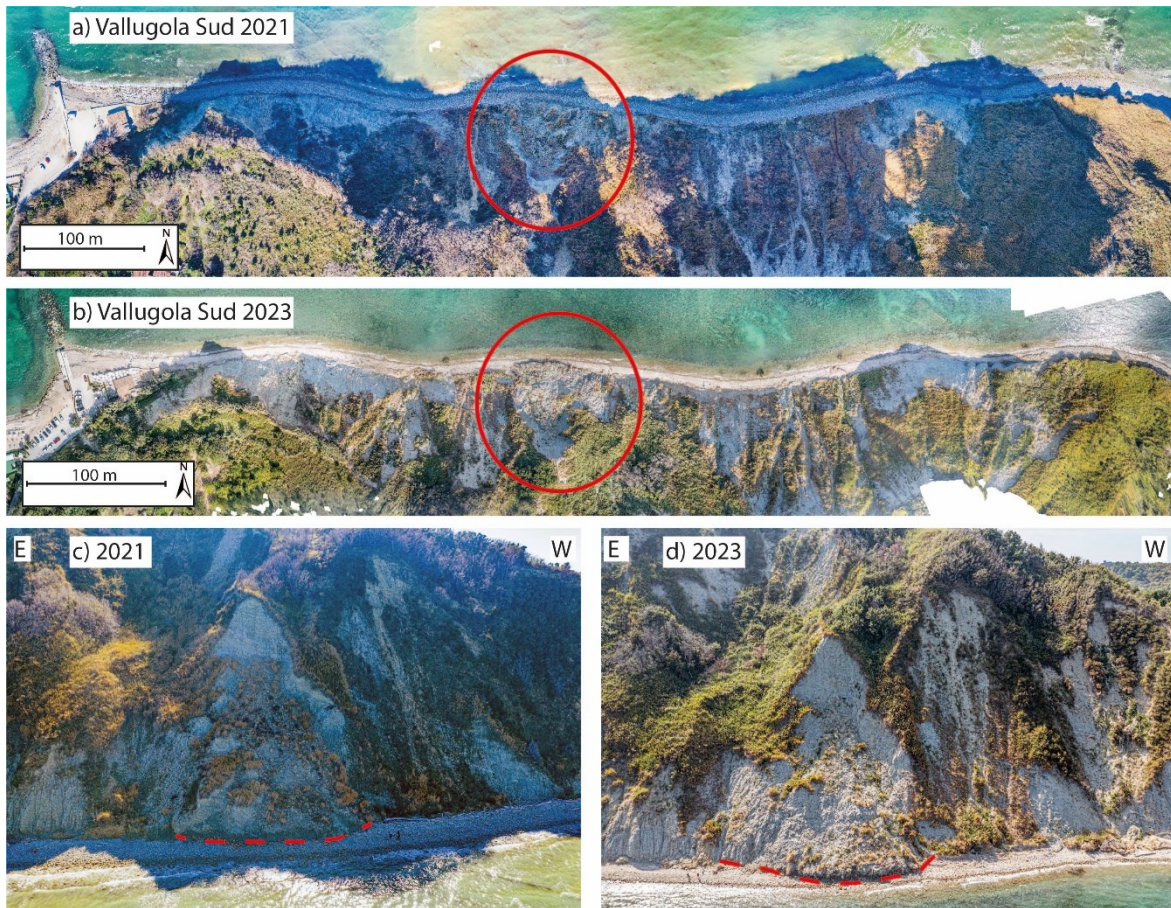


Figure 26. (a) and (b) Orthomosaics, derived by UAV surveys in the years 2021 and 2023, of Southern sector of the Vallugola area. (c) and (d) local reactivations on the wave erosion scarp that have advanced onto the beach and are confined to its edge.

In the northern sector of Vallugola, the difference between the two orthomosaics from 2021 and 2023 immediately stands out (Fig. 27a, b). Here, the overall erosion of the slope appears to be more pronounced, and the changes in vegetation over the years can be easily observed. The reactivations of the wave erosion scarp are of greater magnitude and reach the sea completely obstructing the beach (Fig. 27c, d). Furthermore, it should be noted that this stretch of coastline requires vigilant monitoring because there are buildings in the ridge area, and just slightly to the north is the village of Gabicce Monte.

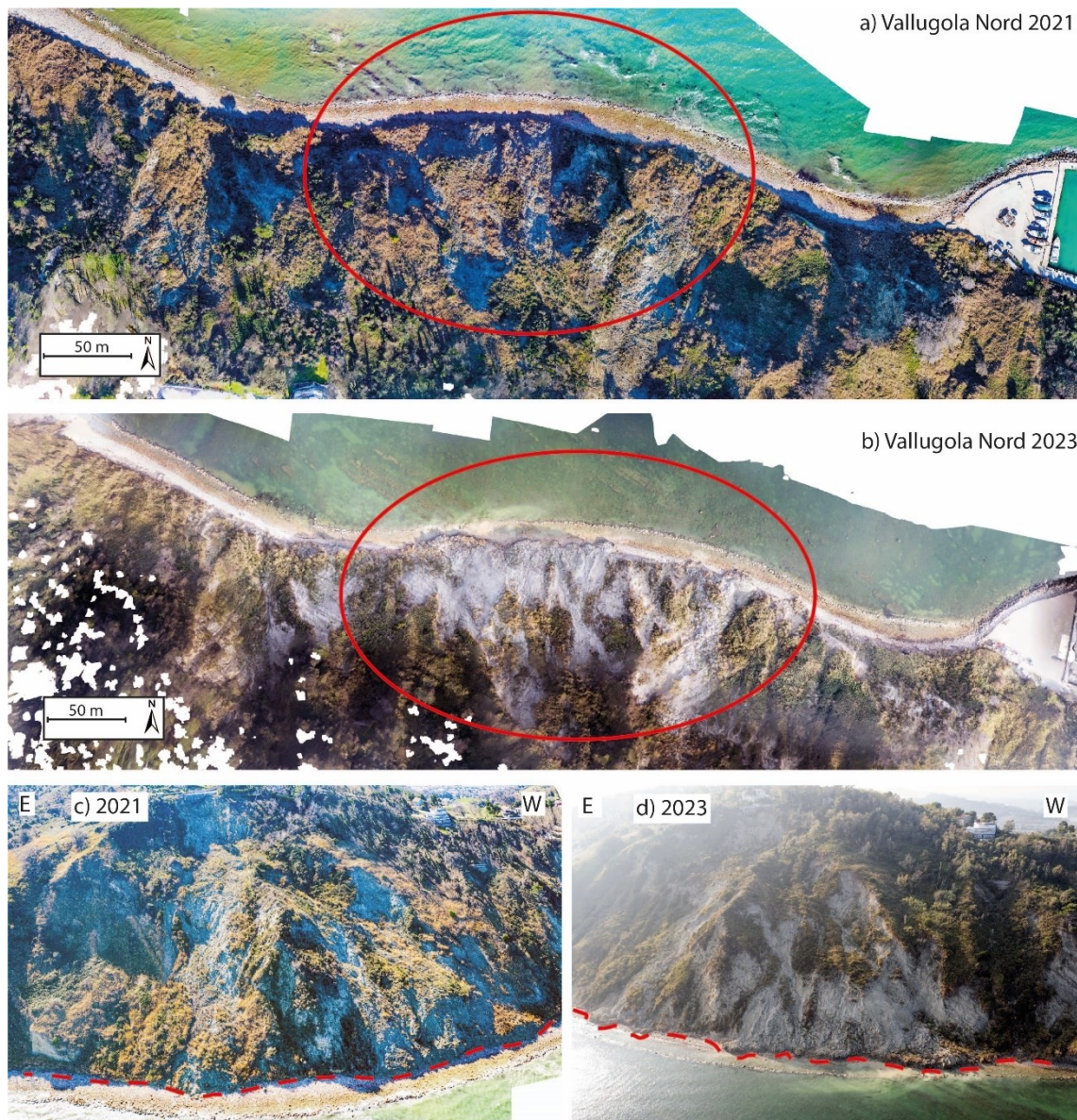


Figure 27. (a) and (b) orthomosaics, derived by UAV surveys in the years 2021 and 2023, of northern sector of the Vallugola area. (c) and (d) local reactivations on the wave erosion scarp that have advanced onto the sea and hinder the passage. In addition, in the photo (d) it can be seen buildings in the ridge area.

4.3.2 Spatial Distribution and Descriptive Statistic of Morphometric Variables

One of the first step after the calculation of the four variables is to get an evaluation of their spatial distribution through color-coded maps. In the divided sectors, the distribution is quite different: in the southernmost sector (Sector 1) low values for all the four variables were found, in contrast to the Sector 2 that clearly stands out with respect to the surrounding zones and the Sector 3 that presents high local variability. The distribution of the four variables have been

analysed, in order to evaluate relations with the presence/absence of recognized landslide phenomena and to identify the landslide types.

The SA variable (Fig. 28) shows maximum and mean values quite in agreement with each other in the different sectors, with only the exception of the Sector 3 with significantly higher values (mean around 40° and maximum values $>80^\circ$). The distribution of the SA values seems instead to differ between the sectors. In fact, taking the values in the table of the Fig. 28a it is possible to distinguish the different sectors from the values of standard deviation, kurtosis, and skewness (Fig. 28b). These trends are further appreciable considering the slope values normalized in relation to the spatial extent of each sector (Fig. 28c). SA values and distribution are quite similar for areas in landslides and for those where landslides are not recognized (Fig. 28d), although analyses of the delineated trends are more evident considering the normalized values (Fig. 28e). Different landslide types are well distinguished by the SA value distributions (Fig. 28f, g): slides and slumps show similar SA values ranging from 0° to 74° but distinct mean and median of about respectively 23° and 32° . Flows and diffuse instability reach higher values, around 80° , but they too are distinguished by different mean and median. Kurtosis and skewness together with the previous SA distribution values can differentiate the individual landslide typologies.

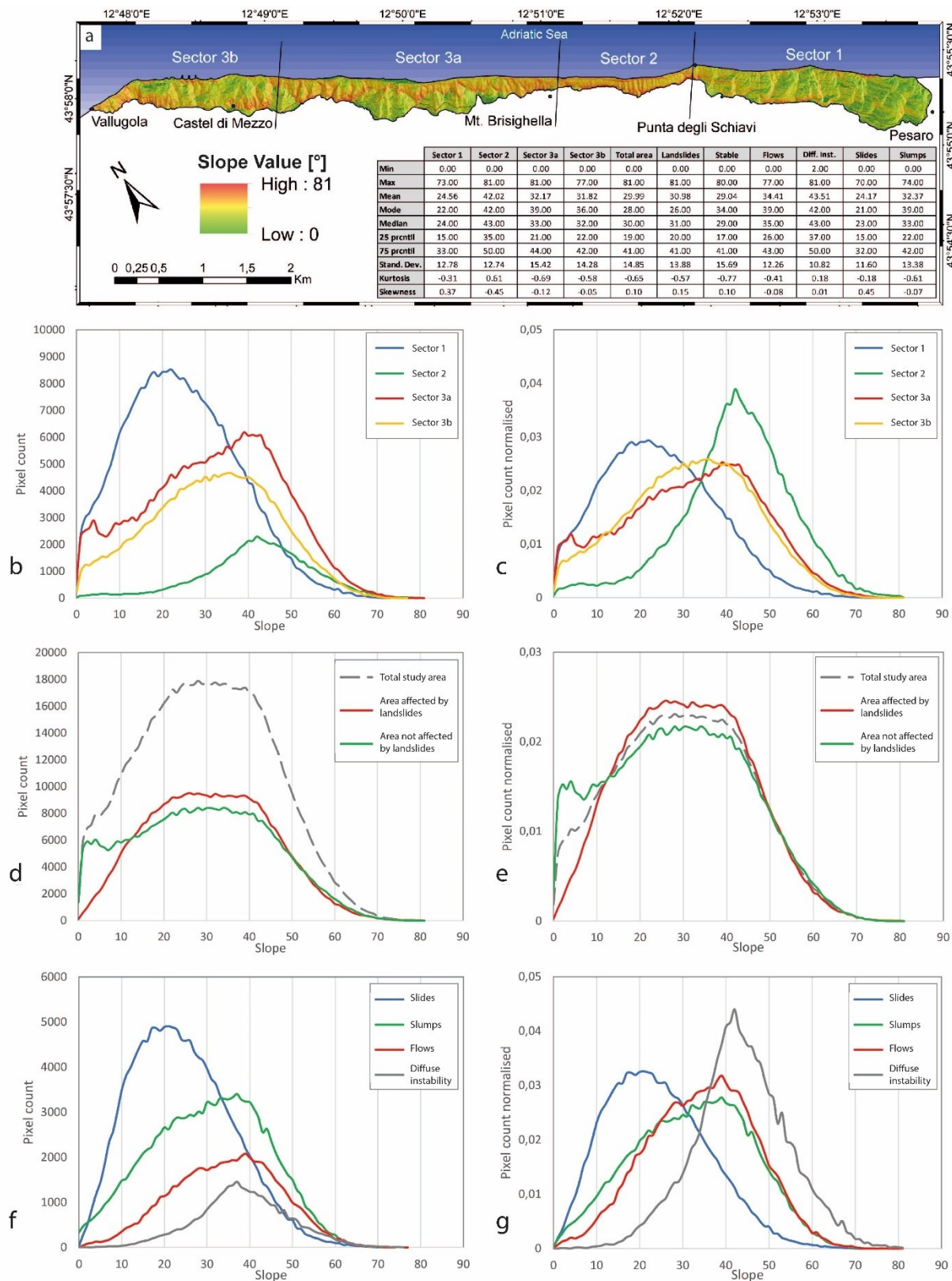


Figure 28. Spatial distribution of the SA variable along the Mt. San Bartolo coastal slope. Trends of the SA variable for the different sectors are represented in (b) and normalized values in (c); trends of the SA for areas affected and not by landslides are shown in (d) and normalized values in (e); trends of the SA for the different landslide typologies are represented in (e) and normalized values in (g).

The three types of roughness types are now analysed on by one, with the relative images and graphics that follow each other.

The ESD variable (Fig. 29a) displays fairly similar maximum values, up to about 11 m, for Sectors 2 and 3a but different values of mean and median; Sectors 1 and 3b have lower maximum values up to 6.87 m and also mean and median lower than the other sectors. ESD value distribution converges in all four sectors, with the skewness which is slightly more variable and the kurtosis of the Sector 2 which reaches a value of 10.95 (Fig. 29b, c). As for the areas in landslide and those not in landslide (Fig. 29d, e), the ESD does not detect large differences, only the kurtosis has quite different values. The ESD trend revealed distinct landslide types (Fig. 29f, g): slides and diffuse instability zone are characterized by distinct mean and median values; slumps and flows instead show a similar trend. These trends are further appreciable considering the normalized ESD values (Fig. 29c, e, g).

The R variable (Fig. 30a) exhibits values comparable with those of the ESD, but with a wider range of values reaching a maximum of 28.64 m in the Sector 2. The mean and median shows higher values than the ESD sectors mean and median values. The ESD of the Sector 2 shows high values of kurtosis while the skewness is not very variable (Fig. 30b, c). Landslide areas and stable areas (Fig. 30d, e) are not well identified through the R variable, with only the kurtosis values which ranges from 5.65 m for areas with landslides to 2.17 m for areas without landslides. For different landslide types (Fig. 30f, g), slumps and flows are characterized by higher maximum values and similar both in mean and median values; slides and diffuse instability differ by maximum values respectively of 13.50 m and 5.22 m. Also, for the R variable, the trends described above are also further appreciable considering the normalized values (Fig. 30c, e, g).

