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ABSTRACT
Geomorphological mapping is a powerful tool for reconstructing the evolution of landscapes inhabited by human communities since prehistory. We present high-resolution (1:1000) geomorphological mapping of the Balzi Rossi archaeological area (Liguro-Provençal coast, NW Italy), an outstanding site for European prehistory which has been inhabited since the Middle Pleistocene. The map was produced by combining different types of remote sensing data, complimented with field survey. Both surface and submerged landforms are included from 70 m a.s.l. to the depth of ca. 10 m. All elevations were referenced to a tidal datum. The study area comprises a tectonically formed vertical cliff where karst dissolution along faults and fractures created several caves and rock shelters that were later settled by Middle and Upper Palaeolithic human groups. During the Pleistocene, the area experienced significant climatic shifts from interglacial to glacial conditions. Our work will aid archaeologists to unravel the responses of our ancestors to climatic and environmental changes.

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1. Introduction

Earth Sciences are providing a crucial contribution to the understanding of the lifestyle and use of natural resources of archaeological communities, and in this respect, a major role is played by Geomorphology (e.g. Goldberg et al., 2013; Morley et al., 2023). The latter discipline is actively supporting archaeological research by offering an array of tools to reconstruct the evolution of landscapes settled by ancient communities and to understand the interaction between surface processes of weathering, erosion, transportation, and sedimentation, and humans (e.g. Goldberg et al., 2022). This is especially true in the case of prehistoric archaeological sites, preserving evidence of early interactions between human groups and the natural environments, and where humans often adopted survival strategies based on the geological opportunism (sensu Vita Finzi, 1969; Butzer 2008). More explicitly, geomorphological mapping offers the opportunity to identify the major traits of landscapes and reconstruct their evolution, ultimately permitting an understanding of archaeological sites' distribution based on the identification of geomorphological units (landforms and deposits) influencing the development of settlements (Coratza et al., 2021).

One of the regions of the Mediterranean basin settled during the Middle and Upper Pleistocene is the Balzi Rossi coastal area (Liguria, NW Italy, Figure 1), where human communities adapted to exploit natural resources during subsequent phases of rising and lowering sea level in response to global climate change (Ryan et al., 2024). The Balzi Rossi high cliff hosts some caves and rock shelters that presently open very close to the coastline and preserve depositional sequences including natural and archaeological (i.e. anthropogenic) sediments. From the archaeological and palaeoanthropological point of view, the importance of the Balzi Rossi caves and rock shelters is well known due to the findings of human remains and artefacts dating back to the Palaeolithic period (e.g. Pappalardo et al., 2023; Rossoni-Notter et al., 2016). Moreover, inside and outside the caves of the Balzi Rossi area, palaeoenvironmental and palaeo-sea-levels indicators are widespread (Federici & Pappalardo, 2006; Ryan et al., 2024 and references therein). Despite the importance of the area and the

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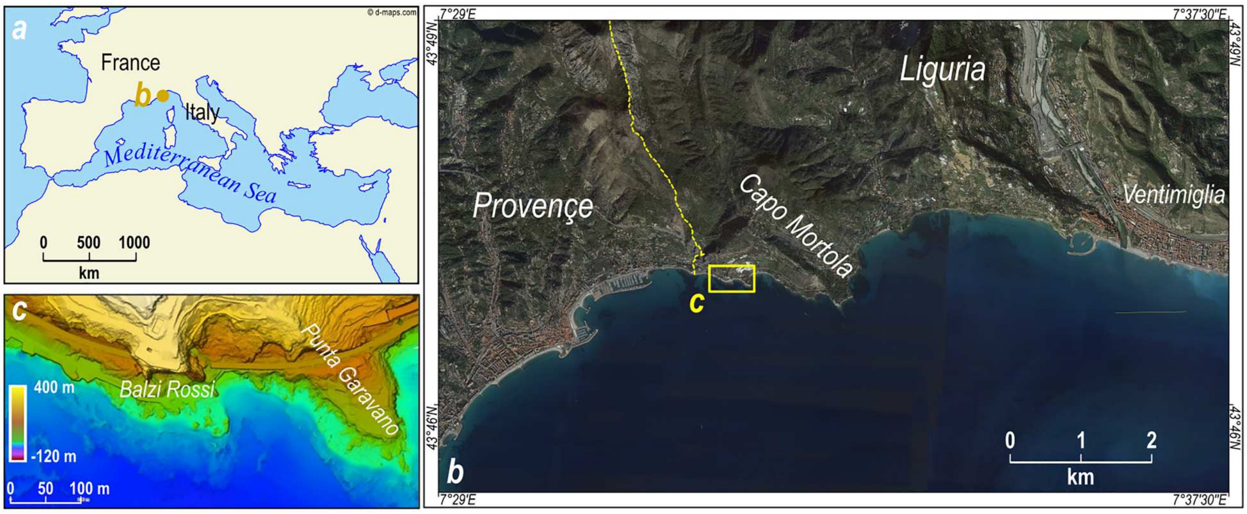

