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Geomorphological assessment as basic complement of InSAR analysis for landslide processes understanding

Abstract Landslide research has benefited greatly from advances in remote sensing techniques. However, the recent increase in available data on land surface movement provided by InSAR techniques can lead to identifying only those areas that were active during data acquisition as hazardous, overlooking other potentially unsafe areas or neglecting landslide-specific geological settings in hazard assessments. Here, we present a case study that serves as a reminder for landslide researchers to carefully consider the geology and geomorphology of study areas where complex active movements are detected using InSAR technology. In an area extensively studied using InSAR and UAV-related techniques, we provide new insights by applying classical approaches. The area is the coastal stretch of La Herradura, and its importance lies in the fact that it has served as an illustrative example in the Product User Manual of the European Ground Motion Service, a platform that provides ground motion data on a European scale. Our approach is to revisit the area and carry out qualitative geological and geomorphological assessments supported by UAV surveys and GIS spatial analysis on a broader scale than previously published investigations. Our classical approach has yielded the following new observations, crucial for risk assessment and land management: active landslides identified by InSAR techniques since 2015 are bodies nested within large mass movements that affect entire slopes. A variety of processes contribute to slope dynamics, such as large slumps, marble rock spreading and block sliding, and surface rock falls and topples. The revised delineation of the landslide bodies reveals an area almost five times larger than previously mapped. These new findings in a well-known area highlight (1) the importance of updating and downscaling previous maps and (2) the ongoing importance of classical fieldwork and desk studies as basic complements to modern InSAR analyses.

Keywords Geomorphological mapping · Rocky coast · InSAR · Landslides · Block sliding

Introduction

The knowledge of the geomorphological processes of an area is fundamental to understand changes in the territory for risk identification and mitigation as well as urban development (Howard 2013; Sreenivasan and Jha 2022). In the present day, geomorphological assessments are assuming an increasingly important role in supporting engineering geology (Hearn 2019; Laimer 2021). Contemporary remote sensing methodologies are facilitating the acquisition and analysis of spatio-temporal data. In this sense,

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 common tools for geological and geomorphological mapping and ground characterization.

The increasing accessibility of remote data, now readily available, may lead to base landslide research mainly on remote sensing information alone. However, it is crucial always to consider the specific geological and geomorphological conditions, which can only be known by developing comprehensive studies integrating classical field surveys and desk studies with remote sensing analyses as Griffiths (2019) or Hearn (2019) point out. In the landslide research environment, fieldwork and desk study are considered essential for obtaining sound results but, as methodological procedures, these classical techniques nowadays have been relegated to a secondary role. In some cases, field work is perceived laboriousness or difficult to develop in the time frames within which contemporary science operates. This particularly occurs under challenging conditions due to field accessibility problems of diverse nature and, in this case, fieldwork is reduced and left out of the picture to only underscore the technologies or methods applied to analyze data acquired by remote sensors. In our experience in other professional spheres, classical approaches are sometimes considered obsolete if not coupled with new technology or dismissed when there is existing data in the study areas. In the latter scenario, problems may arise as the prior information may be outdated or not refined to the necessary detail required by the research scale. Although classical approaches remain theoretically fundamental for the surface dynamics scientific community, there is a growing trend in practice to decrease the focus on qualitative information acquired by classical techniques such as geological and geomorphological observations, although, it is widely accepted that this information is a basic complement to remote sensing analysis in order to interpret results, and it should be given its due importance. Here, we present a case study that reflects the above described, in which some authors of the study themselves have realized that they overlooked a more general research based on classical surveys in an area extensively studied using InSAR and UAV technologies. Observations obtained through traditional approaches, which aim for a thorough understanding of the terrain of the study area, have yielded a more detailed model of the geological context that helps to interpret the ground motion detected by InSAR techniques. Through this study, we can highlight

the importance of considering the "big picture" and updating geological and geomorphological data for an accurate diagnosis of an area affected by complex landslides.

Background of the case study

Remote sensing techniques play a crucial role in assessing coastal areas (Sreenivasan and Jha 2022). These regions, characterized by high population density, cultural significance, valuable ecosystems, and critical freshwater resources face substantial impacts from many interactions between natural and human processes. Global Change factors, including sea-level rise, escalating aridity, and intense and sudden rainfall (López-Fernández et al. 2022), further contribute to the challenges. In this context, one of the most human-altered areas globally is the Mediterranean shoreline (Falcucci et al. 2007), with half of it composed of rocky coasts (Furlani et al. 2014), where unstable slopes are common (e.g., Mantovani et al. 2016; Polcari et al. 2018; Svigkas et al. 2020). Identification and monitoring of coastal landslides are a priority in this setting, and the research using remote sensing techniques focused on the coast of Granada province in the Mediterranean shoreline of Southern Spain has attracted international attention on this topic (Notti et al. 2015; Galve et al. 2017; Mateos et al. 2017; Barra et al. 2022). So much so that the European Ground Motion Service (EGMS), a Europe-wide project on InSAR applications, has taken this stretch of coastline as one of its example cases to show the results of the service (Crosetto et al. 2020; Kotzerke et al. 2022). The EGMS is an ambitious initiative of the Copernicus Land Monitoring Service (CLMS) that provides information on ground motion 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. This initiative is focused on providing ground motion data, but the interpretation of the results is the concern of those who use the platform.

The present study returns to the abovementioned stretch of the Granada's coast, albeit with a complete approach that underlines the importance of classical geomorphological assessments as an important asset for remote sensing studies. For that, in-depth geological-geomorphological surveys have been conducted in the La Herradura section revealing meaningful changes in the previous interpretations of the ground movements detected by InSAR and photogrammetry (Notti et al. 2015; Galve et al. 2017; Mateos et al. 2017; Barra et al. 2022). This contribution includes a wide range analysis of the landforms, as well as a comprehensive geomorphological map, which serves as a basis for the subsequent interpretation of the movements detected by the aforementioned techniques. In that sense, we have (i) enlarged landslide extensions compared to the previously mapped landslide area and, amongst other observations, (ii) determined the process underlying a deformation of unknown origin detected by Notti et al. (2015). These two points have important implications for land-use planning, urban development, the design of structural engineering measures as well as superficial and groundwater management, especially considering the occurrence of local aquifers within marble units (Andreo et al. 2018; Montiel et al. 2018) affected by slope instabilities. The main purpose of this work was to refine the conceptual model of landslides along the coastline of La Herradura to validate

interpretations derived from EGMS, which will also help to design effective landslide mitigation measures there and in other coastal areas around the Globe.

The results of the work hold particularly significant, especially considering that previous research, including contributions from some authors of this paper, extensively examined the study area in recent years, leading to the perception that the area was fully understood from a geological/geomorphological point of view. It appeared that existing knowledge and evidence regarding the landslides in La Herradura were comprehensive and conclusive, leaving little expectation for significant new discoveries. However, it is crucial to note that previous research has relied on prior information based on 1:50,000-scale geological maps and site-scale geomorphological assessments that did not allow the geomorphic "big picture" to be seen. This is the first medium-scale geomorphological assessment of the area that brings to light new aspects of the slopes. The new perspective gained from this assessment has the potential to reshape the interpretation of monitoring data in an area of high interest for InSAR studies, particularly within the EGMS.