The TRI variable (Fig. 31a) shows trends that are aligned with the ESD and R trends. The range of the TRI values with the maximum of 10.74 m and the kurtosis value of 10.95 m, reached in

the Sector 2 (Fig. 31b, c), are comparable with the ESD. Also, the TRI do not vary significantly between the different areas affected and not affected by landslides (Fig. 31d, e). Landslide types are clearly evident (Fig. 31f, g): slumps and flows present intermediate values, slides are characterized by maximum values of 4.25 m (lower than the others) and the diffuse instability reaches higher maximum values of about 10.74 m and kurtosis value higher than the others landslide types. The trends described above are also appreciable when considering the normalized values for the case of TRI values (Fig. 31c, e, g).

A cross comparison pixel by pixel of the different roughness variables (ESD, R and TRI) was carried out in order to evaluate the most representative one and then compare it with the S parameter. The favourable correlation between TRI and both R and ESD, led to use this single variable as a representative metric in combination with the S variable. Examining the curves of these two chosen variables, distinct frequency peaks become readily discernible when their spatial distribution is analysed in no-landslide areas, landslide areas and detachment zones (Fig. 32a-c). In the Mt. San Bartolo case study, this ratio highlights the existence of these distinct areas, as evidenced in clusters in various sectors of the plot (Fig. 32d, e). In the following table are shown the range of values for the ratio SA/TRI in stable areas (St), landslide areas (L) and scar areas (Sc):

	<i>Stable areas</i>	<i>Landslide areas</i>	<i>Detachment areas</i>
<i>Slope</i>	$< 10^\circ$	$10 < x < 43^\circ$	$> 43^\circ$
<i>TRI</i>	$< 0.3 \text{ m}$	$0.3 < x < 1.4 \text{ m}$	$> 1.4 \text{ m}$

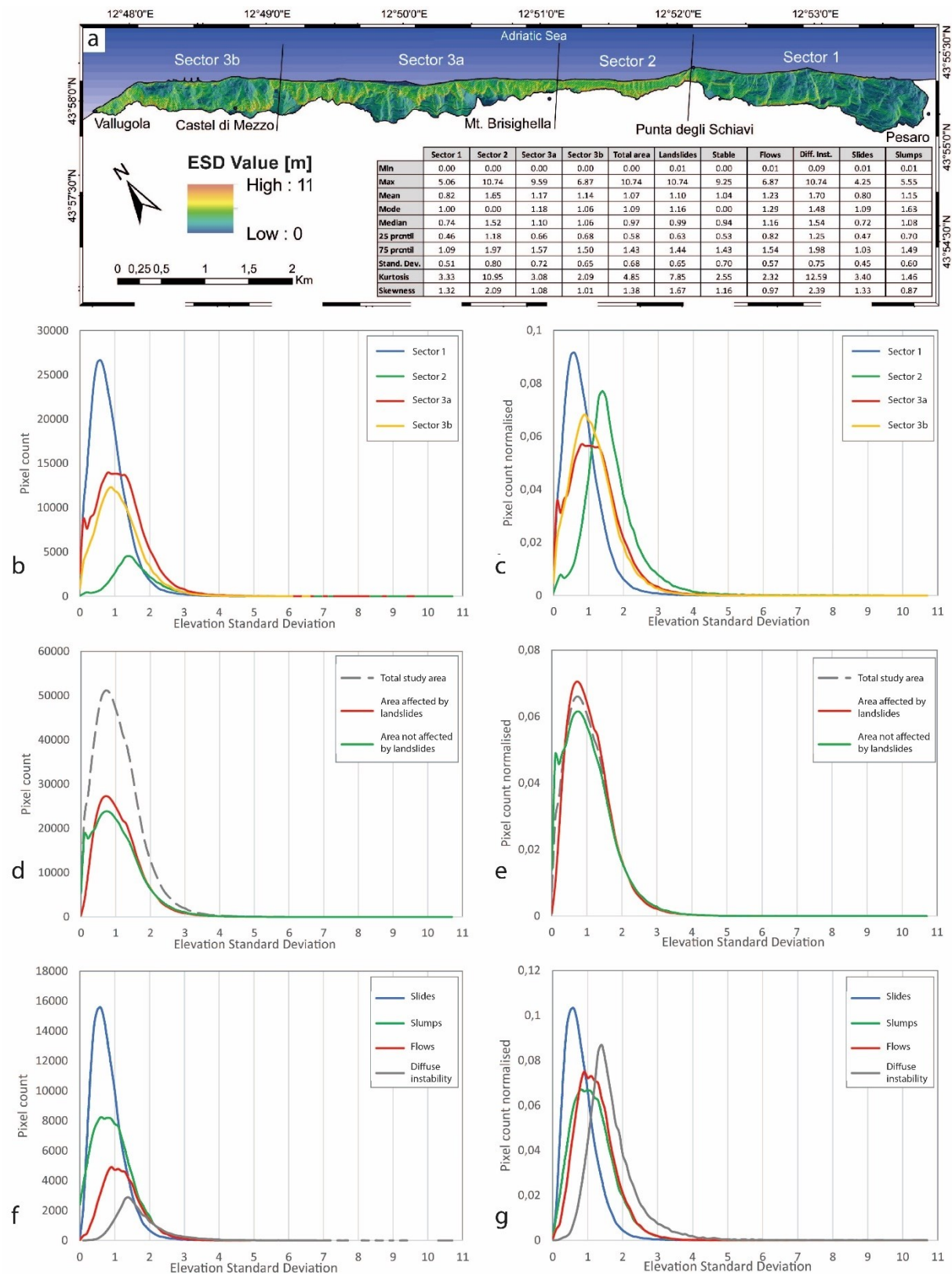
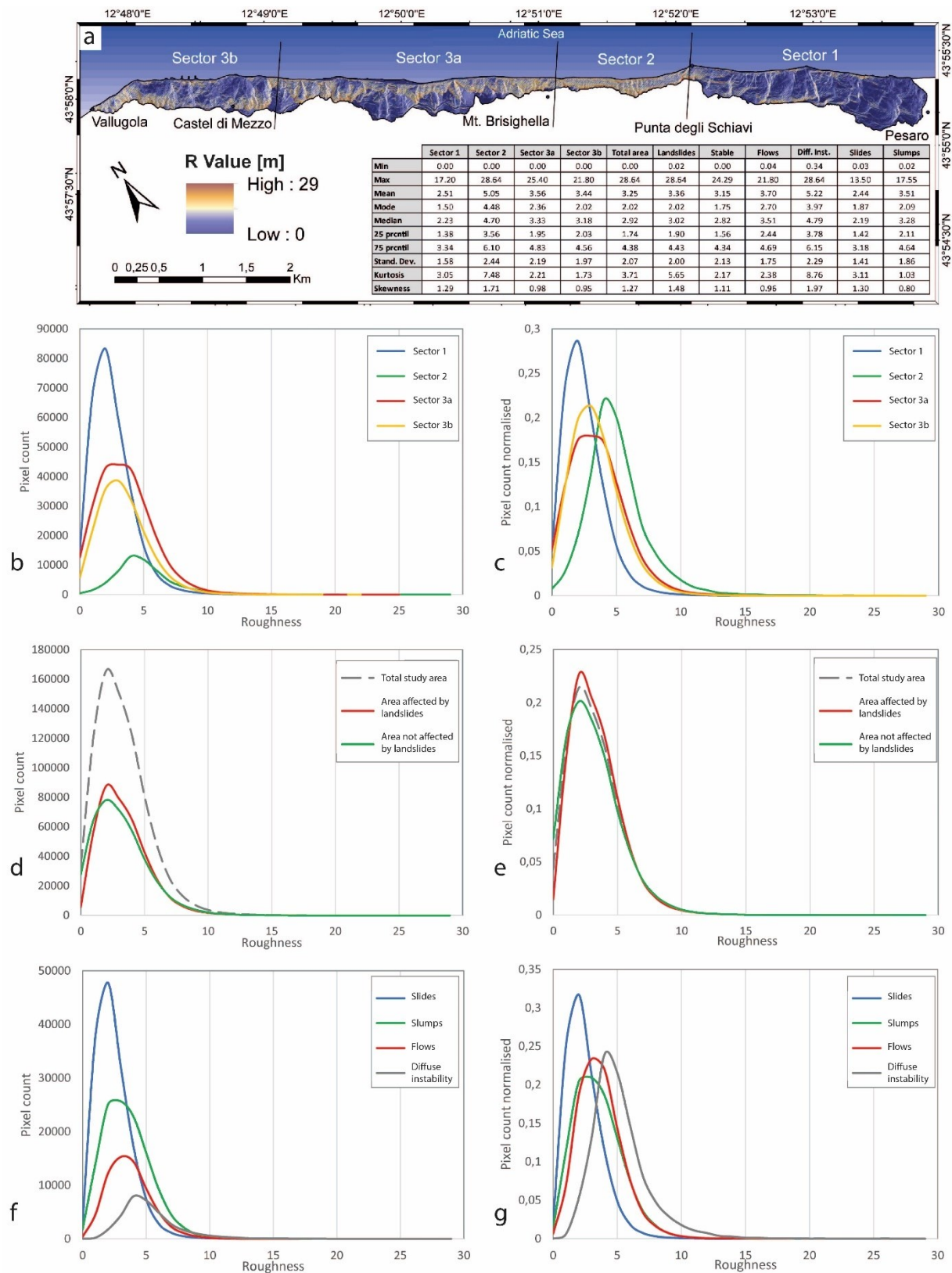


Figure 29. Spatial distribution of the ESD variable along the Mt. San Bartolo coastal slope. Trends of the ESD variable for the different sectors are represented in (b) and normalized values in (c); trends of the ESD for areas affected and not by landslides are shown in (d) and normalized values in (e); trends of the ESD for the different landslide typologies are represented in (f) and normalized values in (g).



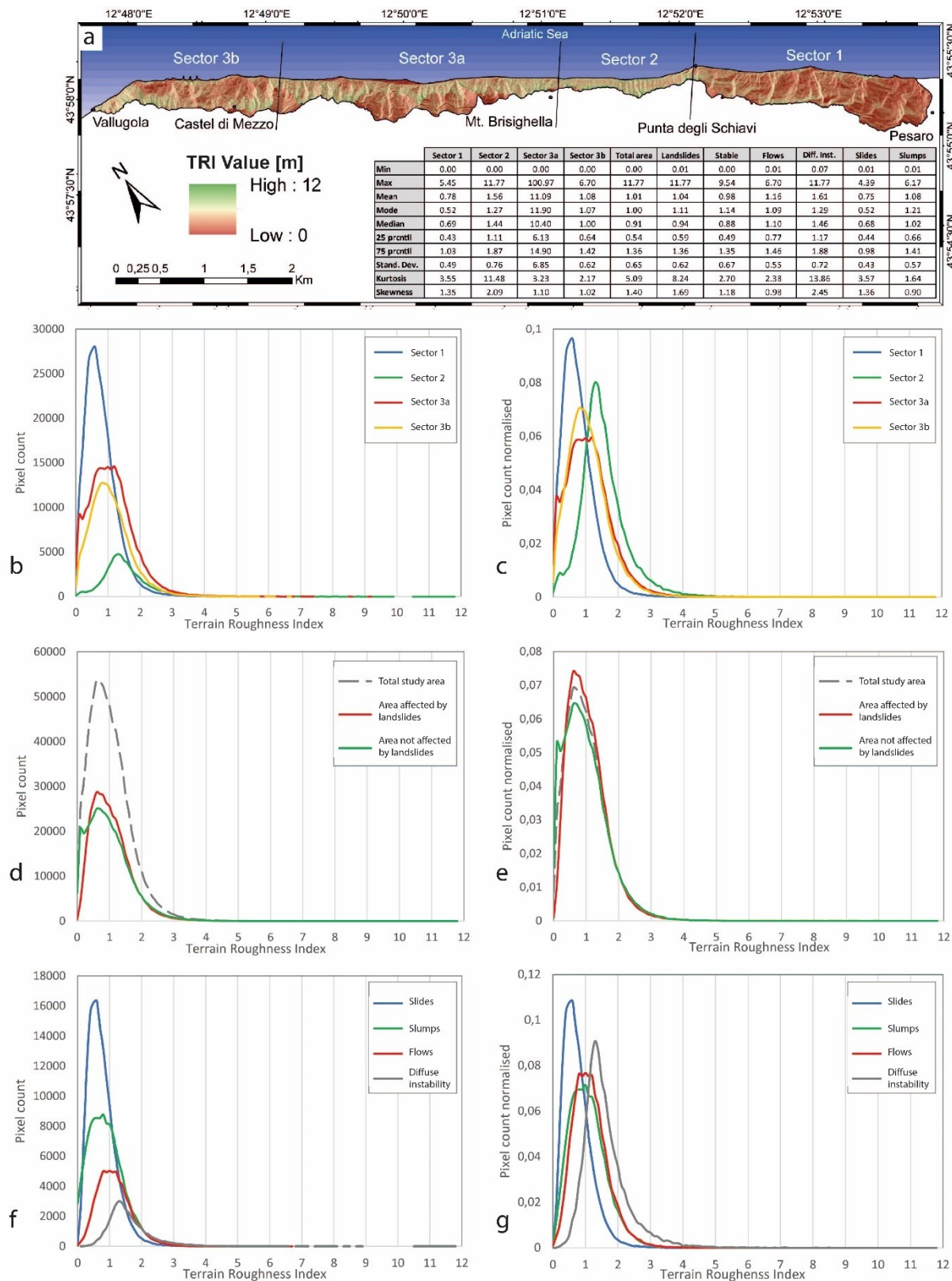


Figure 31. Spatial distribution of the TRI variable along the Mt. San Bartolo coastal slope. Trends of the TRI variable for the different sectors are represented in (b) and normalized values in (c); trends of the TRI for areas affected and not by landslides are shown in (d) and normalized values in (e); trends of the TRI for the different landslide typologies are represented in (f) and normalized values in (g).