Figure 1. Location of the study area and of the localities cited in the text; for more details, consider the Main Map.

many archaeological investigations carried out in the last 150 years, scarce geological and/or geomorphological studies exist focused on the area between the Italian-French border and the municipality of Ventimiglia (e.g. Boni et al., 1991; Dallagiovanna et al., 2017). Among them, only Calvino and Stefanon (1963) investigated with acceptable detail the area between the Balzi Rossi and Capo Mortola (Figure 1(b)). Moreover, scholars have considered only subaerial landforms, and the continental shelf has never been investigated. Most likely, the presently submerged shelf was used by Palaeolithic populations as well. In fact, they extensively settled this area during the sea-level lowstand phases of the last glacial cycle, when the shelf was a coastal plain (Carobene & Firpo, 2004). Therefore, the Balzi Rossi area – from land to the sea – represents a palimpsest of landforms formed under different climatic conditions and a stratified cultural landscape preserving evidence of crucial events in human Prehistory (Pappalardo et al., 2023).

To fill this knowledge gap and make available a reliable reconstruction of the Balzi Rossi landscape evolution since its ancestral formation and across glacial/interglacial phases, we performed a new and detailed survey of the surface and underwater (e.g. on the continental shelf up to the depth of about 10 m) landforms and produced a high-resolution geomorphological map (Main Map). The very large scale (1:1000) of the geomorphological map presented in this work is aimed at providing a comprehensive and detailed view of the landforms of an area that, because of its natural features, has been a crossroad for humans during the Middle and Upper Palaeolithic. The relationship between sea-level changes and human settlement over the last 400,000 years in the Ligurian-Provençal area is the research subject of the interdisciplinary SPHeritage Project (Pappalardo et al., 2023). The aim of this project (https://spheritage.dst.unipi.it/index.php/en) is to investigate, using the Balzi Rossi site as a case-study, the resilience and adaptation capacity of human beings in the face of changes in their living space caused by coastline shifts and climatic fluctuations. The creation of a detailed geomorphological map is a fundamental step to understand the interplay between the evolving landscape and human peopling of the area, and a crucial activity of the SPHeritage Project.

2. Background on geological and archaeological context and palaeoenvironmental indicators

The mapped area is located along the Liguro-Provençal Coast, in the Liguria Region (North-Western Italy), including the Balzi Rossi Archaeological Area, an outstanding heritage site occupying a narrow strip of land between a 70 m high coastal cliff, the Mediterranean Sea, the Italy–France national border and a small headland called Punta Garavano (Figure 1(c)).

Geological formations along the coast between the Italian-French border and Capo Mortola consist of sedimentary rocks dated from the Jurassic to Eocene (Dallagiovanna et al., 2017). The older formations outcrop to the west, so that from west towards east, we have Jurassic limestone/dolomite of the Monte Grammondo Formation (GMM), the Cretaceous marl and limestone of the Marne e Calcari marnosi of the Trucco Formation (TUC), the Palaeocene-Eocene marl, micritic limestone and conglomerate of the Microcodium Formation (MIC), and the calcareous sandstone and conglomerate of the Calcareniti di Capo Mortola Formation (NCM). The Jurassic limestone constitutes an anticline relief that acts as a border crest between Italy and France. Near the coast, the anticline lies on its western flank so that, in the French territory, the stratigraphic succession is inverted

(Calvino & Stefanon, 1963). The tectonic evolution of the region is characterized by uplift and tilting lasting throughout the Quaternary, also triggering the formation of a major set of NW–SE oriented faults and fractures (Boni et al., 1978; Boni et al., 1980; Giammarino et al., 1978). The name Balzi Rossi (meaning 'red bluff' in Italian) comes from the reddish colour of the clay-rich coating covering a large part of the coastal cliff, derived from the weathering of the local Jurassic limestone.