Study area

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 coastal sector under study shows a NW-SE orientation, with local N-S variations due to the promontories morphology (Fig. 1). It is characterized by a Mediterranean climate, a humid temperate climate with dry and hot summer (Csa, according to the Köppen-Geiger classification) (Cunha et al. 2011), 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, the coastal orientation, and 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 Junta de Andalucía 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. 1);
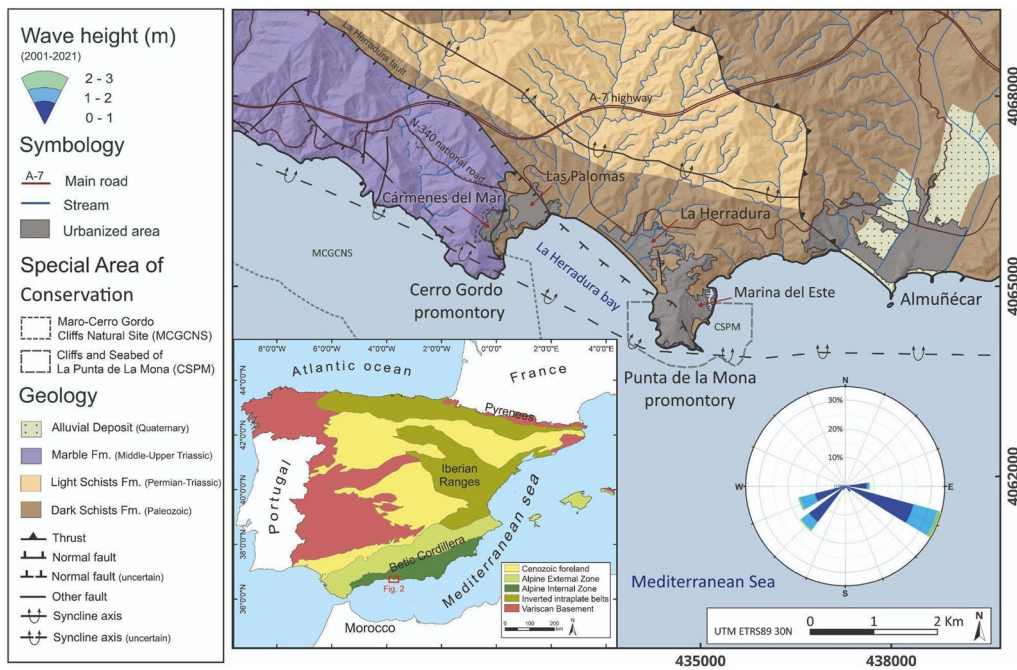
Fig. 1 La Herradura coastal section, showing major urban areas, main roads (A-7 highway, N-340 national road), and special conservation areas. The map of Spain with zones of Betic-Rif orogen is after Moragues et al. (2021). The geological map is after Marín-Lechado et al. (2009). La Herradura fault is after Ruano (2003) and Ruano et al. (2004). Preferred wave movement direction in percent and wave height by colour range in the range 2011–2021 (is from State Port, Ministry of Transport, Mobility and Urban Agenda of Spanish on https://www.puertos.es/es-es)

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).

Geological and geomorphological setting

La Herradura coastal sector is settled in the Alpujárride Complex, formed by deformed metamorphic rocks belonging to the Alboran Domain of the Betic Cordillera (Azañón et al. 1994; Azañón and Crespo-Blanc 2000). The main structures of the Alpujárride Complex are Alpine regional-scale anticline folds, with a mean E-W trend and NW vergence (Simancas and Campos 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-Zaldívar 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): (i) Dark Schists Formation (Fm.), dark-coloured schists and graphitic micaschists (Paleozoic), 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 1993). The normal fault displaced the Marble Fm. belonging to the hanging wall towards the S-SW.

Marble Fm. is classically considered a karst aquifer with high fissuration and a 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 (Sunamura 2015), which reaches a depth of over 40 m below the sea level (Consejería de Medio Ambiente y Ordenación del Territorio Junta de Andalucía 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/run-off processes in slopes. Slope processes involve prominent landslides impacting Cármenes del Mar and Marina del Este resorts (Fig. 1). 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).

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), analyzing 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, the most studied is Calaiza landslide previously reported by several unpublished geotechnic studies, by Landslide Database of the Spanish Geological Survey (CN IGME 2016), the inventory of the Granada Province (Chacón et al. 2007) and by Azañón et al. (2016), Mateos et al. (2017), Chacón et al. (2019), and Barra et al. (2022). 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, Marina del Este and Peñón del Lobo landslides were reported by unpublished geotechnic studies, Chacón et al. (2007), CN IGME (2016), Azañón et al. (2016) and Notti et al. (2015); 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 the Marina del Este and Punta de la Mona landslides from November 2015 to May 2020, using InSAR techniques and without delimiting landslide extension, both with LOS average displacement rates ranging from − 10 to − 20 mm/yr. The ground displacement was inferred to be 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 the Product User Manual of EGMS (Kotzerke et al. 2022; Crosetto and Solari 2023).

Materials and methods

The geomorphological and geological map of La Herradura coastal section was carried out 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. The cartography 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 DInSAR studies.

The approach used for this study involved consulting the literature, geotechnical reports, and historical pre-urbanization aerial images. Geological and geomorphological terrain models were developed based on various in situ and remote sensing surveys. Moreover, a comparison was made with studies that investigated the same areas using InSAR data from the EGMS Explorer (European Environment Agency 2023). The calibrated displacement data in ascending and descending orbits from the period January 2018–September 2022 were downloaded by using the EGMStream app (Festa and Del Soldato 2023), which facilitated the data management. For both geometries, the stability range was established as two times the standard deviation of the data (Barra et al. 2017), and satellite Line-Of-Sight (LOS) velocity maps were displayed. Moreover, the average time series of accumulated displacement of the main unstable areas was extracted and analyzed.

In the laboratory, aerial photography, land, and submarine Digital Elevation Models (DEM), and previous geological maps were performed and analyzed using ArcGIS 10.8.2 (ESRI®, 2022/2023-licensed "DISPEA University of Urbino"). Aerial photos were downloaded by the National Geographic Institute (IGN) of Spain (https://centrodedescargas.cnig.es/; https://fototeca.cnig.es/fototeca/) resulting from photogrammetric flights conducted by the USA 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 landslide 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 DEM with a 1 m cell-size resolution. Data for bathymetric reconstruction were downloaded from the 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 analyzing also the hillshade model derived by the DEM and were later verified by fieldwork carried out from September to December 2022. The landslide mechanisms were classified according to Cruden and Varnes (1996) and Hungr et al. (2014). The field surveys were novelty supported by UAV flights to visualize hard-to-reach spots such as the rocky cliffs along the coast. The drone model used 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. Mobile device applications (e.g., FieldMove Clino) were also utilized to collect data directly in digital form.

Results

Desk study and field investigations provided the first comprehensive geological-geomorphological map of La Herradura coastal section at a scale of 1:20,000 (Fig. 2). Three landslides (named Cantarriján, Calaiza, and Las Palomas) have been identified, surveyed, and/or studied in Cerro Gordo promontory. Additionally, four major instabilities (namely Playa, Punta de la Mona, Marina del Este, and Peñón del Lobo landslides) have been delimited and studied in the surroundings of Punta de la Monta promontory. 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. 3). The studied instabilities are affecting or could impact resorts, infrastructures (highway, national road) and other urban areas. Subsequently, we compared the results with previous works that have analyzed only some of these landslides, particularly through InSAR data.