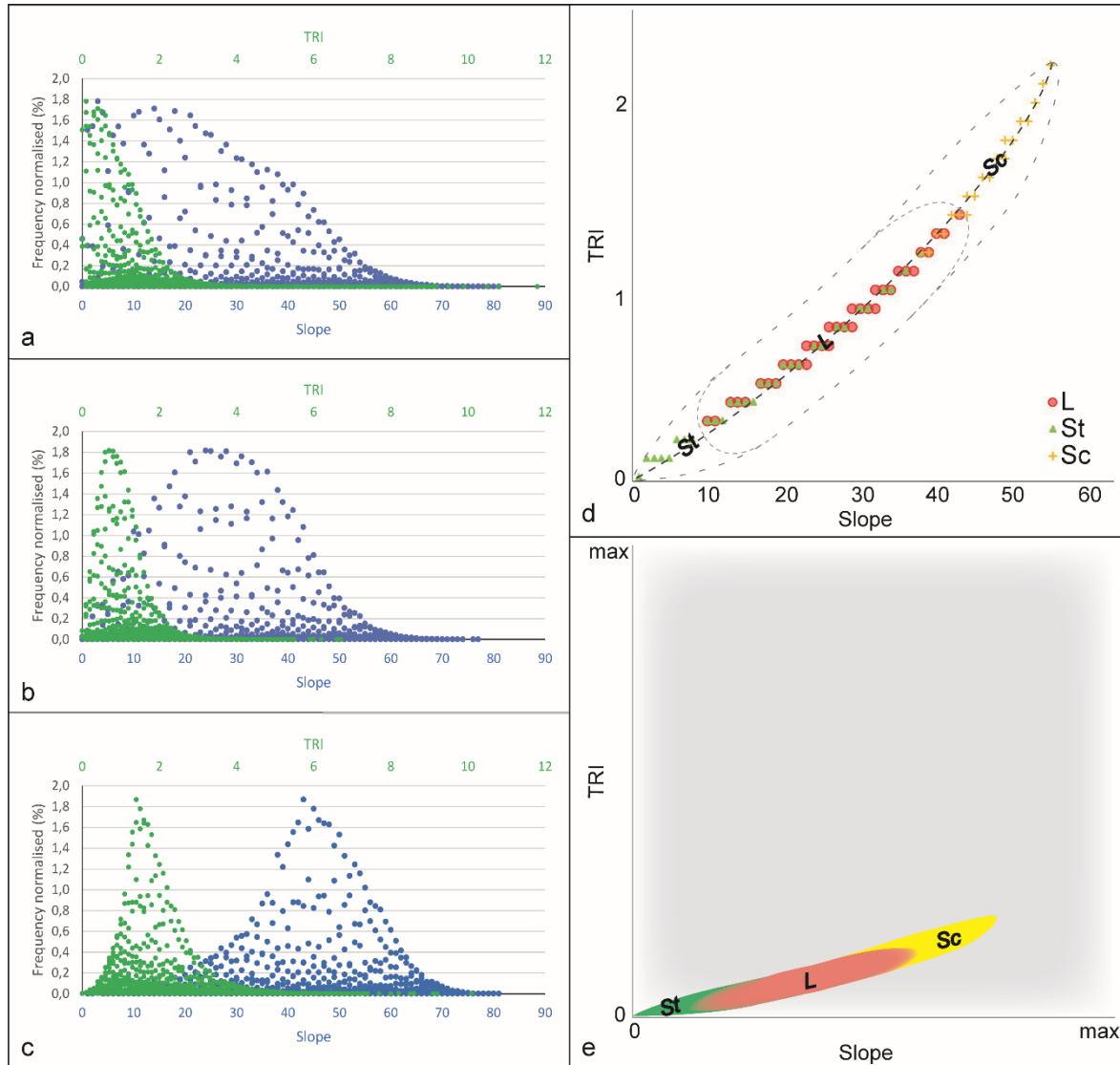


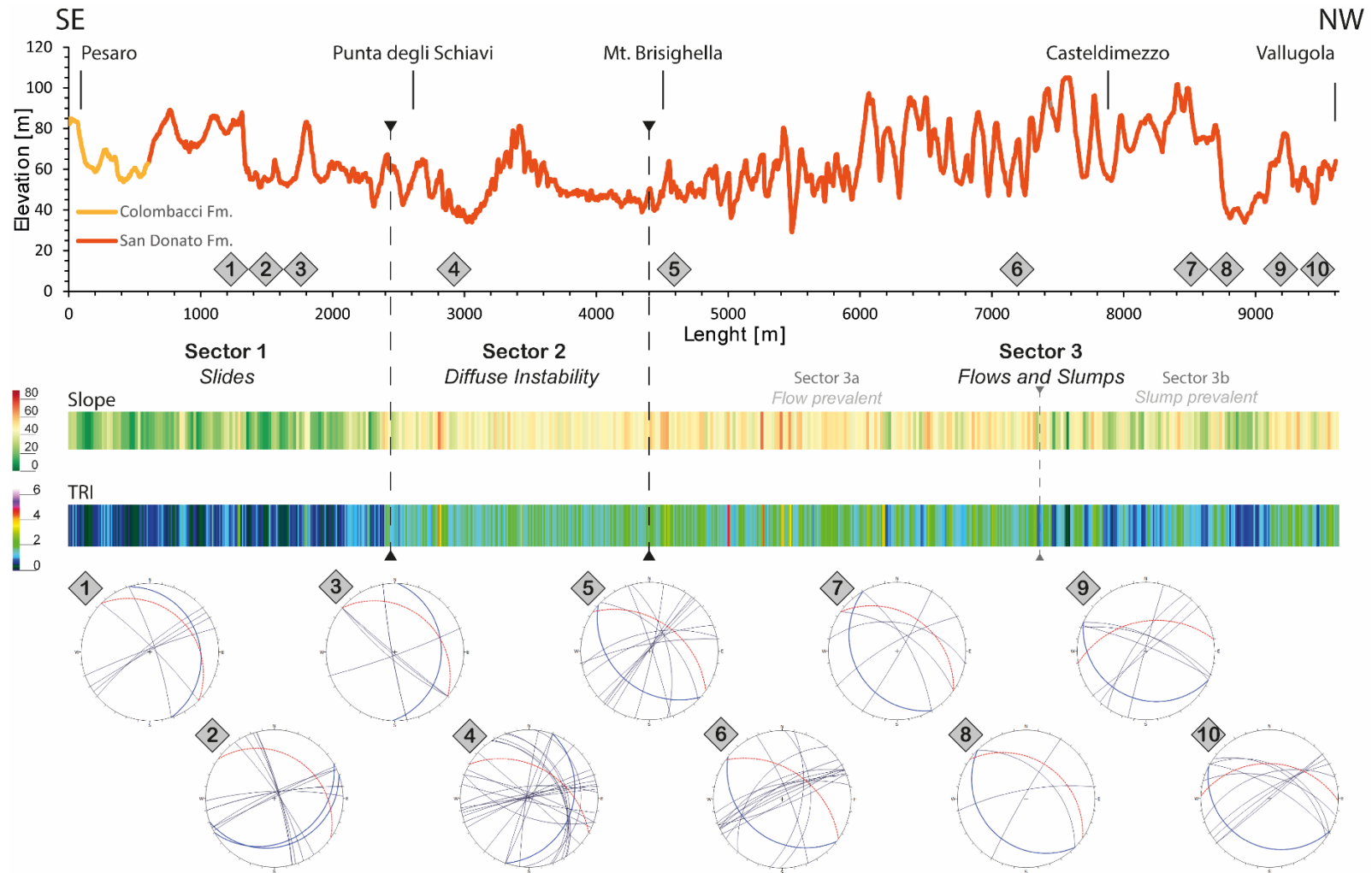
Figure 32. TRI and SA plots: (a) scatter plot of normalized frequency in stable areas; (b) scatter plot of normalized frequency in areas intersected by landslides; (c) scatter plot of normalized frequency in areas with scarp landforms; (d) TRI vs. S plot indicating the grouping sector of stable areas (St), areas interested by landslides (L), and areas with scarp landforms (Sc); (e) TRI vs. SA plot obtained by constraining the correlation to the overall value range of each variable and indicating the clustering sector of stable areas (St), areas interested by landslides (L), and areas with scarp landforms (Sc).

To better visualize the spatial variation of the SA and TRI across the entire coastal slope, in combination with litho-structural setting, an altimetric profile along the coastal slope was carried out (Fig. 33). This profile was conducted through an altimetric profile oriented along the coastline direction covering a range of distances from 50 to 160 m from the current shoreline; it is also serves as a crucial tool for revising or confirming the sector divisions with their

typological characterization. In fact, the sector divisions, carried out with the field surveys, is confirmed by the signature of the SA and TRI variables. The SA shows extremely high values for the whole Sector 2, while in the Sector 1 there are lower values; in the Sector 3 more variable values are present with an increment of lower values density in the Sector 3b. The TRI parameter is comparable with the SA variable, displaying lower values in the Sector 1, followed by higher values in the Sector 2; in Sector 3 the TRI is characterized by homogeneous values with isolated higher and lower peaks.

	<i>Sector 1</i>	<i>Sector 2</i>	<i>Sector 3a</i>	<i>Sector 3b</i>
<i>Slope</i>	20-25°	40°	<40°	>40°
<i>Angle</i>	(peaks up to 40°)	(localized values of 60-80°)	(localized values of 15°)	(more current localized values of 15-20°)
<i>TRI</i>	< 1.5 m	~ 2 m	~ 2 m (localized values of ~ 1 m and higher values > 2 m)	> 1.5 m

Moreover, landslide types are influenced by the relationship between bedding attitudes, joints, and geometry of the slope. Slide instabilities are prevalent in the Sector 1, favoured by E-NE dipping bedding; diffuse instability and flows are common in the Sector 2, characterized by a high slope; in the Sector 3 flows and slumps are predominant, due to the W-SW dipping bedding. Including the fracturing condition of the rock mass, it can be noted that: in Sector 1 two joint sets, striking ESE-WSW and NW-SW favour the wedge sliding; in Sector 2, with diffuse instability conditions, various joint sets are observable; in Sector 3a, with prevalence of flows, a NE-SW joint system is evident, while in Sector 3b, where slumps are widespread, NE-SW and NW-SE joint sets are visible.



1

2 **Figure 33. Altimetric profile along the coastline direction correlated with lithological information (the Colombacci Fm. in orange and the San Donato Fm. in red), SA**
 3 **value variation, TRI value variation, sector subdivision, indication of predominant landslide typologies occurring, and the stereographic projection in the lower**
 4 **hemisphere of the bedding attitude (continuous thick blue line), slope geometry (dashed red line), and main joint sets (thin dark lines).**

4.4 Discussion

Conventional geomorphological field mapping in rocky coastal areas can be difficult because of the logistic issues and site inaccessibility. According to Guzzetti et al. (2012), specifically those focused on landslide inventorying often face limitations in terms of cost-effectiveness. However, it is worth to note that these surveys are just one of the various techniques currently employed for landslide identification and mapping in diverse environmental settings (Evans, 2012). The LSQ analysis can be a valuable tool in addition to visual interpretation of optical images and hillshade maps, especially along rocky coasts (Troiani et al., 2020); the practical application of all these techniques together was confirmed in the Mt. San Bartolo. By extracting quantitative data through the LiDAR DTM and combining it with geomorphological interpretations derived from both fieldwork and remotely sensed datasets, the identification, categorization and mapping of landslides have been significantly enhanced. In the case of the Mt. San Bartolo, the results not only delineated the area marked by slope instabilities but also facilitated the identification of landslide boundaries and the categorization of their types. In this context, the findings of this analysis corroborate the results presented in Troiani et al. (2020) and exposed in the Chapter 3 of this thesis. This offers progress toward the development of a methodology designed to facilitate the extraction of features (Sofia, 2020), particularly gravitational landforms in coastal areas. Four variables (SA, ESD, R and TRI) have been chosen, taking into account the prior scientific literature (Wilson and Gallant, 2000; Hengl and Reuter, 2008; Florinsky, 2017; Amatulli et al., 2020). The three types of roughness variables were then evaluated on the results of the field surveys and through a cross-comparison.

In the first part of the analyses an evaluation of the visual alignment and the distinctive distribution of variable values have been carried out. The graphs displayed in Fig. 28 and 31 indicate a distinct topographic signature in the slope sections affected by landslides and illustrate the topographic contrast between stable areas and landslide areas. With the cross-

comparison, just TRI was taken into account and then compared to the S, which both have frequency peaks distinguishable for stable areas, landslide areas and escarpment areas (Fig. 32a-c). Hence, the combination of SA and TRI values enables the identification of a clearly delineated morphometric area where the concentration of landslides is more pronounced (Fig. 32d). This identified domain represents a valuable initial step in the preliminary recognition of the possible topographic signature associated with gravitational processes (Fig. 32e). The assessment of the spatial variation of the chosen morphometric variables, along a coastal slope, has served to validate the characterization of the sea cliff as initially determined through field surveys. This analysis highlights a strong correlation between the occurrence of landslides and the structural assets, with the effectiveness of LSQ analysis, which can serve as a preliminary approach or as a valid substitute of traditional field survey especially when the study area is inaccessible.

Chapter V

5. Enhancing InSAR data with the geomorphological assessment: the case of La Herradura coastal stretch

Arguments developed in the three years of PhD and in the following publication submitted and under review in *Landslide*:

- Torre D, Galve JP, Reyes-Carmona C, Alfonso-Jorde D, Ballesteros D, Menichetti M, Piacentini D, Troiani F, Azañón JM (2024, under review) Geomorphological assessments as basic complement of InSAR analysis for landslide processes understanding.

5.1 General setting

The coastal section of La Herradura (36°44'N, 3°44'W; Fig. 1) is a 3 km long bay located in the province of Granada (Southern Spain). The bay is bounded by two promontories, Cerro Gordo (ca. 343 m a.s.l.) and Punta de la Mona (ca. 126 m a.s.l.), which are included in two Special Areas of Conservation (SAC): Maro-Cerro Gordo Cliff Natural Site (MCGCNS) and Cliffs and Seabed of La Punta de la Mona (CSPM), stated within the framework of the European Union Habitats Directive (9242/EEC). The area is heavily anthropized with agricultural terraces, housing, resorts, and hotels, which contribute to the regional economic vitality. The inner part of La Herradura bay is the most densely urbanized sector of the study area, while both promontories also feature urban developments. Notably, the resorts of Cármenes del Mar (on the Cerro Gordo promontory) and Marina del Este (on the Punta La Mona promontory) were built on the eastern slopes of the capes, which are affected by active slope movements.

The study coastal sector shows a NW-SE orientation, with local N-S variations due to the promontories morphology. It is characterized by a Mediterranean climate, Csa according to the Köppen-Geiger classification (Cunha et al., 2011) (Fig. 33), with a mean annual precipitation of about 430 mm (Chacón et al., 2019). Rainfall in this coastal area above the yearly average occurred in the wet seasons of 1995–1997, 2000–2003, and 2009–2010 (Irigaray et al., 2000; Vicente-Serrano et al., 2011) breaking all the previous records in 2010, with an annual average value of about 857 mm (Chacón et al., 2019); the greatest amount was reported in 1973 with 350 mm in 24 h (Notti et al., 2015). Due to the latitude, to the coastal orientation and to the Betic Cordillera, which protects the coastline from the Northern winds (Mooser et al., 2021), temperatures are mild both during winter and summer with a mean annual range of 18-20°C (Chica-Ruiz and Barragán Muñoz, 2011; Consejería de Medio Ambiente y Ordenación del Territorio, 2015). Dominant winds approach from E-SE with a speed up to 9 m/s (Manno et al., 2016; Molina et al., 2019) causing storm waves. The coast is dominated by E-SE high-frequency waves (significant wave height 1 m) (Guisado and Malvárez, 2009), that generate a littoral drift towards W (Fig. 34); the average tidal range is less than 20 cm (Manno et al., 2016) and the ongoing local sea-level rising is estimated in 2.65 mm per year (Serrano et al., 2020).

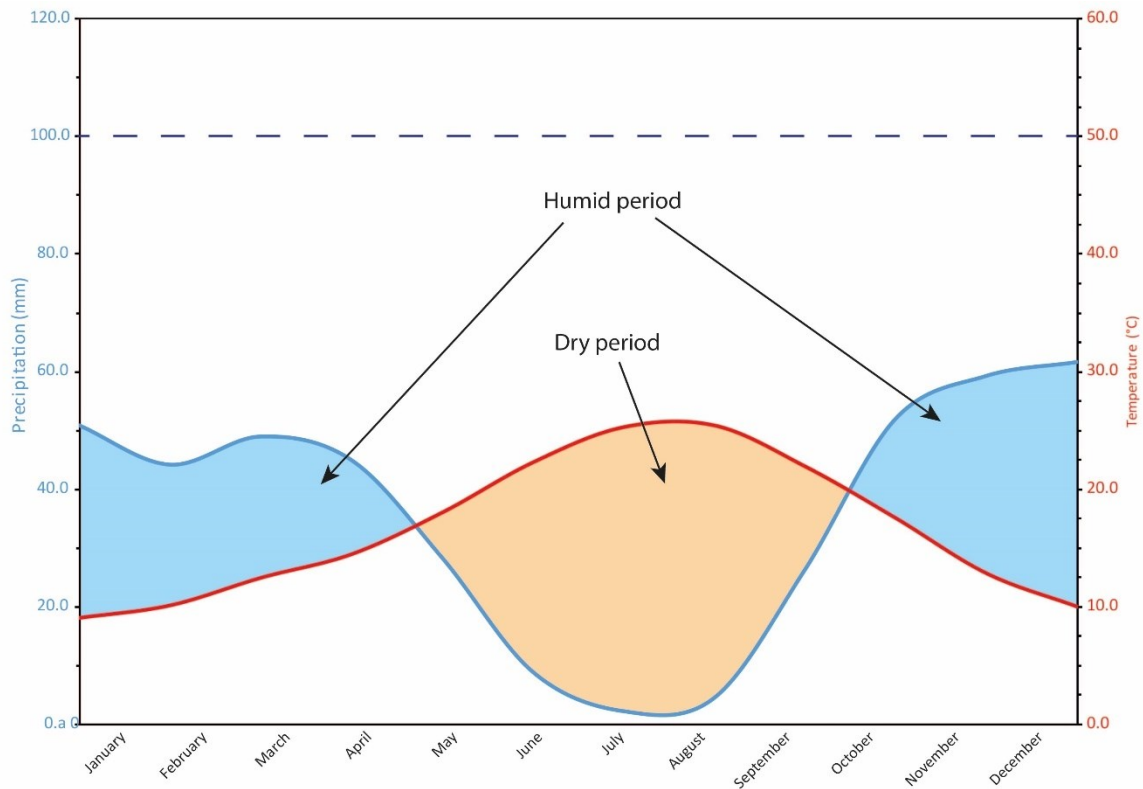


Figure 33. Climatic diagram (Walter and Lieth, 1967) for the La Herradura coastal area, depicting the relationship between monthly average temperature (°C) and monthly average precipitation (mm) from 1990 to 2020. Data are downloaded from <https://climatecharts.net/> (Zepner et al., 2021).