The archaeological importance of the Balzi Rossi area is due to the important stratigraphic sequences spanning from the Middle to Upper Palaeolithic preserved in the caves and rock shelters located at the base of the cliff. Archaeological materials have been recovered from seven caves (plus one, the Bausu da Ture cave now destroyed), four rock shelters, and two open-air sites (Figure 2). Each of them is generally considered as a single archaeological site: the Costantini, Fanciulli, Florestano, Caviglione, Barma Grande, and Prince of Monaco correspond to the atrial parts of caves, whereas the Lorenzi, Mochi, Blanc-Cardini, and Bombrini are rock shelters; the so-called Ex Casinò and Ex Birreria are preserved patches of formerly more extensive open-air archaeological deposits. Since the mid-nineteenth century quarrying activities, the building of a railway and bombing during World War II have altered the landscape. The bombing almost destroyed the Barma Grande cave. The rock shelters and caves preserve evidence for the prehistoric presence of *Homo neanderthalensis* and *Homo sapiens,* including burials, engravings and artefacts dating from Middle to Upper Palaeolithic (see Ryan et al., 2024, and references therein). The most relevant finds are 16 individuals buried between 25,000 and 11,000 years BP and a series of female stone figurines about 10 cm tall known as 'Venuses of the Balzi Rossi' also from the upper Pleistocene. The oldest evidence of the human presence is a bone fragment attributed to *Homo erectus,* dated to 230,000 years BP.

In addition to archaeological finds, the study area offers several paleoenvironmental indicators. Many of them have been observed during the excavations of archaeological sequences and retrieval of numerous remains of fauna (including marine fauna) contemporary to human presence (de Lumley, 1969). Palaeobotanical analyses were carried out by Arobba and Caramiello (2009). Traces of ancient sea levels, such as remains of marine deposits, notches and *Lithophaga lithophaga* hole bands (Table 3 of Ryan et al. 2024), are widespread in the area. Some of them are still visible, but others were destroyed or removed. Most of them could not be reported in the map (Main Map) as they are either located inside the caves or sheltered by modern anthropogenic features.

3. Data and methods

3.1 Data sources

This work is based on remote sensing data and field surveys conducted between 2021 and 2022. First observation was made on satellite imagery available thanks to the free tools and services offered by Google (GoogleEarth™), Microsoft Bing (www.bing.com/maps) and ESRI World Imagery (livingatlas.arcgis.com/wayback/) and orthorectified aerial imagery from Regione Liguria acquired in the years 1986, 2007, 2010, 2013, 2016 and 2019.

The Italian Ministry of the Environment provided terrestrial LiDAR data acquired from 2008 to 2010. These data are in the form of a point cloud with points regularly spaced with distances of 0.00001 geographic degrees (about 0.8 m in E–W direction and 1.1 m in the N–S direction). The vertical accuracy of LiDAR data is 15 cm, while the horizontal accuracy is 30 cm. Each point has information about ellipsoidal elevation, intensity of the signal and typology (ground or not ground). French LITTO3D© data from SHOM (Service Hydrographique et Océanographique de la Marine) were also used; unfortunately, they only cover the western part of the study area. These data are derived from LiDAR and bathymetric surveys, and they measure both emerged and submerged areas with about 1 m resolution. The submerged part of the mapped area at shallow depths (0–10 m below sea level) was entirely covered by high-resolution bathymetric data acquired in December 2021 in the framework of the SPHeritage Project with multibeam technology (acquisition system RESON SeaBat 8125 with a central frequency of 455 kHz plus APPLANIX POS-MV inertial system for correction of direction angles, roll, and pitch, and vessel positioning and Valeport MiniSVP sound velocity probe).

The terrestrial LiDAR data were integrated with the bathymetric ones and with LITTO3D© data for the terrestrial area not covered by the previous (marginal areas and voids after removing the vegetation). The collated data partially overlap, thus making it possible to check their correct alignment. All data were referenced to the geodetic system of the National Dynamic Network RDN2008 (ETRF2000-2008) – UTM 32 North and to the 0.0 IGM vertical datum (i.e. the Italian National reference system datum). They were subsequently gridded, generating a Digital Elevation Model (DEM) with a cell size 1 m × 1 m. Using the QGIS software, a contour map with an interval of 1 m between contours was also extracted using the contour extraction function.