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 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°. 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. 4a, and the corresponding improved geological-geomorphological map (Fig. 4b) shows a zoom of Fig. 2. Here, Dark Schists Fm. has been identified in areas previously mapped as Marble Fm. in previous works. Moreover, we observed that Paleozoic Dark Schist Fm. lies over the Marble Fm. through a contact of tectonic origin. This evidence and the absence of the Permian-Lower Triassic Light Schists Fm. (which stratigraphically appears between the Marbles and the Dark Schists
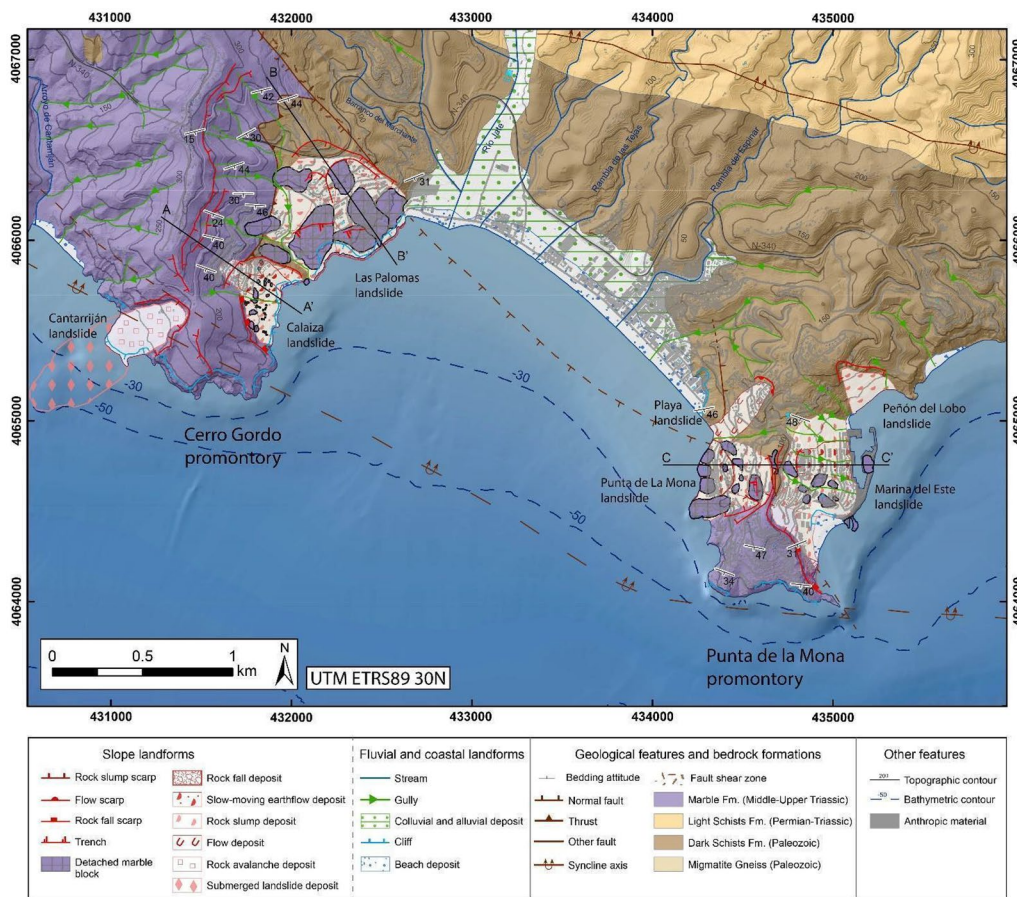

Fig. 2 Detailed geological and geomorphological map of La Herradura coastal section. Bedrock geology is after Avidad et al. (1973) and Marín-Lechado et al. (2009). In the legend and in the map light-coloured features remain inactive/quiescent, dashed-line features are supposed/uncertain, and barbs (in normal fault) and triangles (in thrusts) are in the hanging wall
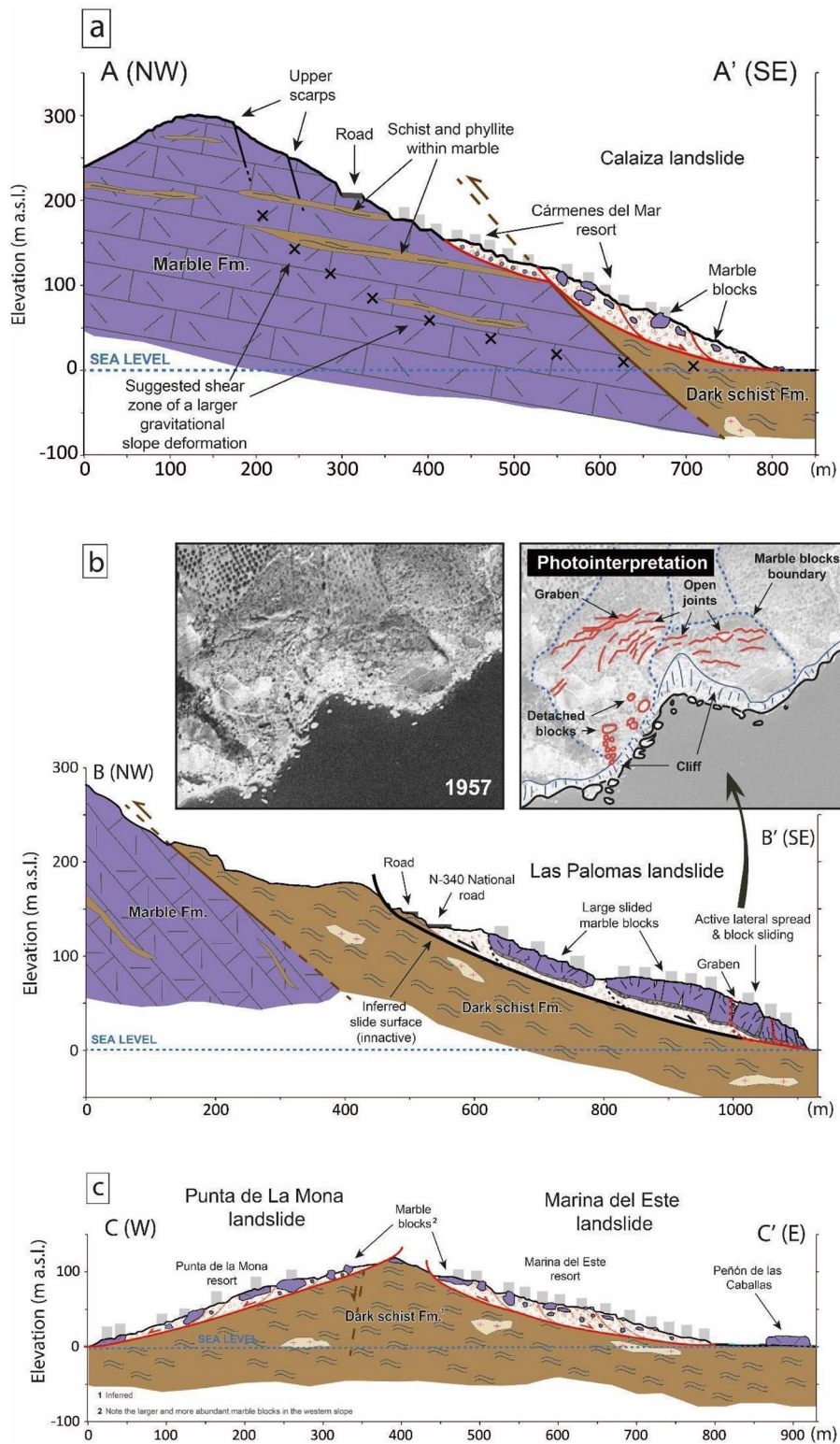
Fig. 3 Geological-geomorphological cross-sections along La Herradura coastal section. The legend and position of the sections are depicted in Fig. 2 and the zoom position of the aerial image in profile b can be seen in Fig. 4a. **a** Cross-section along the active Calaiza landslides, where Cármenes del 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 times exaggerated. **c** Cross-section along Punta de la Mona promontory exhibiting active Punta de la Mona and Marina del Este landslides
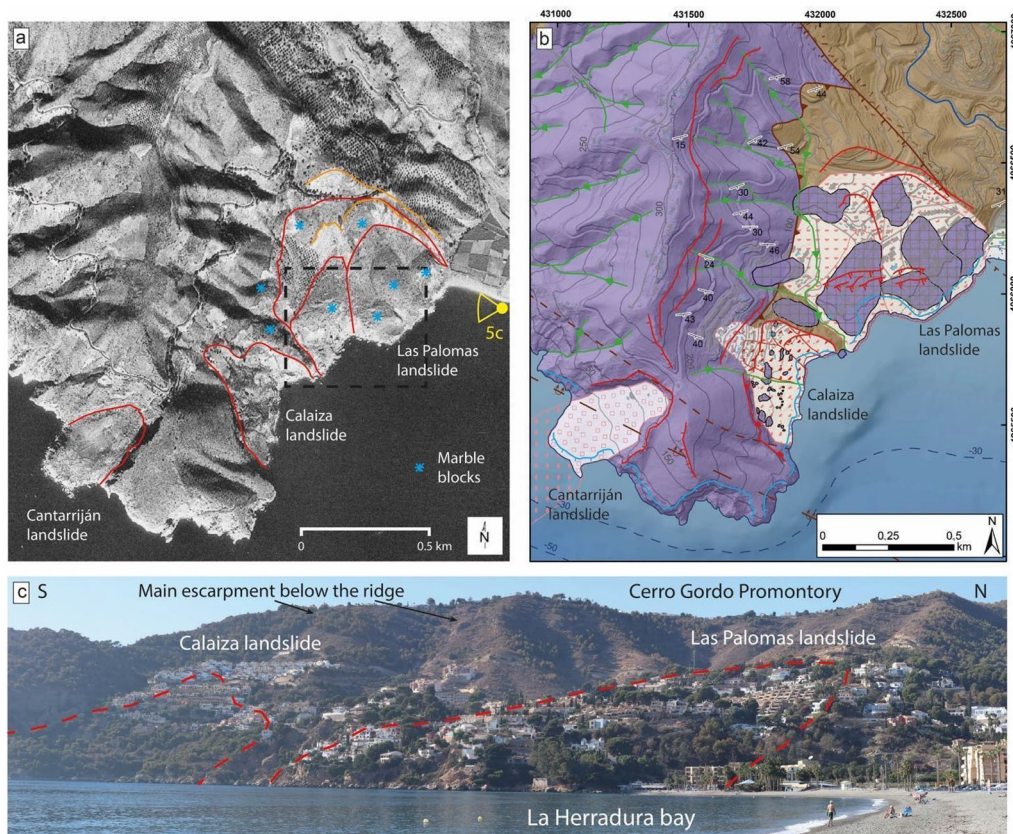
Fig. 4 a Aerial image of 1957 exhibiting landslides and their detachment areas, where the landslides are clearly visible without anthropization. Continuous red lines indicate landslide bodies, orange lines indicate the detachment areas, black rectangle indicates zoom in Fig. 3b; **b** Zoom of the geological and geomorphological map (Fig. 2) on the Cerro Gordo promontory. The survey details each single slipped block of marble. The legend for **b** is in Fig. 2; **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**