5.1.1 Geological and geomorphological settings

La Herradura coastal sector is settled in the Alpujarride Complex, formed by deformed metamorphic rocks belonging to the Alborán Domain of the Betic Cordillera (Azañón et al., 1994; Azañón and Crespo-Blanc, 2000). The main structures of the Alpujarride Complex are Alpine regional-scale anticline folds, with a mean E-W trend and NW vergence (Simancas and Campos J., 1993; Azañón et al., 1997; Williams and Platt, 2017). These compressive structures are cut by top-to-the-SW low-angle normal faults and later high-angle transtensional faults and other structures, formed since the Miocene (Azañón et al., 1997; Ruano, 2003; Ruano et al., 2004; Simancas, 2018). However, a NE-SW extensional phase characterizes the whole region at present (Azañón et al., 2015; Galindo-Zaldivar et al., 2015).

The study area is settled in the tectonic unit of La Herradura, formed by the following lithostratigraphic sequence, from bottom to top (Azañón and Crespo-Blanc, 2000) (Fig. 34): (i) Dark Schists Formation (Fm.), dark-coloured schists and graphitic micaschists (Palaeozoic), with Migmatite Gneisses at the bottom; (ii) Light Schists Fm., light-coloured fine-grained schists with calcschists in the uppermost part (Permian-Triassic); (iii) Marble Fm., calcareous and dolomitic marbles with interbedded phyllites and schists (Middle-Upper Triassic). The geological structure of the coast stretch is complex and exhibits a km-scale recumbent syncline affected by SW-dipping low-angle normal faults and other Alpine structures (Simancas and Campos J., 1993). The normal fault displaced the Marble Fm. belonging to the hanging wall towards the S-SW.

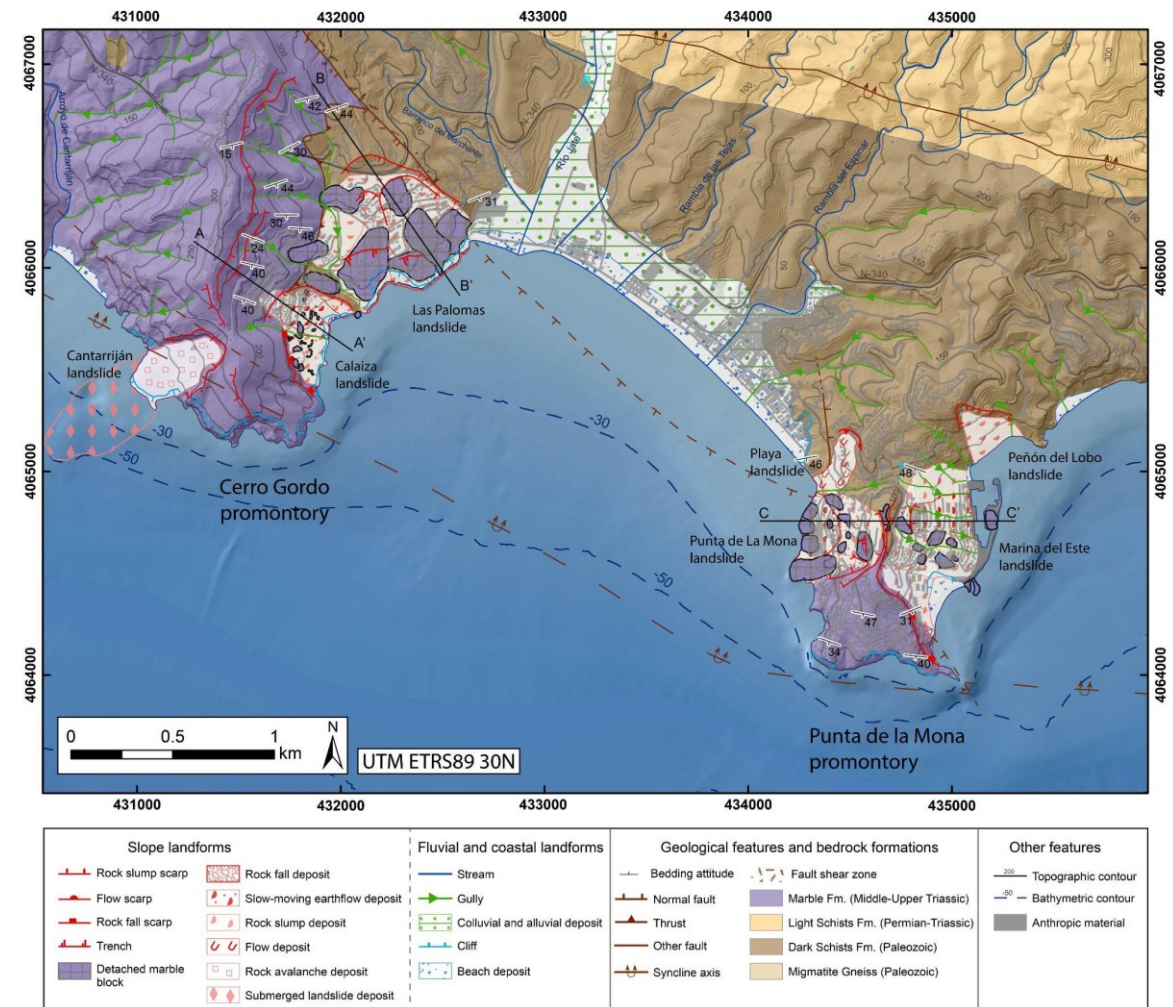


Figure 34. Detailed geological and geomorphological map of La Herradura coastal section, a reference site for the EGMS. Bedrock geology is after Avidad et al. (1973) and Marín Lechado et al. (2009). In the legend and in the map light-coloured features remain inactive/quiescent, dashed line features are supposed/uncertain, and barbs (in normal fault) and triangles (in thrusts) are in the hanging wall.

Marble Fm. is classically considered as a karst aquifer with high fissuration and low degree of karstification, while the remaining rocks, such as schists, are aquitards (Andreo et al., 2018; Calvache et al., 2020). The main recharge of the aquifer occurs by rainfall infiltration inland and the discharge takes place via submarine outlets or through karst springs located at sea level (Montiel et al., 2018). Both promontories are associated with Triassic marble that exhibits karst features often related to fractures and faults, especially in Cerro Gordo cape, where 11 caves totalling 330 m in length have been reported by speleological teams.

The plunging cliff (Type-C of Sunamura classification), which reaches a depth of over 40 m below the sea level (Consejería de Medio Ambiente y Ordenación del Territorio, 2015), is the main coastal morphology along the shoreline. Alternating with the plunging cliff, there are small coves with beach deposits and larger pebbly and sandy beaches such as La Herradura bay. The seabed in front of the coast consists of a continental shelf that slopes dipping 1.4° to the continental escarpment zone located at about 4 km from the coast. The promontories are dominated by small torrential streams within short and narrow valleys and slope/runoff processes in slopes. Slope processes involve prominent landslides impacting on Cármenes del Mar and Marina del Este resorts (Fig. 34). Chacón et al. (2014) reported the occurrence of landslides with slide kinematics mostly at the contact between marble and schist or phyllite units. The activity of these instabilities was directly correlated with extreme rainfall events (Notti et al., 2015; Mateos et al., 2017; Chacón et al., 2019).

5.1.2 Previous landslides studies

The terrain instability studies of the Cerro Gordo and Punta de la Mona promontories started with their urban development of Cármenes del Mar and Marina del Este resorts. From 1977

onwards, the first buildings were constructed, with urbanization increasing very rapidly from 1997 to the 2000s (Notti et al., 2015; Mateos et al., 2017). Signs of coastal instability in this area were firstly described in 1988. From 2005 onwards, unpublished technical reports, described in Chacón et al. (2019), analysing landslide areas were carried out, focusing on the urbanization of Cármenes del Mar. After those reports centred on geotechnical aspects, scientific research was developed focused on remote sensing techniques. Thus, the recent activity of landslides in both the Cerro Gordo and Punta de la Mona promontories have been largely confirmed by applying Differential Interferometric Synthetic Aperture Radar (DInSAR) (Notti et al., 2015; Mateos et al., 2017; Chacón et al., 2019; Barra et al., 2022). Regarding the Cerro Gordo Promontory, a Line-Of-Sight (LOS) displacement rate of up to 2.5 mm/yr was obtained in the period 1997-2000, related to the Calaiza landslide activity (Chacón et al., 2019). Mateos et al. (2017) estimated a maximum LOS displacement rate of -10 mm/yr for this landslide from May 2003 to December 2009, a period in which the first damages of the Cármenes del Mar resort appeared. These authors also estimated displacements of up to 1.98 m in 8 years through UAV digital photogrammetry in relation to the intense rainfall period during 2009-2010. Regarding the Punta de la Mona promontory, an average LOS displacement rate of -11 mm/yr was registered on the landslide affecting the Marina del Este resort (Notti et al., 2015). More recently, Barra et al. (2022) confirmed the activity of these two landslides from November 2015 to May 2020, both with LOS average displacement rates ranging from -10 to -20 mm/yr. The ground displacement was inferred in around 10 mm/yr affecting the Marina del Este resort.

Finally, landslides have resulted in a dramatic situation. The authorities have currently proclaimed an emergency state after ground movement damage forced the evacuation of 42 buildings in the resort of Cármenes del Mar (Chacón et al., 2019). For these reasons, all the

investigations bring the La Herradura coastal section to be one of the selected illustrative cases of Product User Manual Kotzerke et al. (2022) of EGMS.

5.2 Specific investigation methods

The geomorphological and geological map of La Herradura coastal section was performed at a scale of 1:20,000 to identify gravity-induced deposits, to recognize surface processes acting on the rocky coastline, and to establish a relationship between slope processes and bedrock lithology and structure. Both cartographies allowed to know the landslide extent and dynamics and to elaborate cross-sections along the main slope instabilities, as the basis for performing a conceptual model of the slope processes previously detected by InSAR data available through EGMS (<https://egms.land.copernicus.eu/>). This comparison aimed to assess the accuracy and limitations of InSAR as a resource for monitoring ground movements and evaluating its applicability in the La Herradura coastal section.

In the laboratory, aerial photography, land, and submarine DEM, and previous geological maps were performed and analysed using ESRI-ArcGIS software. Aerial photos were downloaded by the National Geographic Institute (IGN) of Spain (<https://centrodedescargas.cnig.es/>; <https://fototeca.cnig.es/fototeca/>) resulted from photogrammetric flights conducted by United States of America over the years 1945-1946 and 1956-1957 and by Spanish administrations since 1973; these were used to visualize the area previously to its heavy urbanization and to define the recent pre-urbanization landslides activity. The images were interpreted using a stereoscope for a 3D interpretation of landforms in combination with Google Earth optical satellite images providing a multitemporal analysis. The IGN also provided base maps and the 3D LiDAR point cloud in LAZ format; this zip file was decompressed into LAS archives and filtered with LAStools (Isenburg, 2014), generating a continental DEM with a 1 m cell-size resolution. Data for bathymetric reconstruction were downloaded from Ministry for the Ecologic Transition and Demographic Challenge of Spain

(<https://www.miteco.gob.es/es/costas/temas/proteccion-costa/ecocartografias/ecocartografia-granada.aspx>), generating a 5 m-resolution bathymetric DEM. Previous geological cartography is from Avidad et al. (1973) and the Continuous Digital Geological Map of Spain performed at a 1:50,000 by Marín Lechado et al. (2009).

Lineaments (related to landslide failure surfaces, faults, and/or fractures) and landforms were identified by analysing also the hillshade model derived by the DEM and were later verified by fieldwork carried out from September to December 2022. The field surveys were novelty supported by UAV flights to visualize hard-to-reach spots such as the rocky cliffs along the coast.

5.3 Results

Laboratory and field investigations provided the first comprehensive geological-geomorphological map of La Herradura coastal section at a scale of 1:20,000 (Fig. 34), a reference site for the EGMS. Three landslides (named Cantarriján, Calaiza, and Las Palomas) have been identified in Cerro Gordo promontory. The most studied is Calaiza landslide previously reported by several unpublished geotechnical studies, by Landslide Database of the Spanish Geological Survey (CN IGME, 2016) and inventory of the Granada Province (Chacón et al., 2007) and by Azañón et al. (2016) Mateos et al. (2017) Chacón et al. (2019) Barra et al. (2022). Additionally, four major instability events (namely Playa, Punta de la Mona, Marina del Este, and Peñón del Lobo landslides) have been mapped in the surroundings of Punta de la Mona promontory. Here, Barra et al. (2022) detected the surface displacements using InSAR techniques, without delimiting landslide extent. Marina del Este and Peñón del Lobo landslides were reported by unpublished geotechnical studies, but only the first was detected and studied by CN IGME (2016) and by Azañón et al. (2016), Notti et al. (2015). In our work, we examined Calaiza, Las Palomas, Punta de la Mona, and Marina del Este landslides in detail by means of three geological cross-sections to synthesize all newly gathered observations in the vertical

dimension (Fig. 35). The studied instabilities are affecting or could impact resorts, infrastructures (highway, national road) and other urban areas.