To gather more detailed data about the morphology, especially for the cliff and the cave's entrances, a photogrammetric survey with a DJI mini 2 drone was made in 2021 (available on the

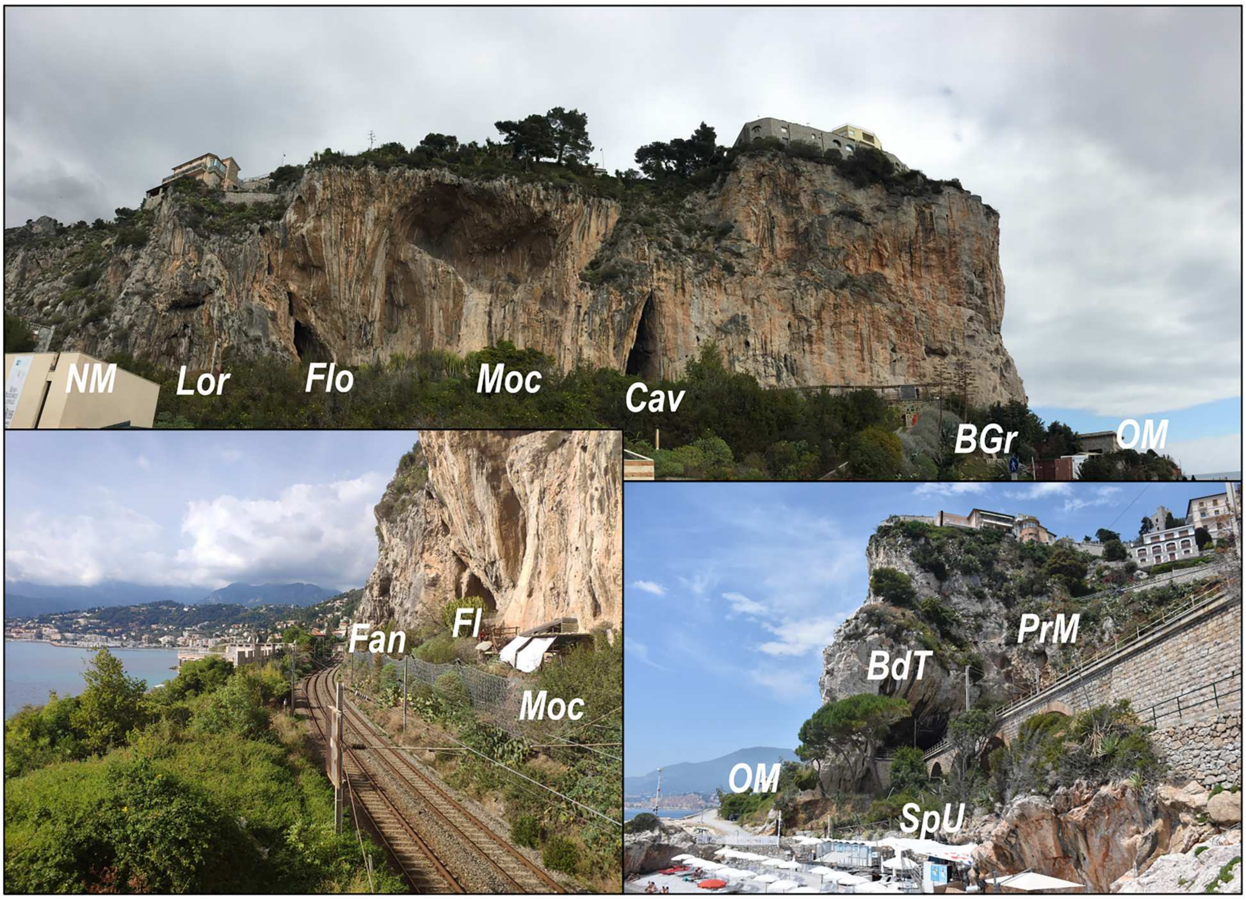

Figure 2. Landscape picture of the Balzi Rossi Cliff and some of the major caves carved by dissolution along fault plains/fractures. Fan: Fanciulli cave; Lor: Lorenzi rock shelter; Fl: Florestano cave; Moc: Mochi rock shelter; Cav: Caviglione cave; BGr: Barma Grande; BdT: Bausu da Ture cave; PrM: Prince of Monaco cave; NM: new archaeological museum; OM: old archaeological museum; SpU: 'Spiaggia delle Uova' beach.