Fms.; Azañón and Crespo-Blanc 2000) suggest 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.

Cantarriján landslide stands out in the western slope of the Cerro Gordo promontory (Fig. 4). This inactive landslide is a rock avalanche, has a minimum volume of 3×10^6 m³, and produces a significant effect on the littoral relief and the bathymetry until the depth of -50 m visible in the Visor de Cartografiado Marino (https://sig.mapama.gob.es/marino/). 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 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. 8×10^5 m³, and its cartography has been updated in our work (Figs. 2, 3, and 4). Lateral spread and block sliding of marble blocks with volumes over 300 m³ (within and above the landslide) have been detailed in the southernmost sector, detached from the 25 m height escarpment (Fig. 5a–c), some of them already mapped by Mateos et al.

(2017). Just below the ridge, two escarpments have been discovered using the hillshade model of 1 m resolution and later confirmed by fieldwork (Fig. 5d). The uppermost, with an approximately 10 m height and a N30° E mean direction can be recognized along the entire slope (Fig. 4b). 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. 4a) 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. 5e), 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
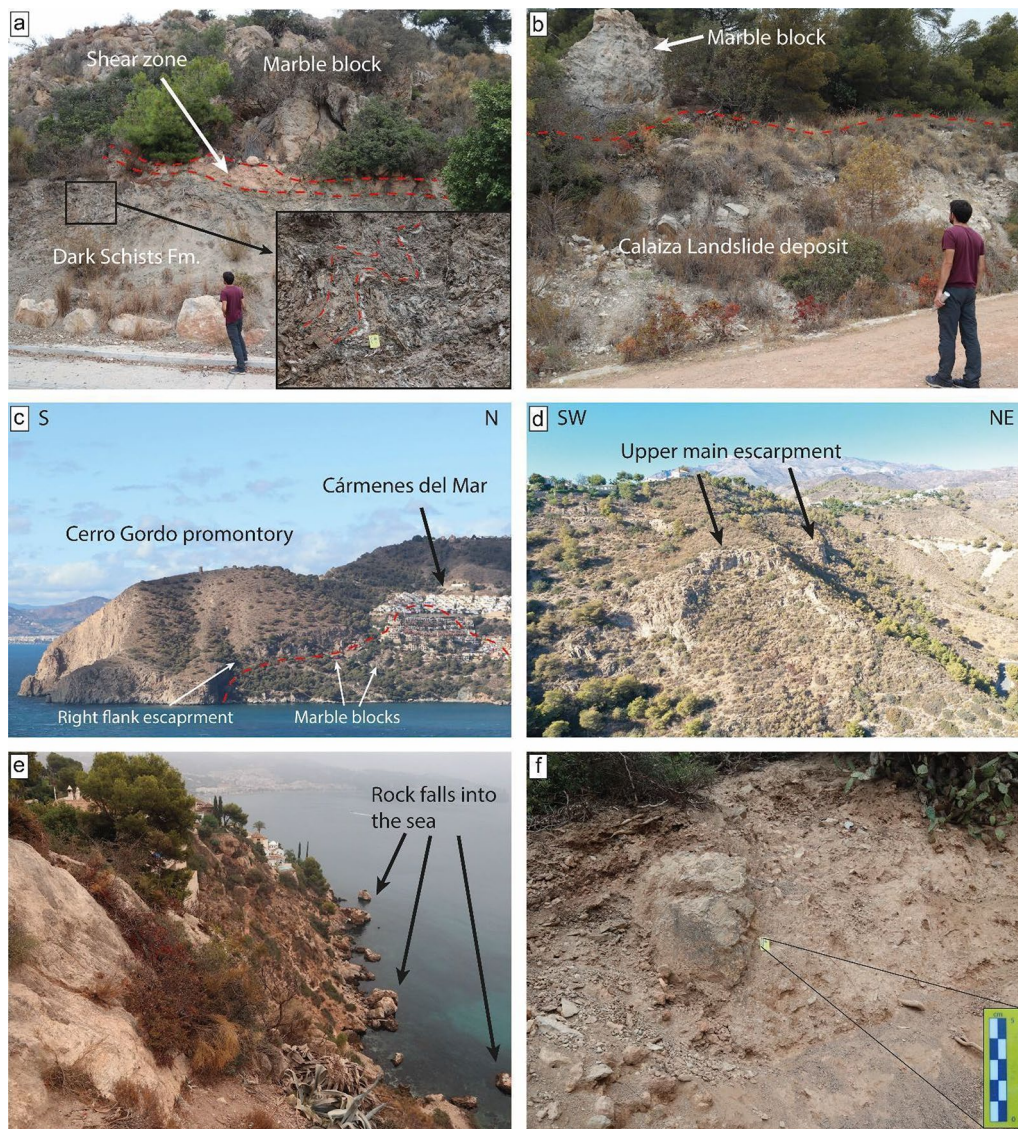
Fig. 5 a Contact between a detached marble block and the Dark Schists Fm. marked by a shear zone made of a sandy gouge. In the insert frame are visible drag folds in the foot of the deformation zone; **b** Marble block detached from the escarpment **c** and slipped above the Calaiza landslide deposit 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