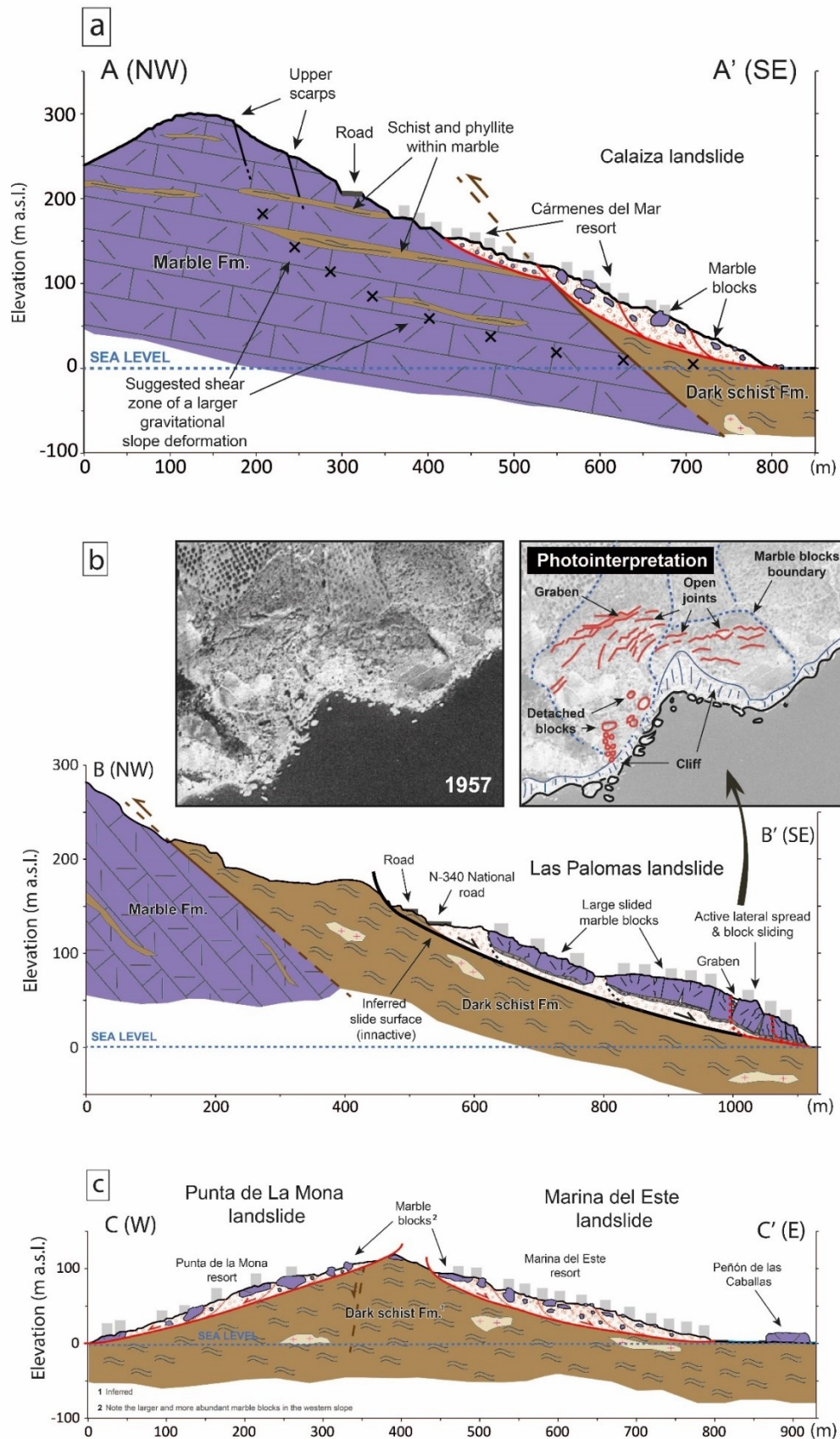


Figure 35. Geological-geomorphological cross-sections along La Herradura coastal section. The legend and position of the sections are depicted in Fig. 34 and the zoom position of the aerial image in profile b can be seen in Fig. 36a. (a) Cross-section along the active Calaiza landslides, where Cármenes del Mar resort was built on the eastern slope of Cerro Gordo promontory. An inferred shear zone associated with a larger gravitational slope deformation is also shown. (b) Cross-section of Las Palomas landslide that showcases the foundations of Las Palomas resort, at the vicinity of Cerro Gordo hill. While the majority of this landslide is currently inactive, there is activity observed in its lower part, where Marble blocks are sliding at the present day. Aerial image of the 1957 flight displays trenches revealing the occurrence of large slipped marble blocks (highlighted by red ellipses). Vertical scale is ca. two time exaggerated. (c) Cross-section along Punta de la Mona promontory exhibiting active Punta de la Mona and Marina del Este landslides

5.3.1 Landslides in the Cerro Gordo promontory: reconfiguring the conceptual model of slope failures

Cerro Gordo promontory (343 m altitude) is mainly composed of Marble Fm. exhibiting the typical massive morphology influenced by the occurrence of a recumbent syncline (Simancas and Campos J., 1993), with a NW-SE to E-W trend. Here, bedding dips 15° to the SE at the summit while it is subvertical in the southern plunging cliff of the cape. The fold shows an axial plane tectonic foliation towards S-SE dipping $30-40^\circ$. Both Marble and Schists Fms. are partially weathered, although the schists show a more extreme alteration. The deformation that the Dark Schists Fm. has undergone and the high degree of fracturing due to the tectonics present in the area, led to a more ductile than brittle rheology.

The eastern side of the Cerro Gordo promontory before the urban development is shown in Fig. 36a and the corresponding improved geological-geomorphological map (Fig. 36b) shows a zoom of Fig. 36. Here, Dark Schists Fm. has been identified in areas previously mapped as Marble Fm. in previous works. Moreover, we observed that the contact between Palaeozoic Dark Schist Fm. and Triassic Marble Fm. is of tectonic origin. This latter formation lies over the carbonate unit, and Permian-Lower Triassic Light Schists Fm. (which stratigraphically appears between the Marbles and the Dark Schists Fms.; Azañón and Crespo-Blanc, 2000). Altogether, the evidence suggests that the contact between Dark Schists and Marble Fms. is a

thrust in line with observation carried out by Sanz de Galdeano and López-Garrido (2003) in Betic Cordillera.

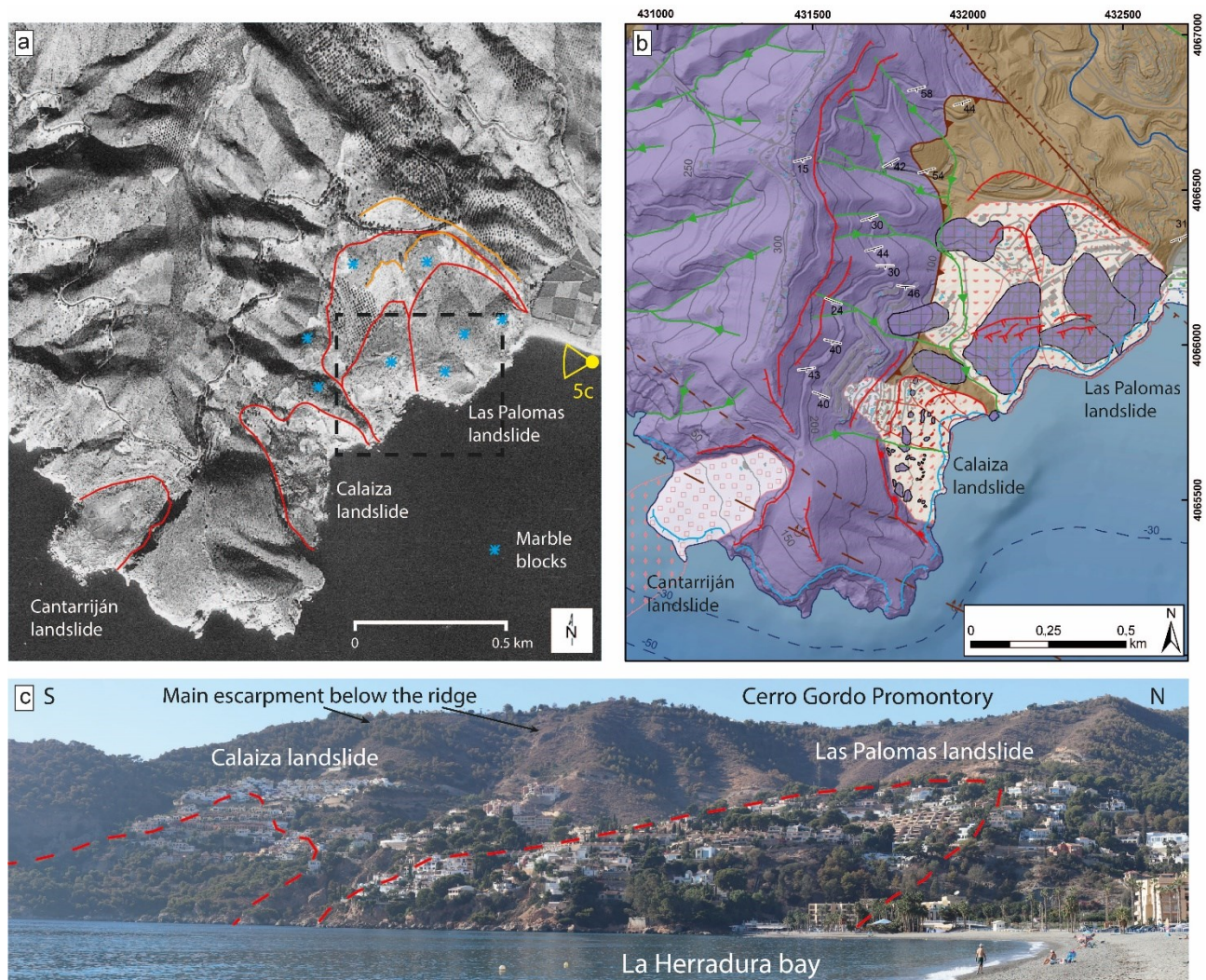


Figure 36. (a) Aerial image of 1957 exhibiting landslides and their detachment area, where the landslides are clearly visible without anthropization. Continuous red lines indicate landslides bodies, orange lines indicate the detachment areas, black rectangle indicates zoom in Fig. 35b; (b) Zoom of the geological and geomorphological map (Fig. 34) on the Cerro Gordo promontory. The survey details each single slipped block of marble. The legend for (b) is in Fig. 34; (c) Panoramic view of the eastern slope of Cerro Gordo promontory with the villages built on Calaiza and Las Palomas landslides. The point of view of (c) is shown in (a)

Cantarriján landslide stands out in the western slope of the Cerro Gordo promontory (Fig. 36). This inactive landslide is a rock avalanche, has a minimum volume of $3 \times 10^6 \text{ m}^3$, and produces a significant effect on the littoral relief and the bathymetry. The landslide deposit is

quiescent/inactive, except for sporadic rock falls along the landslide scarp and along the cliff of the landslide deposit generated by marine erosion. The Cantarriján landslide deposit conditioned the coastline producing a minor cape formed mainly by a great accumulation of marble blocks, which reaches -50 m depth, eroding an escarpment on the seabed and forming a small submarine fan in its bottom. The submerged landslide deposit is clearly visible in the hillshade model of the continental platform on the website of the Visor de Cartografiado Marino (<https://sig.mapama.gob.es/marino/>).

The eastern slope of the Cerro Gordo promontory is affected by the Calaiza landslide, which has impacted on Cármenes del Mar resort up to the present (Chacón et al., 2014, 2016, 2019; Notti et al., 2015; Azañón et al., 2016; Mateos et al., 2017). The landslide volume was estimated by Chacón et al. (2019) in ca. $8 \times 10^5 \text{ m}^3$ and its mapping has been updated in our work (Fig. 34-36). Marble blocks with volumes over 300 m^3 (within and above the landslide) have been detailed in the southernmost sector (Fig. 37a-b-c), some of them already mapped by Mateos et al. (2017). They were detached from the escarpment (ca. 25 m height) related to the southwestern limit of the Calaiza landslide by lateral spread and block slide mechanisms. Just below the ridge, two escarpments have been discovered using the hillshade model of 1 m resolution and later confirmed by fieldwork (Fig. 37d). The uppermost, with an approximately 10 m height and a N30°E mean direction, can be recognized along the entire slope (Fig. 36b). The second escarpment at lower altitudes is definitely shorter and discontinuous. The origin of this landform will be explored in the discussion section.

Las Palomas landslide has been discovered towards the NE of the Calaiza landslide. It is almost masked by the urban area and the observation of geological and geomorphological features here is really difficult. Specifically, the northern limit of the landslide is now largely obscured from view, making it challenging to delimit. Fortunately, historical aerial photographs taken in 1957 (Fig. 36a) display key morphological features to map the sliding mass. In addition, the sea cliff

face provides a clear view of the landslide deposit, allowing for an accurate understanding of its structure and composition. Thanks to low-altitude aerial photos captured using a UAV, the inaccessible cliff has been examined revealing: (i) the fallen marble rocks from the landslide deposit into the sea (Fig. 37e), which are not found anywhere else on the promontory where landslides were not reported; (ii) the alternation of massive marble outcrops (huge blocks on Las Palomas landslide) to the landslide deposit. These observations were crucial for developing a more comprehensive understanding of the processes that contribute to landslides in this area.

Las Palomas landslide, had a short runout, with a general composite rock slump kinematic and an estimated minimum volume of about $6 \times 10^6 \text{ m}^3$. The main body involves a large part of the slope reaching the N-340 national road. The crown of a principal large rockslide that encompasses two different types of nested bodies is not very discernible within the landscape. One of these types of nested bodies is a rock slump, which is identifiable by the occurrence of an arcuate scarp and a convex slope morphology at its bottom (Fig. 35b-36b). The other nested movement is composed of local lateral spreads and block slides, which are formed by large marble blocks involved within the main landslide body (Fig. 35b-36b). The structure of the landslide with up to metric-scale marble blocks embedded in a medium-fine matrix derived from the weathering schists and phyllites (Fig. 37f) does not fit with the current source area of the landslide (i.e., crown area) composed of schists. Particularly, it is clear how the Las Palomas landslide changed the previous coastline (as for the Cantarriján landslide), which was about 150 m further back. The largest gravitational process involves the entire slope with a very large and deep sliding surface (Fig. 35b). Superficial reactivations and remobilization occurred only in the Calaiza landslide as documented before.

In some cases, a reddish-brown sandy-rich sediment consisting of fine matrix and angular centimetric marble clasts, not previously described in the area, has been found at the contact between marble blocks and schists (Fig. 37a). This sediment is quite continuous and would be

interpreted as colluvium derived from runoff and slope processes, but its position between two metamorphic formations (Dark Schist and Marble Fms.) is rare. Field evidence observed in an excavated talus reports that this sediment is probably a gouge as a result of large marble blocks sliding process on schists (Fig. 37a). The outcrop exhibits a marble block situated above the layer in question, as well as significantly deformed schist displaying a drag folding zone associated with the movement of the block (zoom in the Fig. 37a). According to this, marble blocks are comparable to ploughing blocks commonly observed in periglacial environments (Goudie, 2004). These blocks exhibit faster downslope movement compared to the underlying sediment due to solifluction processes, which produce inner deformation within the sediment.