Main Map). The elaboration of the images acquired during the drone survey produced a 3D model with a mean spatial resolution of about 5 cm. This model was cleaned by removing non-ground features (vegetation and buildings) to obtain a 3D terrain model. Significant points were measured for ground truthing in multiple GNSS surveys, carried out using an EMLID REACH RS2 receiver connected to the nearest Virtual Reference Station, through the NTRIP service provided by Regione Liguria. The 3D model has been aligned to these points to get a WGS84 UTM32 projection with ellipsoidal elevation.

To refer the DEM to a realistic position of the shoreline, all elevations were converted to tidal heights, i.e. to the current mean sea level. These were calculated from the ellipsoid heights, using the mean of tidal elevations registered by the closest tide-gauge, located in the harbour of Imperia, from 1 April 2022 to 31 March 2023. The mean sea level in the area was stated to be 48.786 ± 0.027 m. This value is 0.08 m lower than the official ellipsoidal elevation of the Imperia tide gauge benchmark provided by ISPRA (https://www.mareografico.it/LIVELLAZ/TABELLA_RIASSUNTIVA_QUOTE_ELLISSOIDICHE_RMN.pdf), which is 48.820 m and corresponds to the 0.0 IGM vertical datum. To get reliable results, it was necessary to verify that no vertical land movements had occurred after the station was established. This was achieved through a direct measurement of the benchmark ellipsoidal elevation by means of a GNSS survey. To improve the accuracy, the measurement was characterized by a long static occupation time. Sea level rise since the benchmark was established is thus broadly coincident with the measurement accuracy. For this reason, it was considered negligible, and the tidal heights were assumed to correspond to the 0.0 IGM vertical datum.

Raster DTM and vector contour lines were used as a base map for the drawing of landforms. The 3D terrain model was also used to determine the extent of most of the caves (Main Map). Only the Costantini Cave was not detected with the drone survey due to the small entrance, completely hidden by vegetation; in this case, the plan reported by Bachechi (2008) was considered.

3.2. Map drawing

The geomorphological features were reported generally following the guidelines of the Italian Geomorphological Working Group for landform symbolic representation (Campobasso et al., 2018), with a specific focus on coastal landforms (Mastronuzzi et al., 2017). Those guidelines provide visual differentiation between landform assemblages created by different processes using a specific colour for each process or geomorphic agent (e.g. gravity, water runoff, etc.) and different tonalities within the same colour to highlight their activity (i.e. active from inactive processes). These guidelines are specifically worked out for a 1:50,000 scale representation of landforms, and thus the symbols of this map, which is set to be visualized at a much larger scale, were slightly modified to improve legibility. For instance, for seafloor landforms representation, the legend adopted by the Liguria Region (https://www.regione.liguria.it/homepage-opendata/item/7070-atlante-degli-habitat-marini-sc-1-10000-2020.html) was used, because it highlights and differentiates biogeomorphological features.

4. Geomorphological units

4.1. Lithology

The bedrock along the Balzi Rossi and Punta Garavano area consists almost exclusively of the Jurassic limestone/dolomite formation (GMM); limited outcrops of stratified Cretaceous limestones (TUC fm.) are distributed in the north-eastern part of the area, where agricultural terraces mask the pristine topography (Calvino & Stefanon, 1963; Dallagiovanna et al., 2017). In a very small depression excavated along the floor of the Principality of Monaco Cave, Cretaceous marls outcrop because of the stratigraphic inversion. In the Main Map, the bedrock was indicated with a single colour because the different formations outcropping in the mapped area respond uniformly to the action of geomorphological agents, regardless of the minor lithological differences between them.

4.2. Tectonic landforms

The steep slope of the Balzi Rossi cliff is the morphological expression of the active displacement effect of faults. The main fault, parallel to the coastline, is an extensional, sub-vertical feature (step-fault) formed during the Miocene in connection with the opening phase of the Ligurian-Provençal Basin and consistent with the normal fault systems located at the bottom of the continental scarp (Dallagiovanna et al., 2017). The caves that open into the cliff (Figure 2), generally high and narrow, are developed along a set of sub-vertical discontinuities perpendicular to the main fault. For example, the eastern vertical wall of the Principe of Monaco Cave shows a NW–SE orientation and most likely corresponds to a fault slope. Moreover, the geological map drawn up by Calvino and Stefanon (1963) and Dallagiovanna et al. (2017) reports a NW–SE fault/thrust at the contact between the Jurassic limestone (GMM) and the Cretaceous limestone and marl (TUC), which intersects the coast at Punta Garavano. Fault slopes gently dipping seaward are visible along the coast facing the Barma Grande Cave, from 3 m of altitude and continuing underwater. Wherever fault slopes are polished by the sea, slickenlines are visible. Slickenlines with NNW–SSE direction testify to the sliding along these surfaces.