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 nested movements of marble block local lateral spreads and block slides (Figs. 3b and 4b). With an estimated minimum volume of about 6×10^6 m³, the main body involves a large part of the slope reaching the N-340 national road. The crown, which is not very discernible within the landscape, encompasses the two different types of nested bodies, with the largest gravitational process that involves the entire slopes with a very large and deep sliding surface (Fig. 3b). 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. 5f) 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.

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. 5a). 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. 5a). 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 Fig. 5a). 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.

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

Punta de la Mona promontory (Fig. 6) 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. 7a). 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. 6a). This is also

related to the lower altitude of the promontory itself, which reaches about 126 m in contrast with over 300 m of the Cerro Gordo cape.

Landslides involve both sides of the Punta de la Mona promontory, which is heavily urbanized. Two landslides are now being analyzed 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 and is characterized by active superficial reactivations in its central part, 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. 7b). In the northern part of the western flank, Playa landslide was recognized, 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, the Marina del Este landslide shows a minimum volume of about 2.5×10^6 m³ and has been much studied in geotechnics 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. 7c), vertical fractures, and detached large marble blocks up
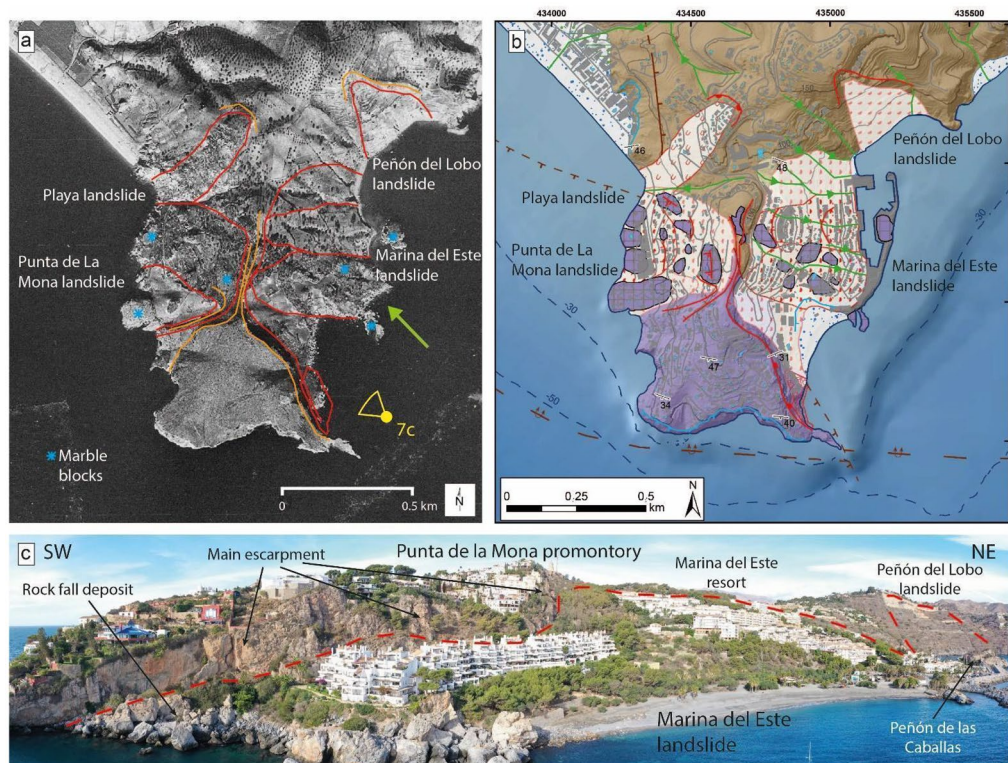

Fig. 6 **a** Aerial image taken in 1957 exhibiting landslides and their detachment areas, which are easily recognizable in the pre-urbanized Punta de la Mona promontory. Continuous red lines indicate landslide bodies, orange lines indicate the detachment areas, the green arrow indicates the part of the body landslide flattened for the parking; **b** Zoom of the geological and geomorphological map (Fig. 2) 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. 2; **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**

Fig. 7 **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 (dashed orange line) 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

to 100 m in diameter such as the Peñón de las Caballas block in the marina (Fig. 7d).

Looking at the aerial images of the 1957 flight, it is clear how the promontory was modified when the resorts were constructed (Fig. 6a). For instance, the bottom of the Marina del Este landslide was flattened for the construction of the harbour car park (green arrow in Fig. 6a) or the 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, mapped in detail in the geological-geomorphological map (Fig. 6b). 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.