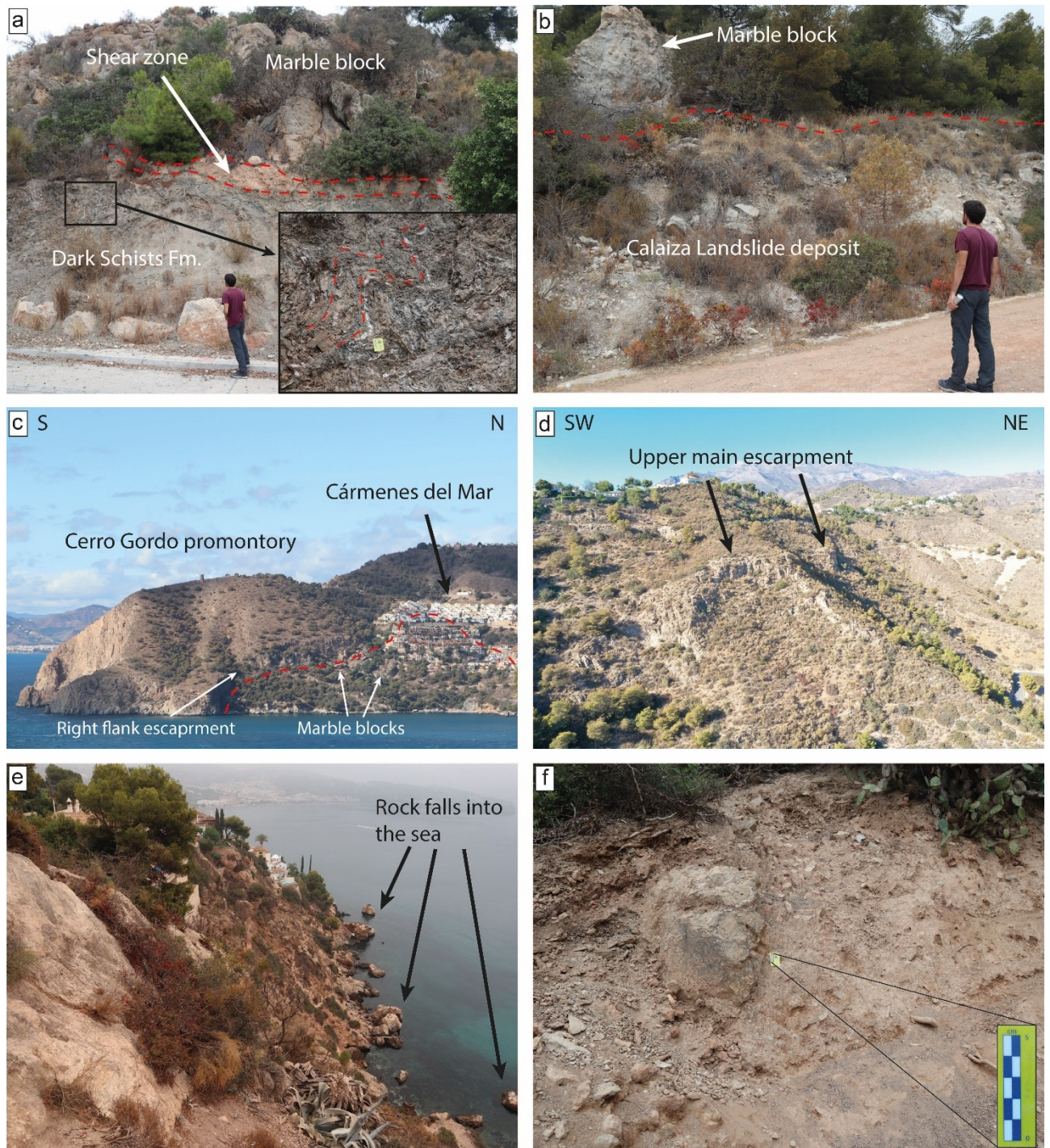


Figure 37. (a) Contact between a detached marble block and the Dark Schists Fm. marked by a shear zone made of a sandy gouge. In the insert frame are visible drag folds in the foot of the deformation zone; (b) Marble block detached from the escarpment (c) and slipped above the Calaiza landslide deposit in the southern part; (c) Panoramic view of the Calaiza landslide (dashed red area) in the Cerro Gordo promontory. The right flank escarpment of the Calaiza landslide is also visible; (d) Main upper escarpment (ca. 10 m height) above the Calaiza landslide; (e) Las Palomas landslide body involving up to metric marble blocks, falling into the sea through marine erosive action; (f) Detail on the Las Palomas landslide body, with medium-fine matrix and up to metric marble blocks.

5.3.2 Gravitational collapse of the Punta de la Mona promontory: redefining the landslide areas

Punta de la Mona promontory (Fig. 38) shows similar lithologies as the previous promontory, with the additional presence of sporadic outcrops of highly altered and fractured Migmatite Gneisses in the eastern slope. Here too, the strata dip towards the S and the recumbent synclinal axis turns in an E-W direction following the coastline. One of the regional extensional faults, with a NW-SE direction, here cutting across the promontory and generating a partially visible tectonic contact in the ridge between Marble and Dark Schists Fms. (Fig. 39a). The main difference from the Cerro Gordo is the scarcity of Marble Fm., which crops out in situ only in the southernmost promontory and at the ridge (Fig. 38a). This is also related to the lower altitude of the promontory itself, which reaches about 126 m in contrast with the over 300 m of the Cerro Gordo cape.

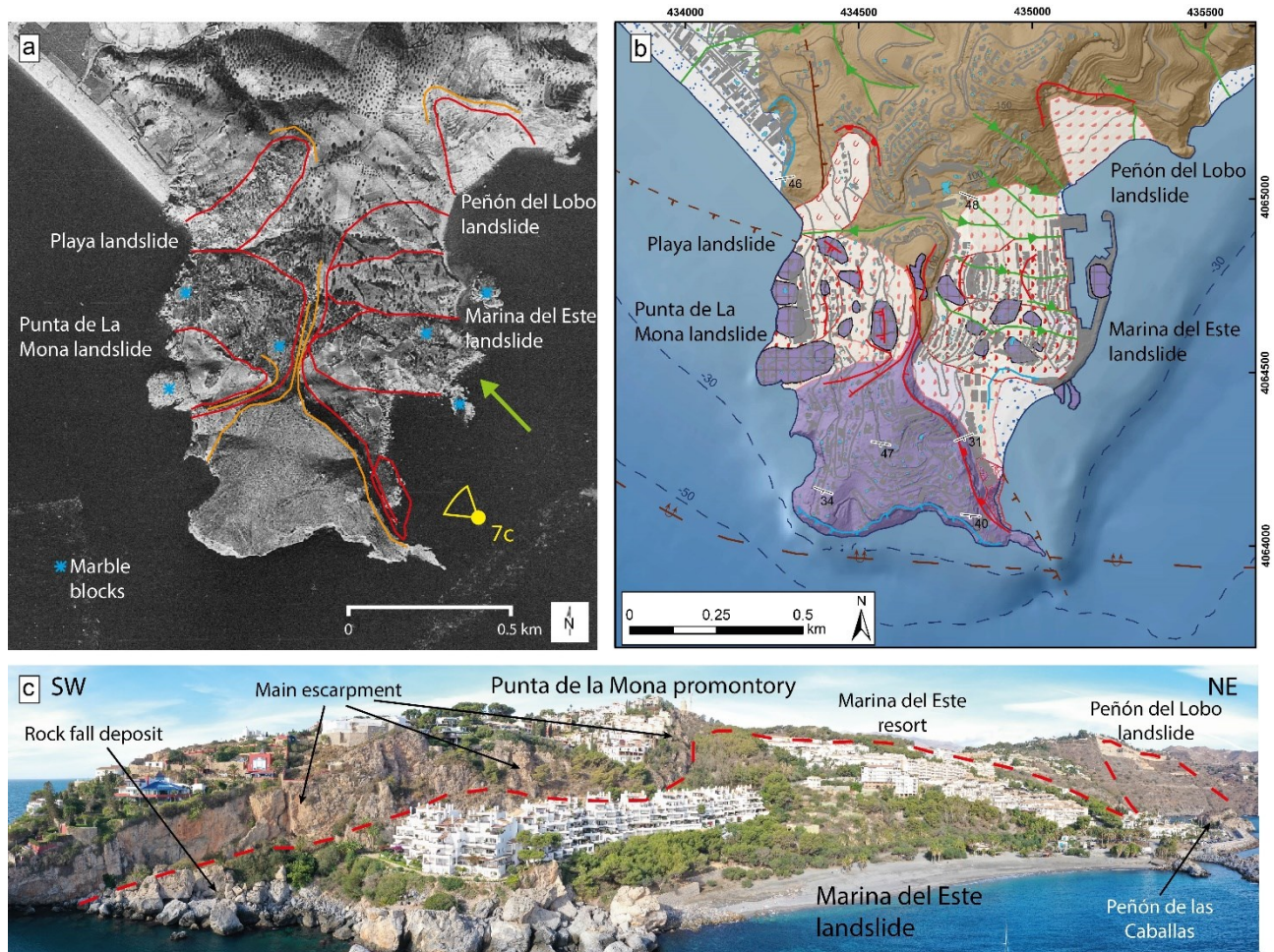


Figure 38. (a) Aerial image taken in 1957 exhibiting landslides and their detachment areas, which are easily recognizable in the pre-urbanised Punta de la Mona promontory. Continuous red lines indicate landslide bodies, orange lines indicate the detachment areas, the green arrow indicates the part of the body landslide flattened for the parking; **(b)** Zoom of the geological and geomorphological map (Fig. 34) on the Punta de la Mona promontory. It can be seen the detail with which the landslide deposits and their shapes have been mapped. The legend of (b) is shown in Fig. 34; **(c)** Panoramic view of the eastern slope of the Punta de la Mona promontory with Marina del Este resort, after which the landslide was named. The rock fall deposit with the up to 30 m height escarpment in the southeastern part of the promontory is clearly visible. The point of view of (c) is shown in (a)

Landslides involve both sides of the Punta de la Mona promontory, which is heavily urbanized. Two landslides are now being analysed that had so far not been catalogued, neither in the Landslide Database of the Spanish Geological Survey (CN IGME, 2016) nor in the inventory of the Granada Province (Chacón et al., 2007). Punta de la Mona landslide, with composite rock slump kinematics, affects the entire western slope, exhibiting a minimum volume of 1.5×10^6

m³. The landslide scarp is not evident, but it would be recognizable S of the landslide body and continues along the southern flank, coinciding with a large open fracture on the plunging cliff (Fig. 39b). The main landslide body is quiescent/inactive but superficial reactivations were identified in the central part of the landslide body. In the northern part of the western flank, Playa landslide was detected, which caused some damages to the overlying buildings and roads. This active landslide has a slow-moving flow kinematic and developed entirely on Dark Schists Fm.

In the eastern sector of the promontory, Marina del Este landslide shows a minimum volume of about 2.5×10^6 m³ and has been much studied in geotechnical reports and through InSAR analysis (Notti et al., 2015 and reference therein). The landslide escarpment follows the entire slope showing heights of up to 30 m (Fig. 39c), vertical fractures and detached large marble blocks up to 100 m in diameter. For instance, Peñón de las Caballas rock outlines in the marina as an enormous marble block that slipped into the sea around (Fig. 39d).

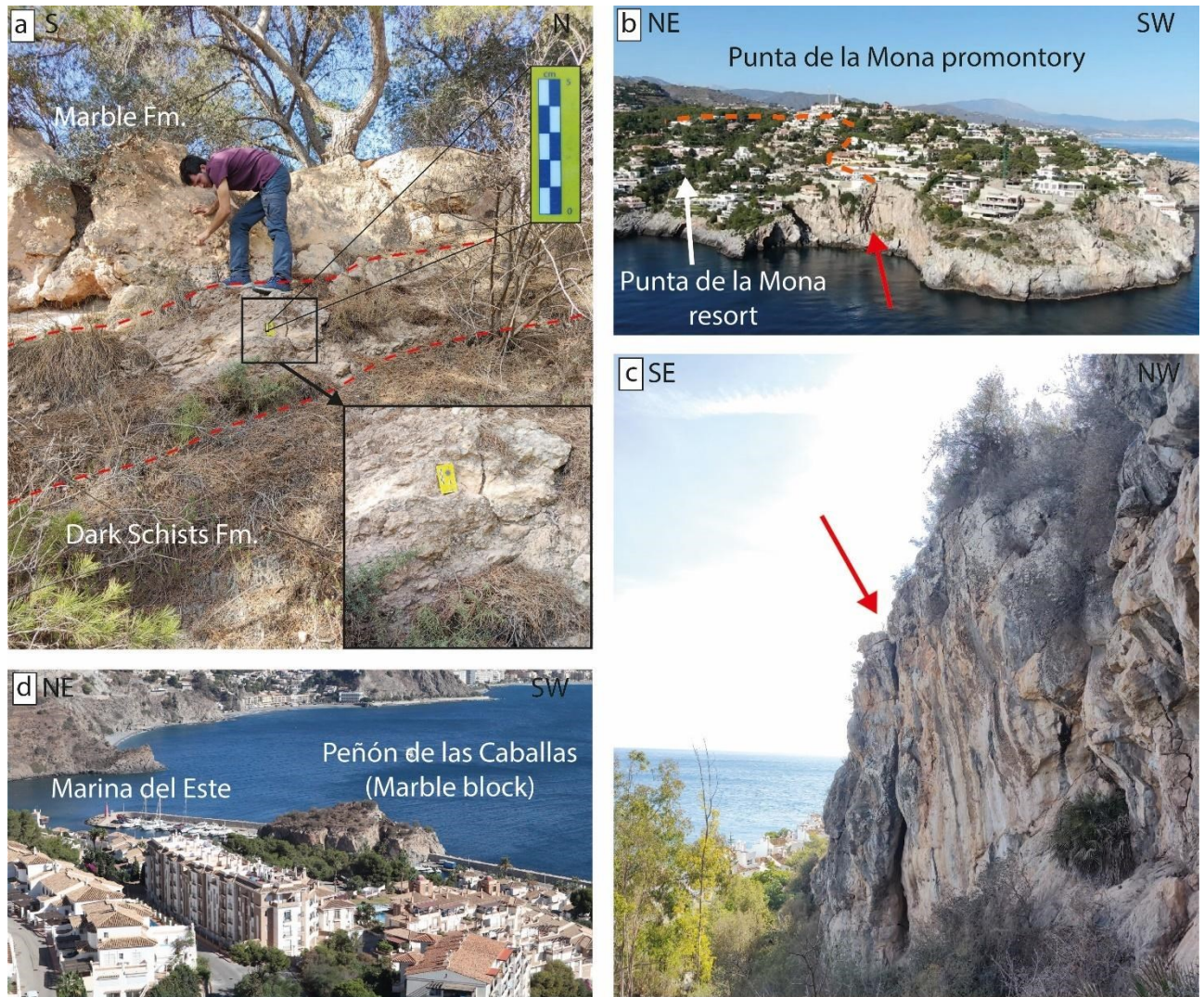


Figure 39. (a) Contact between Marble and Dark Schists Fms. that is associated with a tectonic shear zone composed by brecciated and well-consolidated material. Here one of the extensional faults cuts across the promontory, exhibiting this tectonic contact in the ridge; (b) Plunging cliffs of Punta de la Mona promontory, obtained from a drone video of the Inmobiliaria de La Cuesta. Indicated by a red arrow is an open fracture that coincides with the escarpment of the landslide affecting the western slope; (c) The escarpment (30 m height) of Marina del Este landslide showing vertical open fractures (red arrow) related to the detachment of marble blocks; (d) Peñón de las Caballas rock, a huge marble block slipped into the sea, where the harbour of Marina del Este was built.

Looking at the aerial images of the 1957 flight, it is clear how the promontory was modified when the resorts were constructed (Fig. 38a). For instance, the bottom of the Marina del Este landslide was flattened for the construction of the harbour car park (green arrow in Fig. 38a). This fact reinforces the utility of historical aerial images for recognizing features that can no

longer be seen today, such as innumerable gullies engraving the landslide body. Furthermore, as in the case of Las Palomas landslide, huge slipped marble blocks were found along the coastline and on the landslide deposit along the slope. These can hardly be seen today, whereas they are clearly visible in aerial images taken before urbanization and they have been mapped in detail in the geological-geomorphological map (Fig. 38b). In this context, it is noteworthy that an accumulation of marble rocks can be observed at the bottom of the southeastern slope of the promontory, just situated beneath the crown scarp. Based on their distribution pattern, it is possible to infer that the rocks have been dislodged and fallen into the sea as a result of a topple or rockfall event, rather than through sliding over the underlying schist. This inference is supported by the occurrence here of marble outcrops without preserved marble blocks inland.