4.3. Gravity-induced slope landforms

The most iconic feature of the Balzi Rossi landscape is the vertical cliff parallel to the coastline. The cliff is a partially overhanging feature and reaches a maximum height of 60 m (Figure 2). Its genesis is complex as it is mainly the consequence of tectonic displacement, as stated in the previous section, but different processes contributed to its evolution, including marine erosion at its bottom and karst dissolution. Since the Upper Pleistocene, gravity has been the main agent shaping the Balzi Rossi cliff; minor rockfalls have been recorded historically and are ongoing. At several locations, the cliff is overhanging, forming rock shelters or covering the entrance to the caves. In some cases, such as the Bombrini and Mochi rock shelters (Figure 2), the overhanging wall collapsed. Minor scarp edges are also visible along the slopes. The foot of the cliff is mantled by a scree slope deposit, almost everywhere affected by pedogenesis and colonized by vegetation (Figure 3(a)). Some scree slope sections are exposed by marine erosion, along the coast between the Spiaggia delle Uova beach and Punta Garavano, or because of human activities (e.g. the Ex-Birreria and Ex-Casinò archaeological sequence, Figure 3(b,c)). Such stratigraphic sections show a deposit formed by heterometric angular clasts (mainly centimetric and decimetric) in a reddish sandy-loamy matrix, often organized in bedding plains and cemented by $CaCO_3$ in its upper part. The matrix of such a deposit can be interpreted as a reworked *Terra Rossa*-type paleosols developed on the local limestone during warm phases of the Neogene. Most of the debris once infilling the caves was largely removed during archaeological excavations due to the content of archaeological materials and is no longer in situ, but according to the descriptions reported in the literature (e.g. de Lumley, 1969), it was largely similar to the preserved scree slope. Archaeological excavations revealed the complex stratigraphy of the scree slope deposit (e.g. the Ex-Birreria site, Cremaschi et al., 1993) and the occurrence of layers formed by processes other than just gravity. Apart from anthropogenic contribution to sedimentation, the periglacial origin of some layers controlled by frost action during MIS 3–2 (Douka et al., 2012) has been detected through micromorphological observations in the case of Riparo Mochi (Figure 3(d)). At the bottom of

Figure 3. Slope scree deposits at the foot of the Balzi Rossi cliff. General view of the landform (indicated by white lines and intervening white dots) from the coastal street (a) and anthropogenic exposures showing the Ex-Casinò (b), Ex-Birreria (c) and Mochi rock shelter (d) sequences.

the relict cliff, the top of the scree generally reaches an altitude of 20–25 m a.s.l. Further to the east, it reaches higher altitudes, in the trough backing the Spiaggia delle Uova beach, where the maximum height of the scree is around 40–45 m a.s.l. The bottom of the slope, between the railway line and the sea, is deeply covered by reworked material resulting from the construction of the railway, the bombing during the Second World War, and housing construction.

4.4. Coastal landforms

In the mapped area, coastal erosional landforms prevail as the coast is completely rocky apart from the small pocket beach called 'Spiaggia delle Uova' (Figure 2), made of well-rounded limestone pebbles as its local name ('Beach of eggs' in Italian) suggests. The beach currently has no sedimentary contributions from the slope backing it and is retreating without artificial nourishment. The beach pebbles are likely formed of quarry debris (see Section 4.8) disposed on site, smoothed and rounded by wave action over time. A possible additional source is raised pebbly marine deposits, probably once extensively outcropping along the coast, of which only relic spots are left (see Section 4.6 for description).