EGMS InSAR data in La Herradura coastal section

Figure 8 shows the InSAR calibrated data in ascending and descending orbit, extracted from the EGMS, at the Cerro Gordo (Fig. 8a, b) and Punta de la Mona (Fig. 8c, d) promontories. The stability range was settled from 2.5 to − 2.5 mm/yr for both geometries. All the landslides exhibit ground motion through at least one geometry, with the exception of Cantarriján, Las Palomas, and Peñón del Lobo landslides where clear ground displacement was not captured. The LOS maximum velocity registered in ascending orbit is 14 mm/yr in the Calaiza landslide (Fig. 8a), while in descending geometry, LOS velocities reach 15.3 mm/yr in the Punta de la Mona landslide (Fig. 8d). The average velocities of the Calaiza, Punta de la Mona, and Marina del Este landslides range from 3.5 to 8.1 mm/yr (absolute values), while the Playa landslide shows a lower mean LOS velocity of − 2.8 mm/yr. Moreover, the displacement pattern provided by EGMS in these four landslides follows a linear and constant trend during the measured period of time
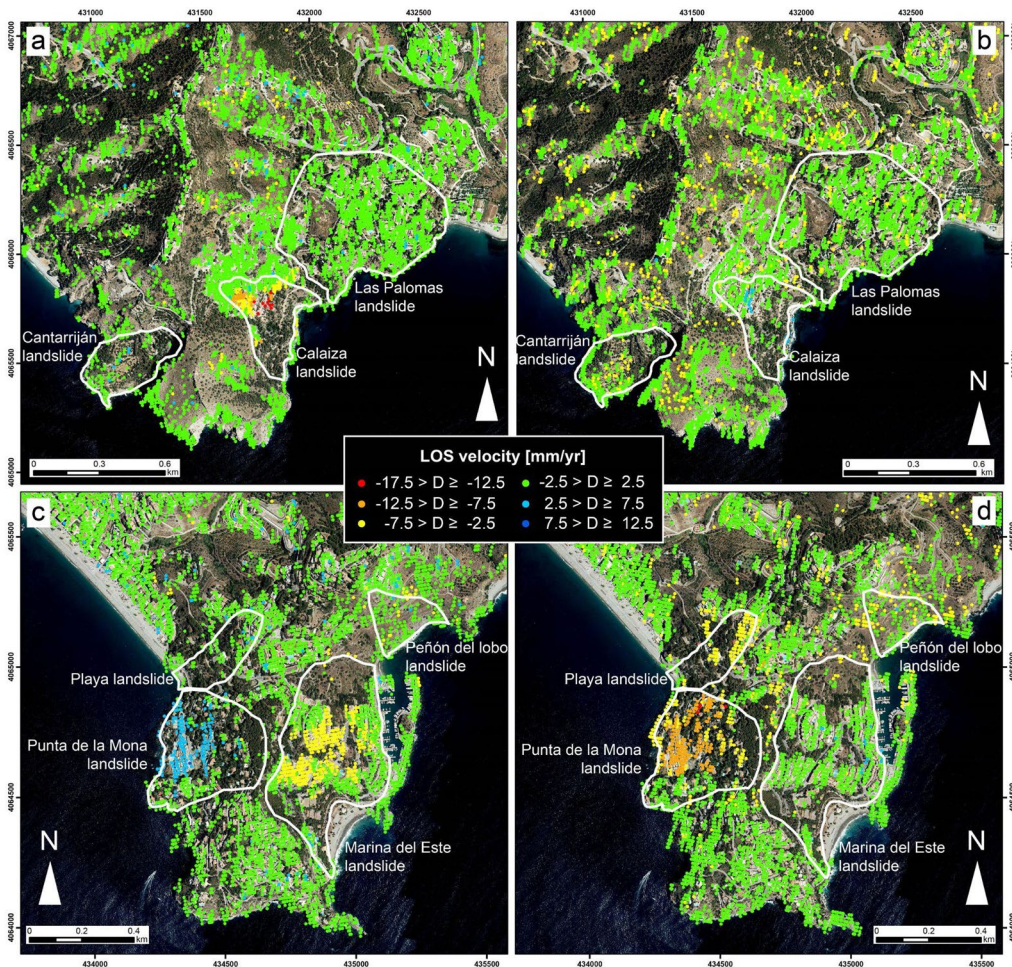
Fig. 8 Line-Of-Sight (LOS) velocity maps in ascending (**a**) and descending (**b**) orbits in the Cerro Gordo promontory; and in ascending (**c**) and descending (**d**) orbits in the Punta de la Mona promontory (data downloaded from https://egms.land.copernicus.eu/). The main landslide boundaries delimited in this research (Fig. 2) are also indicated in order to compare current active areas according to EGMS with the entire area of landslides

(from January 2018 to September 2022), as evidenced by the time series of accumulated displacement (Fig. 9). There is no significant acceleration of the movement in any of the landslides, and the total LOS accumulated displacement is up to − 30 mm in the Calaiza (Fig. 9a) and Punta de la Mona (Fig. 9b) landslides, in ascending and descending orbit, respectively.
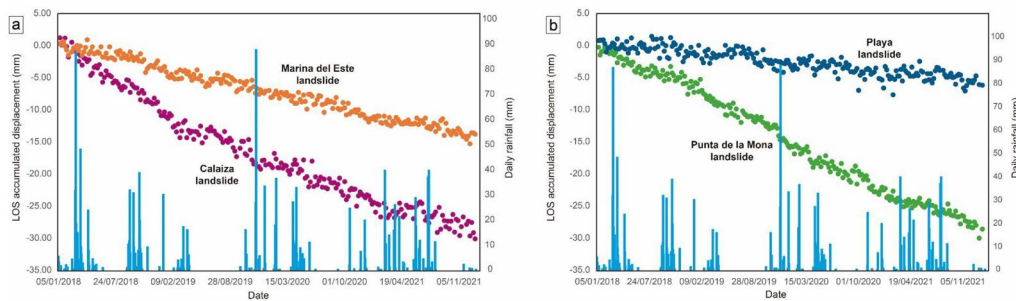

Fig. 9 Times series of accumulated displacement, measured along the satellite Line-Of-Sight (LOS), of the Calaiza and Marina del Este landslides in ascending geometry (**a**) and Punta de la Mona and Playa landslides in descending orbit (**b**). In both graphs, daily precipitation recorded by the closer meteorological station of the Spanish State Meteorological Agency (Station Salobreña 6267X, 36°44′54″ N 3°34′43″ W) to the study area is represented. No clear accelerations of landslide displacements are observed in relation to daily rainfall peaks or periods of prolonged rainfall in the timeframe analyzed

Discussion

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. 2) and cross-sections (Fig. 3a, 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 (utilizing high-resolution aerial images, LiDAR DEM, and an extensive field survey supported by UAV technology) 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. 10. 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. 10a) 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. 10b.

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 characterized 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 hypothetic shear zone in depth (Fig. 10a). The scarps would be formed by a gravitational process, and it 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 characterize the Alpujarride 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 old 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 the Punta de la Mona promontory (Fig. 10b) 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. 6b). 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.

As can be seen, the evolution of both promontories is very similar, with equal 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 (Figs. 4 and 6). Due to the development of major discontinuities (Fig. 7c) 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. 10). 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). In the La Herradura coastal section, we present one of the few comprehensible examples of 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. 1).