5.4 Discussion

5.4.1 New landslide conceptual model of La Herradura coastal section

The field survey developed in the present investigation has corroborated that the evolution of the eastern slope of the Cerro Gordo promontory was undoubtedly influenced by the outcropping Dark Schists Fm. as previous investigations had highlighted. Notwithstanding, the new geological-geomorphological map (Fig. 34) and cross-sections (Fig. 35a-b) have yielded dissimilar results compared to earlier works, which were based on the geological map of Avidad et al. (1973). This map was created prior to significant advancements in tectonics during the 1980s (a period when, for instance, the conceptual understanding of thrust systems underwent significant development) and suggested that the promontory has a core of dark schists covered by the marble unit. Our investigation conducted at a scale of 1:20,000 (utilising high-resolution aerial images, LiDAR DEM and an extensive field survey assisted by outputs of UAV-DP technique) unveiled the occurrence of a NW-direct thrust dipping to the SE. This geological structure is parallel to the eastern slope of Cerro Gordo promontory and, therefore, would influence widely the slope processes here. These novel insights and new

geomorphological evidence allowed us to redefine the geological and geomorphological conception of the study area and subsequently to revise the local landslide conceptualization made by Notti et al. (2015), Mateos et al. (2017) and Chacón et al. (2019).

The new landslide conceptual model of Cerro Gordo and Punta de la Mona promontories is shown in Fig. 40. In both cases, the general attitude of the strata dips to the S-SE. The contact between the geological formations would be an Alpine thrust (Fig. 40a) although this is not evident in Punta de la Mona promontory. According to this, the contact here is represented by a vertical fault in Fig. 40b.

In general, the geological structure of the bedrock favoured the primary development of landslides on the eastern hillsides, creating an apparent suitable smooth area for building. The landslides are really complex and involve three main clear movements: (i) a deepest movement characterised by rock slump kinematics at a 40 m depth in Cerro Gordo promontory (Mateos et al., 2017) and 20 to 25 m depth in Punta la Mona Promontory (Notti et al., 2015); (ii) superficial movements composed of a slow-moving earthflow in combination with lateral spreads and sliding of large marble blocks, and (iii) local toppling and rockfall processes on scarps and detached marble blocks, confined in areas proximal to escarpments and cliffs. Another potential main movement is related to the escarpments recognized at the top of Cerro Gordo promontory and a hypothetical shear zone in depth (Fig. 40a). The scarps would be formed by a gravitational process, and this is related to one of the most persistent joint family with a NE-SW orientation (Mateos et al., 2017). This joint family is also correlated with the NNE-SSW extensional tectonic structures that characterise the Alpujárride complex (Azañón et al., 1997; Simancas, 2018). The presence of enormous detached marble blocks and the mentioned escarpment suggests that the entire eastern slope of Cerro Gordo promontory is affected by a complex and past gravitational movement. The morphological features resulting from this gravitational process appear to have been largely obliterated by watershed erosion, which

implies that the development of such phenomena has been notably slow and over a long period of time.

Internal discontinuity planes of the marble bedrock manifested as bedding, tectonic foliation, and joint families, constrained the mobilized blocks. Meanwhile, the presence of schist interbedded into the Marble Fm. would act as a sliding layer for marble blocks, leading to their eventual mingling with the underlying weathered and slid-down Dark Schists mass. In addition, the Dark Schists Fm. is of low permeability and concentrated groundwater on its top, favouring landslide movements. This agrees with the InSAR monitoring that reordered higher ground movement velocities during wet periods (Notti et al., 2015; Mateos et al., 2017; Chacón et al., 2019).

Landslides affected both sides of Punta de la Mona promontory (Fig. 40b) according to Notti et al. (2015) and Barra et al. (2022), showing detached large marble boulders. Again, the landslides that are highlighted in the literature are only the active bodies. From the morphological evidence, the eastern side, where Marina del Este is located, was completely involved in a very extensive mass movement, with only the central portion currently active, above which the Marina del Este resort was built. From the bathymetric trend, it is visible that the seabed slopes more gently than on the western side of the promontory, most likely due to the transport of sediments from the landslide deposit to the seabed close to the shoreline. As a further indication of the above, the -50 m isobath also has an extension in the area below the slope (Fig. 38b). The western side is also entirely affected by gravitational processes, which activity was recently displayed by Barra et al. (2022) and mapped in our research for the first time.

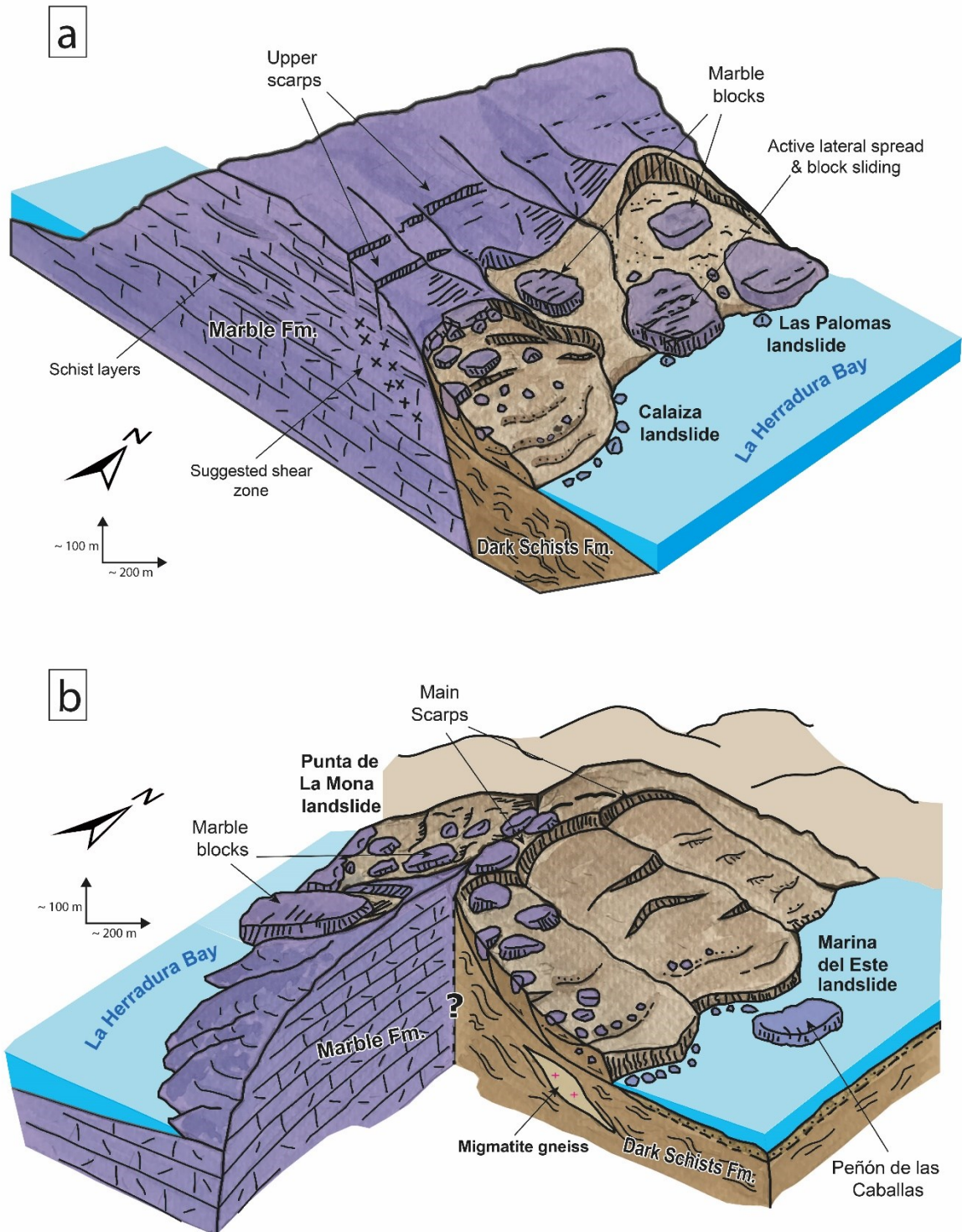


Figure 40. Conceptual landscape model. 3D illustrations show the morphodynamic style that characterizes the promontories of Cerro Gordo (a) and Punta de la Mona (b). In addition to the large landslides present, the process of lateral spreading and block sliding is highlighted. For some features (such as marble blocks or detachment areas) vertical scale is exaggerated more or less two times for a better view of the single block

As it can be seen, the evolution of both promontories is very similar, with same landslide kinematics and quite similar sliding surface depths. Surface movements, detected by InSAR, are nothing more than reactivations of previous landslide deposits, caused by a combination of exceptional rainfall events and rapid and massive urban development. Another important common feature is the presence of marble blocks of varying size (from metric to decametric scale) that lie along the slope or on the coastline (Fig. 36-38). Due to the development of major discontinuities (Fig. 39a) within the marbles, with an approximately NNE-SSW trend, the detachment of blocks, even large ones, occurs through a process similar to lateral spreading. The weathering of the schists and the landslide deposits means that the block can slide, thus highlighting the evolution from lateral spreading to block sliding (Fig. 40). Examples of this type of kinematics have already been studied on Mediterranean coasts made of sedimentary rocks (Mantovani et al., 2013; Devoto et al., 2021, 2022). In the La Herradura coastal section, we present one of the few comprehensible examples in an Alpine metamorphic setting, highlighted just by few contributions until now in other areas (Poisel et al., 2009). Marine erosive action may have played a key role in the main landslide activities. In fact, the highest concentration of landslide phenomena is found on the eastern slopes, where the prevailing waves and storm waves with the highest frequency are active (Fig. 34). In relation to the existing mapping, that is the BD-MOVES catalogue of the Geological and Mining Institute of Spain (CN IGME, 2016), the total landslide areas in the La Herradura coastal stretch would be $2 \times 10^5 \text{ m}^2$. According to our surveys and to the new landslide mapping, the landslide area would amount to about $1 \times 10^6 \text{ m}^2$, five times more extension than the previously mapped landslides. It is important to clarify that not all the areas affected by landslides are presently exhibiting clear signs of instability. Nevertheless, it should be noted that landslide deposits typically lack consolidation, and as such, an area currently deemed stable, such as those

discernible by InSAR, may undergo reactivation in the future. This is particularly true during periods of exceptional rainfall events or earthquakes, which are common in the region.

5.4.2 Classical methods offer fresh insights in areas extensively explored by advanced technologies

Calaiza landslide is one of the most studied landslides in Spain, because of the countless significant damages to the overlying buildings and the forced evacuation of 42 dwellings (Chacón et al., 2019). This led to analysing the activity, speed, and extent of landslide displacement with all the latest techniques, particularly remotely. The absence of a comprehensive geological and geomorphological survey and mapping covering the entire slope, using solely on remote sensing recent techniques, has resulted in a lacking foundation for a complete knowledge of the slope processes. This is also partly demonstrated by the Las Palomas landslide. It is noteworthy that photointerpretation of historical images allowed the novel identification of Las Palomas landslide, which with a short runout, a large part of the landslide body is mainly lying on the slope. This observation can be attributed to the fact that all investigations thus far have been limited to the damaged area of Cármenes del Mar resort, without any broader research being undertaken in the region at a more detailed scale. Furthermore, in the historical images, it can be recognized that the lower part of the landslide shows two large marble blocks affected by an internal process of lateral spread and block sliding provoked by the coastal erosion (zoom of the aerial image in Fig. 35b). Nowadays this zone is covered by urban areas which prevents us from observing these features. These features suggest an active movement in the date when those photographs were taken. Currently, the landslide appears to be inactive, which is also partially confirmed by InSAR (Fig. 42a-b) data (from 01/2016 to 12/2021) that have not detected any movement in that area up to now. However, this should be treated with caution because the InSAR data cover a limited range of time and ground movements (few millimetres), and the technique could be blind for movements

with N-S orientations. Another feature worth mentioning in the area of the Las Palomas landslide is the perturbation on the drainage network caused by this landslide. The path of the main impluvium of the slope is deflected showing a sharp bend. In the longitudinal profile of the ravine, it is clear how there is an anomaly, in part certainly due to the anthropic component, but with a change in convexity downstream of the anomaly (Fig. 41). This could indicate a diversion of the ravine due to lithological contrast between schist and marbles, due to the existence of a slipped marble block, or the recent advance of the landslide body, in a centennial temporal scale. The impluvium, in the section previous to the anomaly, engraved the main rock slump landslide deposit by crossing it and is diverted due to the subsequent reactivation of the deposit and lithological change of the marble block.

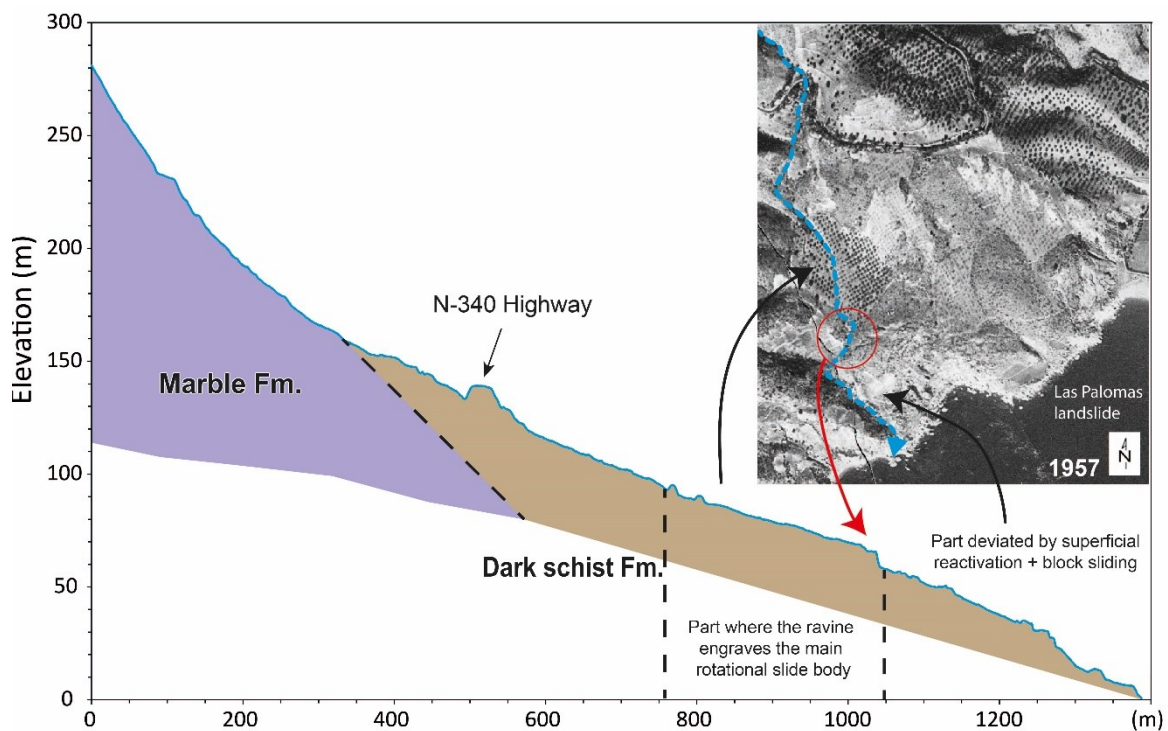


Figure 41. Longitudinal profile of a ravine perturbed by Las Palomas landslide. The red arrow shows a relief anomaly (sharp slope) defined by a profile changing curvature. Other relief anomalies are related to anthropic works. In the aerial image, the diverted path of the impluvium is clearly visible (red circle)

Thanks to the geological and geomorphological field survey, the consultation of multi-temporal aerial images and only later the consultation of InSAR data, it was possible to give a complete evolutionary picture of the La Herradura coastal section. In Table 1, the present work is compared with the previous ones, which have worked in this coastal section, through the methods used, work products, and results obtained. It can be easily seen that by going through the steps described by Griffiths (2019) and Hearn (2019), one can fully understand landforms and processes and then at a more certain assessment of natural hazards. The application of a large variety of remote sensor techniques and limited fieldwork by previous works (Notti et al., 2015; Mateos et al., 2017; Chacón et al., 2019; Barra et al., 2022) allowed to identify only 40% of the existing landslides in La Herradura coastal section. All the landslides previously reported correspond to active instabilities, which occurrence is also evidenced by damages observed on urban areas. However, the comprehensive geological and geomorphological mapping conducted in our work has enabled the identification of inactive landslides. It is crucial to consider the occurrence of inactive landslides in land management as they have the potential to be reactivated by human activities (e.g., excavations, new constructions, drainage network modifications). Consequently, their reactivation could significantly impact urban areas and infrastructures. In addition, the meticulous field surveying has led to the recognition of novel instability processes, including the lateral-spreading, and sliding of marble blocks. The presence of these boulders has been previously documented by Notti et al. (2015) and Mateos et al. (2017). Two escarpments have been also discovered in Cerro Gordo promontory through intensive fieldwork, suggesting the development of a major potential instability that affects the entire slope.