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 2×10^5 m^2. According to our surveys and to the new landslide mapping, the landslide area would amount to about 1×10^6 m^2, five times more extension than the previously mapped landslides (Fig. 11). It is important to clarify that not all the areas affected by landslides are presently exhibiting clear signs of instability.
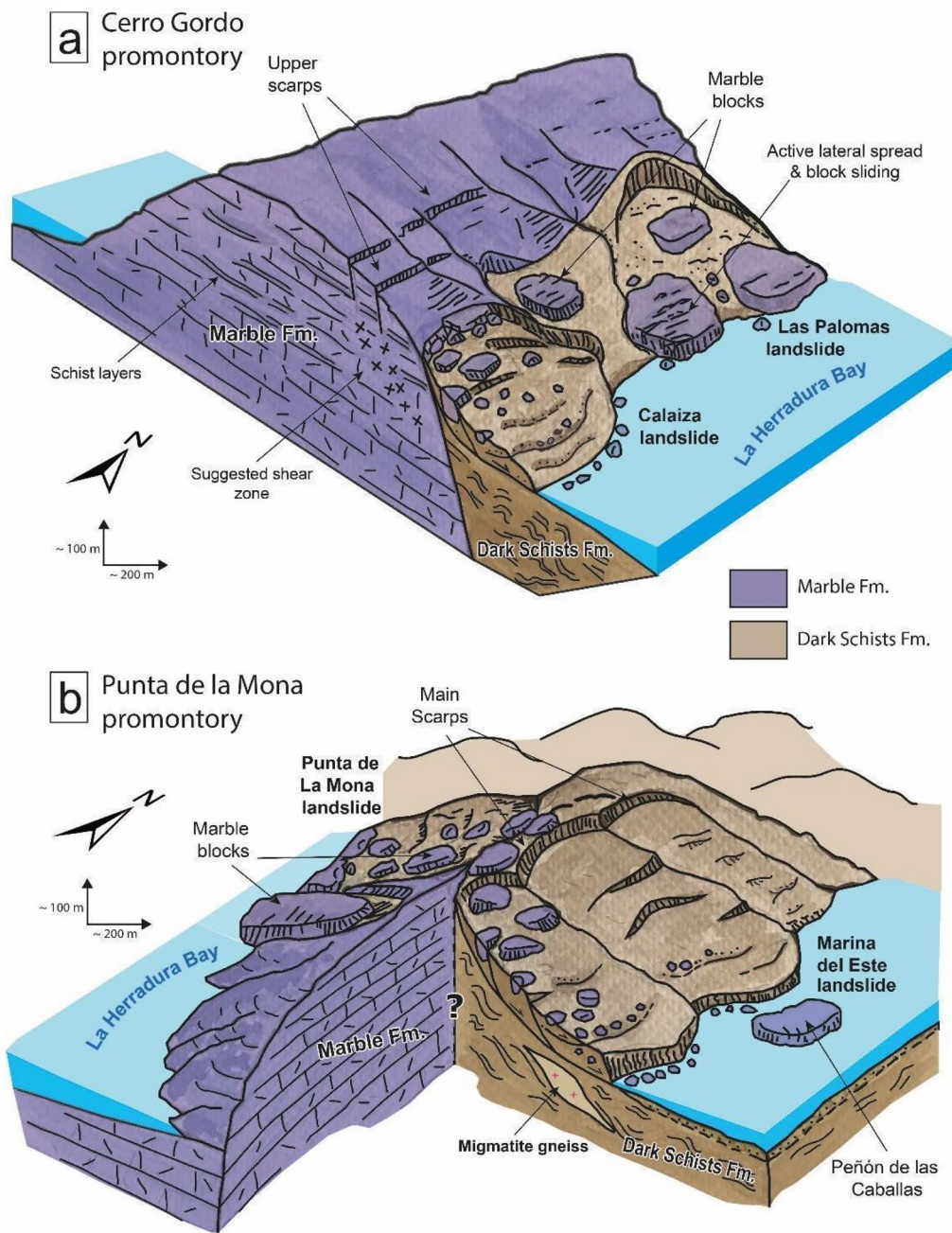
Fig. 10 Conceptual landscape model. 3D illustrations show the morphodynamic style that characterizes the promontories of Cerro Gordo **a** and Punta de la Mona **b**. In addition to the large landslides present, the process of lateral spreading and block sliding is highlighted. For some features (such as marble blocks or detachment areas) vertical scale is exaggerated more or less two times for a better view of the single block

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. These extraordinary events could also alter the linear constant trend of the active landslides (Fig. 9) and trigger catastrophic accelerations of these movements as it has already occurred in the extraordinary wet period between 2009 and 2010 (Notti et al. 2015; Chacón et al 2019).

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 analyzing the activity, speed, and extent of landslide displacement with all the latest techniques, particularly remotely and from the geotechnical point of view. By concentrating only on
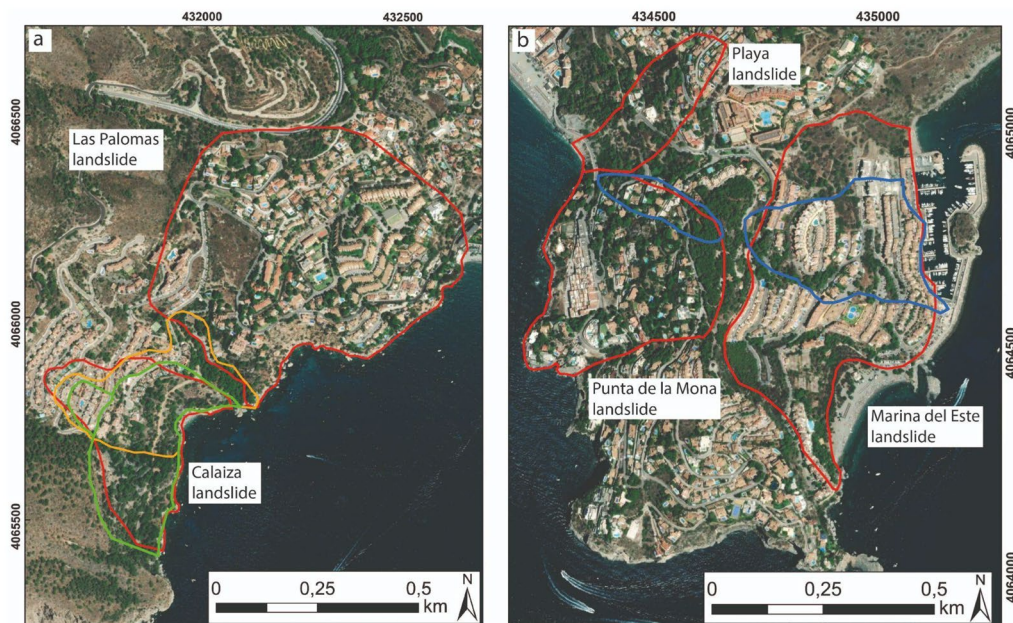
Fig. 11 Comparison of landslide boundaries defined by this study (red lines) and previous works (blue lines Notti et al. 2015; orange lines Mateos et al. 2017; green lines Chacón et al. 2019) in both Cerro Gordo (**a**) and Punta de la Mona (**b**) promontories. It is clearly visible how the use of different techniques leads to a much more defined picture of an area, mapping not only the active landslide portions but also those that could reactivate

the analysis of the abovementioned things and not carrying out a detailed geological and geomorphological survey at the scale of the entire slope, the basis on which all the following analyses can then be carried out has been lacking. This is also partly demonstrated by the Las Palomas landslide. It is noteworthy that photointerpretation of historical images allowed the novel identification of the latter 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. 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. 3b). 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 seems to be inactive, which is also indicated by the calibrated EGMS InSAR data (Fig. 8), as movement has not been detected 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 of 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. 12). 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.