					Notti et al. (2015)	Mateos et al. (2017)	Chacón et al. (2019)	Barra et al. (2022)	This work
<i>Methods</i>	Interferometry	InSAR			x	x		x	
	Photointerpretation	Recent aerial or satellite images			x	x		x	x
		Historical images			x	x	x		x
		UAV (drone) images				x			x
	Field surveying	Geological mapping			x	x	x		x
		Geomorphological mapping							x
		Damages inspection			x	x		x	
	Landslides activity	Active processes			x	x	x	x	x
		No evidence of active processes							x
<i>Products</i>	Products	Geomorphological assessment							x
		Geological map				x			x
		Geomorphological map							x
		Building damages inventory			x	x	x	x	
<i>Results</i>	Landforms	Landslides	Cerro Gordo promontory	Cantarriján		x	x		x
				Calaiza		x	x	x	x
				Las Palomas					x
		Punta de la Mona promontory		Playa					x
				Punta de la Mona				x	x
				Marina del Este	x			x	x
				Peñón del Lobo					x
		Detached large marble blocks			x	x			x
		Upper scarps of Cerro Gordo promontory							x
	Types of instability processes	Rock slump			x	x	x		x
		Superficial slow-moving earthflow			x	x	x		x
		Superficial lateral-spreading and block sliding							x
		Rock falls							x

0 Table 1. Comparison table between the present work and previous works in the La Herradura coastal section.

5.4.3 New technologies supporting classical methods and their synergies

In the previous section, the advantages of carrying out geomorphological and geological surveys as a complement to remote sensing surveys have been outlined. However, it is also important to underline the importance of remote sensing techniques to support classical methods. For example, site accessibility, logistical problems and the presence of the sea are some of the aspects that make classical field surveys difficult on rocky coasts, as in the case study described. For this reason, remote surveys are widely used in these environments, both for their convenience and their lower cost. Furthermore, they have, for example, taken advantage of UAVs and LSQ analysis based on high-resolution DEM, in particular when studying gravitational processes (Devoto et al., 2020; Troiani et al., 2020; Piacentini et al., 2021). In our case, the coastal stretch of La Herradura revealed the important role of UAVs in the exploration of cliff areas, as well as in providing additional perspectives on the ground. In addition, with the help of high-resolution DEM, we were able to discern geological and geomorphological features and understand the landscape from different points of view. Thanks to InSAR techniques, previous works were able to identify active zones where imperceptible movements develop. In this sense, active landslides can nowadays be remotely analysed, monitored and mapped using InSAR techniques or data through various web-based digital platforms (Galve et al., 2017; EGMS, European Ground Motion Service, 2023).

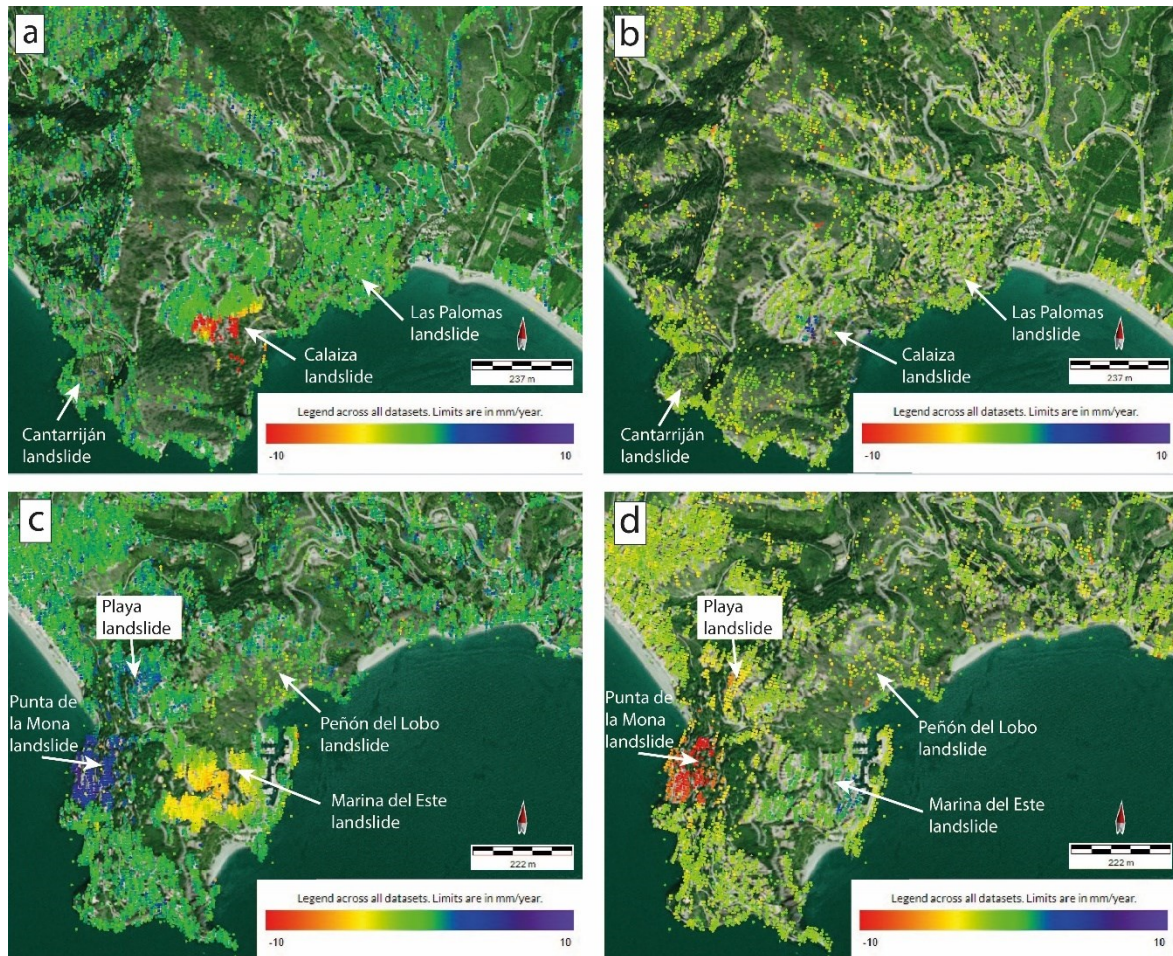


Figure 42. a) and b) respectively ascending and descending orbit on Cerro Gordo; c) and d) respectively ascending and descending orbit on Punta de la Mona. Images showing the extent of localised displacement in the active areas of the landslide bodies described in this work (obtained on <https://egms.land.copernicus.eu/>)

Consulting the InSAR images on the EGMS website (Fig. 42), it can be seen that displacements are present in the most important landslide bodies with exception of the Las Palomas landslide. In the latter, only a few points could be seen with a greater displacement in the descending orbit, but overall there is no clear displacement (Fig. 42b). In the Playa landslide, InSAR data indicate a negative displacement suggesting a movement of the landslide body in the descending orbit (Fig. 42d).

In conclusion, the present work demonstrated the immense value of traditional geomorphological and geological survey approaches that complement novel techniques and

facilitate multidisciplinary investigations, as well as the great advances made in mapping techniques assisted by remote sensing technologies. The accessibility of InSAR data through EGMS has provided widespread access to this valuable information. However, it is essential to emphasize that detailed geological and geomorphological investigations combining fieldwork and remote sensors are crucial to avoid misinterpretations. These investigations play a critical role in validating InSAR data and developing accurate conceptual models of slope instabilities. Geological maps typically prioritize tectonics and stratigraphy and may not specifically address slope instability investigations. Therefore, it is necessary to conduct a thorough review of previous geological maps at the local scale to check them as the first step to gain a comprehensive understanding of slope processes and enable effective risk assessment. By incorporating these investigations, we can ensure a more robust and reliable analysis of slope instabilities.

Chapter VI

6. General discussion and conclusions

The underlying theme of this thesis is to highlight the importance of morpho-structural and geomorphological assessments, specifically the study of landforms and processes, for risk mitigation, land planning, and the preservation of geo-touristic heritage, particularly along rocky coasts. To achieve this, an attempt was made to follow the steps described by Griffiths (2019) and Hearn (2019) in order to obtain the most comprehensive understanding for each study area. The three rocky coasts studied (Mt. Conero, Mt. San Bartolo, and La Herradura) belong to two different geographical and geodynamic contexts, as Mt. Conero and Mt. San Bartolo share the same geodynamic context, but consists of different types of rocks: Mt. Conero is characterized by Mesozoic limestones, Mt. San Bartolo by Cenozoic alternations of marls and sandstones, and La Herradura by Palaeozoic and Triassic metamorphic rocks. It was designed to maintain the same investigation methods with both field surveys and remote analysis techniques, even though each technique has its own advantages and limitations. For instance, InSAR, depending on the satellite's orbit, often hardly detects changes on short time scales and is frequently unable to provide values on rocky coasts for the absence of persistent scatterers or for the coastline orientation. LSQ analysis, on the other hand, relies on the DEM and, consequently, it's challenging to derive reliable terrain values with an altered DEM such as in presence of dense vegetation (for DSM derived by UAV surveys) or in highly urbanized areas. In the areas of Mt. Conero and Mt. San Bartolo, InSAR data from both ascending and descending orbits were consulted, but limited point density prevented their effective use. Only local negative displacements were identified (Fig. 43), such as reactivation of the landslide deposit on the right side of La Vela landslide (Mt. Conero) (red arrow in Fig. 43a) or in the

ridge area of the northern sector of Vallugola (Mt. San Bartolo) (red arrow in Fig. 43b). It is interesting to note that the displacements of the ridge in the northern Vallugola area correspond in spatial distribution with the reactivation of the wave erosion scarp at the base of the cliff (Fig. 27), indicating an entire slope experiencing active erosion even today. On the contrary, in the La Herradura area, the presence of numerous persistence scatterers allowed for the use of such data and enabled a comprehensive mapping of active gravitational movements (Fig. 42).

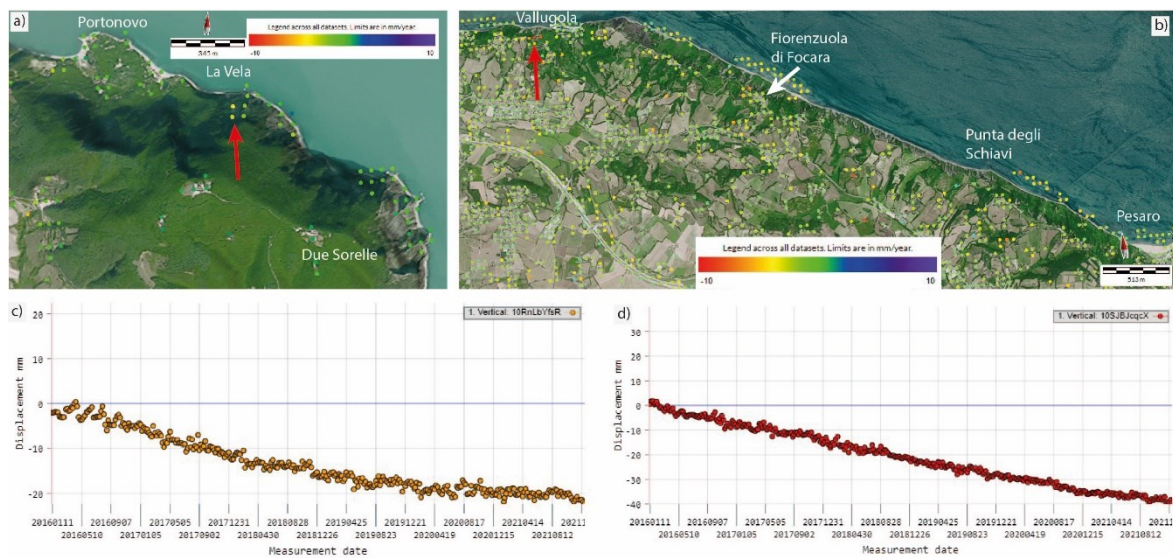


Figure 43. a) and b) InSAR displacement measurements on respectively Mt. Conero and Mt. San Bartolo. Images show the low point density due to the absence of scatterers and the orientation of the coastal slopes. c) and d) The displacement of the points indicated by the red arrows respectively for Mt. Conero and Mt. San Bartolo (data obtained on <https://egms.land.copernicus.eu/>).

Regarding the LSQ analysis, it is the opposite, in fact it provided valuable insights into gravitational phenomena in the areas of Mt. Conero and Mt. San Bartolo, but it was not used in the La Herradura section, because the LiDAR-derived DEM is heavily altered by anthropic activities; consequently, in this last case, the values obtained from a LSQ analysis wouldn't accurately represent the terrain values. The assessment of the spatial variation of the LSQ analysis parameters reveals a good correlation with the geo-structural data obtained in the field survey for the case of Mt. Conero and Mt. San Bartolo.

It is already known that the structural assessment significantly influences the slope's evolution (Bromhead and Ibsen, 2004; Margielewski, 2006; Grelle et al., 2011; Bromhead, 2013; Santangelo et al., 2015; Schlögel et al., 2016; Francioni et al., 2018; Bevan et al., 2022). In the case of Mt. Conero, for example, the predisposing factor of the strata attitude imparts a dual evolutionary style, even when the underlying processes and lithology are similar on the entire coastal slope. Subsequently, by employing LSQ analysis, various events that have shaped the Portonovo and La Vela area have been identified, defining the differential evolution of the slope: to the south, higher temporal recurrence processes, and to the north, phenomena occurring on a much larger time scale. In the Mt. San Bartolo, the structural configuration, characterized by folded structures, predisposes the southern part to large landslide events involving sliding, while the remaining part experiences mainly slump (rotational sliding) and flows. The change in the orientation of the slope from the SE-NW to approximately E-W, resulting from the curvature of the outer thrusts towards the Po plain, has also played a significant role in the sectoral evolution. In fact, this stretch of the slope (Vallugola sector) appears to be the most active, especially in relation to events in the last three years. This is because it is directly exposed to the dominant wind and wave direction. Also, in the La Herradura section the regional structural framework has significantly contributed to the actual conformation of the landscape. The faults that juxtapose the Marbles and Schists Fms. make the slopes of the two promontories prone to significant gravitational phenomena, affecting entire villages. Landslides primarily develop on the Schists Fm., with multiple movements ranging from the slope-scale to single block slides of marbles.

In summary, it is crucial to conduct thorough geological and geomorphological surveys to ensure the accurate interpretation of information obtained from the remote sensing analyses. With the increasing utilisation of InSAR and other advanced technologies in recent years, there is a significant risk of only detecting active landslides at the time of data acquisition,

underestimating their true extent. Without detailed geological, structural, and geomorphological data, erroneous interpretations can occur, rendering effective landslide risk assessment impossible. For the studied rocky coasts, the combination of field surveys and remote sensing techniques applicable to that area proved to be successful in obtaining the “big picture”, which is the comprehensive overview of active, quiescent, and inactive landforms and of the numerous processes shaping the rocky coasts.

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