Thanks to the geological and geomorphological field survey, the use of multi-temporal aerial images and 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 scientific papers, which describe researches in this coastal section apply advanced technologies, through the methods used, work products, and results obtained. Notti et al. (2015) have analyzed landslides in Punta de la Mona promontory using Permanent Scatterers (PS)InSAR technique, mapping all the active processes and made a building damages assessment; furthermore, they compared recent photos with historical pre-urbanization images but focalizing only on the active portion of Marina del Este landslide. Mateos et al. (2017) have examined the Calaiza landslide on Cerro Gordo promontory combining PSInSAR and UAV photogrammetry; they mapped the active landslide deposits and smaller, shallower marble blocks, studied the recent reactivations of the landslide body in relation to exceptional rainfall events, and compiled a building damages inventory. Chacón et al. (2019) focused on the Calaiza landslide, meticulously describing all the interventions carried out to stabilize the slope over the years and compiling an inventory of damages. Barra et al. (2022) chose the two promontories as study areas, starting from the PSInSAR data and providing a map of damages for the Calaiza, Punta de la Mona, and Marina del Este landslides while always considering recent activity. The application of a large variety of remote sensing techniques but
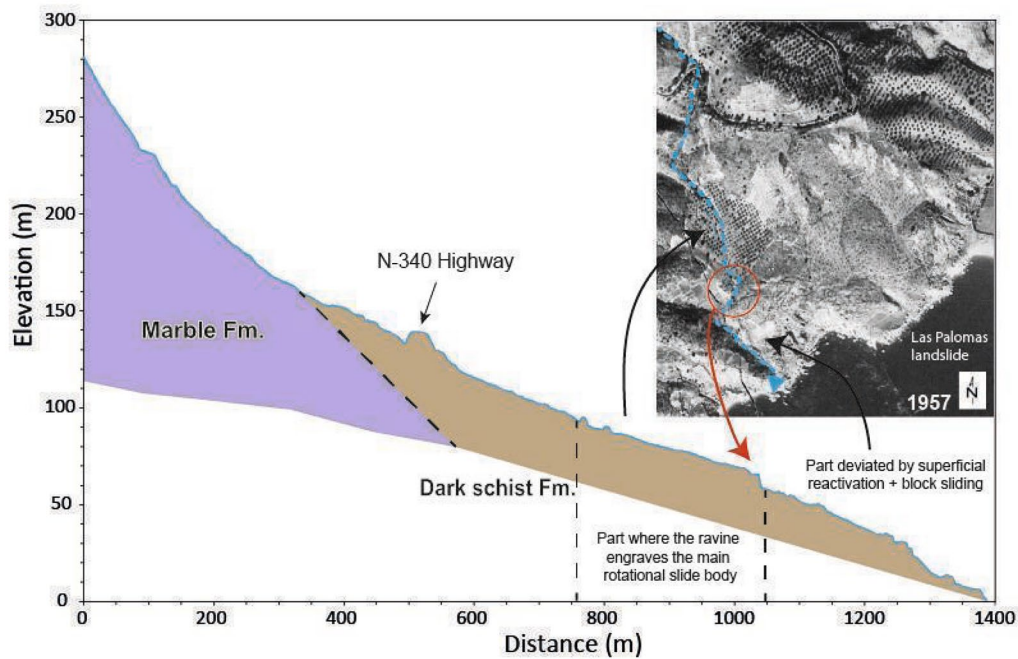
Fig. 12 Longitudinal profile of a ravine perturbated by Las Palomas landslide. The red arrow shows a relief anomaly (sharp slope) defined by a profile-changing curvature. Other relief anomalies are related to anthropic works. In the aerial image, the diverted path of the impluvium is clearly visible (red circle)

without the knowledge provided by a more extensive survey (Notti et al. 2015; Mateos et al. 2017; Chacón et al. 2019; Barra et al. 2022) allowed to describe in detail only 40% of the existing landslides in La Herradura coastal section (Fig. 11). All the landslides previously reported correspond to active instabilities, which occurrence is also evidenced by damages observed in urban areas. However, the geological and geomorphological mapping at the 1:20,000-scale conducted in our work has enabled the identification of additional landslide bodies in the same area. It is crucial to consider the occurrence of a priori 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), but these researches do not link these blocks with the landslides' dynamics. Two escarpments have been also discovered in Cerro Gordo promontory through field-work, suggesting the development of a major potential instability that affects the entire slope.

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 Land Surface Quantitative (LSQ) analysis based on high-resolution DEMs, 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, researchers in previous works were able to identify active zones where imperceptible movements developed. In this sense, active landslides can be remotely analyzed, monitored, and mapped using InSAR data and nowadays, more easily through web-based digital platforms that provide already processed data (Galve et al. 2017; EGMS 2023). By exploiting the InSAR data from the EGMS Explorer (Fig. 8), it can be seen that ground displacement is registered in the most important landslides described in this work: Calaiza, Playa, Punta de la Mona, and Marina del Este. Notice that the detection sensitivity varies between the ascending and descending orbit data, and displacement is not equally captured in both geometries for all landslides. In this regard, the availability of InSAR data in the two geometries of the EGMS was truly valuable, preventing the oversight of active landslides that could be undetected using a single geometry. However, as demonstrated by this study, all the aforementioned techniques are complementary. Each one provides information at

Table 1 Comparison table between the present work and previous works in the La Herradura coastal section. Only 40% of the landslides evidence and processes were detected and mapped by previous works, even those that had not been identified because they showed in the present day no activity

				Notti et al. (2015)	Mateos et al. (2017)	Chacón et al. (2019)	Barra et al. (2022)	This work
Methods	Interferometry	InSAR[a]		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		x
		Damages inspection		x	x		x	
	Landslides activity	Active processes		x	x	x	x	x
		No evidence of active processes						x
Products	Products	Geomorphological assessment						x
		Geological map			x			x
		Geomorphological map		x				x
		Building damages inventory		x	x	x	x	
Results	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[b]					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

[a]InSAR data produced by the authors

[b]Peñón del Lobo landslide was already mapped by Chacón et al. (2007) in their inventory of the Province of Granada

varying spatial and temporal scales with precisions that collectively enable a more certain diagnosis of slope conditions.

In conclusion, the present work shows 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 understanding ground motions detected by InSAR techniques and developing accurate conceptual models of slope instabilities. Furthermore, 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 data 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.

Conclusion

A new comprehensive conceptual model has been developed for the La Herradura coastal section, which serves as an example case in the landslide paragraph of the Product User Manual of the EGMS. The model incorporates instability mechanisms and their extension in relation to the lithology and structure of the bedrock. The conceptual model identifies three main types of instabilities: (i) a deep rock slump movement occurring along a failure surface at a depth of 20–40 m, (ii) surface movements resulting from slow-moving earth flows, lateral spreads, and sliding of large marble blocks resembling ploughing boulders found in periglacial environments, and (iii) local toppling and rockfall processes involving scarps and detached marble blocks. Furthermore, a potential major movement affecting the entire slope has also been deduced. All these landslides are associated with the tectonic contact between Triassic marbles and Permian-Triassic schists. Intensive schist weathering has resulted in a surface deposit with a more plastic behaviour, facilitating the sliding of marble blocks. These blocks were detached following the natural bedding, tectonic foliation, and fissures of the marble, which derived from an intense tectonic deformation.

The development of a new comprehensive model was made possible through an in-depth geological and geomorphological investigation supported by fieldwork, historical and recent aerial photography (1956–2022), a LiDAR 1-m resolution DEM, and advanced technologies such as unmanned aerial vehicle (UAV) imagery and InSAR. The geological map was meticulously revised with the study objective in mind, and the geomorphological mapping focused specifically on slope processes. These techniques have led to the discovery of previously unknown landslides along the La Herradura coast, which were not detected using remote sensing alone over the past two decades. Remote sensing methods only identified approximately 40% of the existing landslides, whereas their actual extent is five times greater than previously known. The detailed geological and geomorphological survey also revealed the presence of apparently inactive landslides, some of which have been urbanized. The occurrence of these inactive or quiescent landslides must be considered in land management due to the potential for reactivation resulting from anthropic activities or extreme rainfalls.

In summary, we illustrate the importance of thorough geological and geomorphological studies focused on understanding the context of landslides in ensuring an accurate interpretation of remotely sensed information. This work serves as a call to action for geologists and geomorphologists to meticulously review existing mapping and update it as needed, thereby enhancing the reliability of terrain information and instilling greater confidence in the interpretation of remotely sensed data. It also highlights the growing reliance on InSAR and other advanced technologies, which may lead to a focus solely on areas in motion during data acquisition, potentially underestimating the true extent of landslides as exemplified in the described case study. In this regard, the incorporation of qualitative geological and geomorphological information can prevent misinterpretations, ensuring the effectiveness of landslide risk assessment.

Data availability

The data employed in this work are available on request from the corresponding authors.

Declarations

Competing interests The authors declare no competing interests.

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