The rocky coastal area currently affected by marine action is in the form of a moderately dipping ramp

(Figure 4(a)), partly developed below sea level to the depth of ca. −4 m. It is backed by a 5–6 m high coastal cliff which marks the limit of wave action. The ramp and the cliff are visible in front of Barma Grande and on Punta Garavano promontory, but they probably continued further west, having been destroyed by the construction of the road embankment. Intermittently, the ramp joins up at sea level with horizontal shore platforms. Their surface is jagged, and their morphology is likely controlled by one of the fault systems affecting the bedrock. Although they are currently evolving under the action of marine processes, there is a possibility that these surfaces have been created or altered by quarrying activities during the past centuries. Some different types of rockpools, up to 1–2 m wide and a few dm deep, are present on the platforms and the ramp. They have been mapped as a unique landform, although different genetic processes may have been responsible for their shaping. In fact, some of them can be interpreted as potholes (Figure 4(b)) cut by abrasion processes (Pappalardo et al., 2023), whereas in other cases they are bowl-karren features (Taboroši & Kázmér, 2013) that can be attributed to the combined action of karst and seawater dissolution.

Along the seaward margin of the ramp, some rock ledges (sea stacks) emerge (Figure 4(a)), isolated by marine erosion. Notches are currently shaped along the most protruding stretches of the coast. In the exposed parts of the promontories, notches display a bioconstructed floor, whereas close to the beach they are sculptured by pebble grinding. Along the slope between the beach and Punta Garavano, in three distinct sites at 5–6 m of altitude, there are relic spots of marine deposits (Figure 4(c)) consisting of rounded pebbles in a poorly cemented reddish loamy matrix, where very rare fragments of bivalve shells are occasionally interspersed. Pebbles sometimes display lithophaga holes and sponge perforations. The deposit overlaps the outer edge of a sub-horizontal narrow bench, likely extending underneath the slope debris, possibly representing the basal surface, carved in the bedrock, of a marine terrace. The Punta Garavano promontory itself is a staircase of two terraces gently dipping seaward and covered by anthropogenic debris (produced by agricultural terracing and modern construction of houses on the cliff above). The Punta Garavano marine terraces are largely reworked by human activity, but two knickpoints can be narrowly detected at 14 and 20 m a.s.l. This feature can be hypothetically interpreted as a poorly preserved polycyclic marine terrace, of which the knickpoints could represent the inner margins, and the deposits could be related to the original cover of the lower step. Another flat, wide but uneven surface at 6–8 m a.s.l. on average, traditionally considered a marine terrace (Cremaschi et al., 1993; Vicino, 1972), currently raised and levelled by means of an artificial embankment, is located on the western tract of the coast between the scree slope and the ramp. All these likely marine terraces were not mapped as such, but as anthropogenic landforms (see also section 4.7).

4.5. Seafloor landforms

The ramp extends down to 3–4 m of depth, from where the seabed gently slopes towards the deeper water with an average dip of around 3%. Extensive s meadows of the seagrass *Posidonia oceanica* occur below the depth of −4 m. They are characterized by a mixing of living meadow and dead matte areas and intermingled sandy accumulations (Boudouresque et al., 2012). Punta Garavano, as well as the small promontory west of it, continues below sea level as a prominent rocky feature bracketing the intermatte sandy body facing the small Spiaggia delle Uova bay.

4.6. Karst landforms

The caves that open along the Balzi Rossi cliff are set along tectonic fractures or faults enlarged by the dissolving action of percolating water on the limestone bedrock. The elevation of the caves' entrances ranges from ca. 7.50 m in the Barma Grande Cave to about 35 m in the Fanciulli Cave. Ancient clastic karst deposits infilling cavities and fractures in the bedrock are visible along the coast at elevations between 2 and 11 m a.s.l. On the western side of Punta Garavano, a relic spot of a dark reddish to brownish loamy-clay deposit, highly cemented by $CaCO_3$, including frequent small clasts (<1 cm) with a few bigger inclusions, is present. Such a clastic deposit is interpreted as the result of the erosion of ancient lateritic soils developed on the limestone at the top of the cliff and their reworking along the underground karst network. Occasionally, the sides of fractures infilled by clastic sediments are draped by a 10–20 cm-thick calcitic flowstone, resulting in a sort of sandwich-like feature. This pattern can be observed in the only karstic clast deposit large enough to be represented on the Main Map with a polygon symbol (Figure 5(a)). More clastic karst deposits outcrop in open-air locations along discontinuities of the bedrock. One of them is shown in Figure 5(b), filled with centimetric/decimetric clasts and fragments of flowstone in a reddish matrix. Minor laminated to massive clastic karst deposits – occasionally cemented in the form of breccias (Figure 5(c)) are distributed throughout Punta Garavano. On the most prominent part of the promontory, along the cliff, a 3 m-deep pocket in the bedrock is infilled by a cemented, laminated sandy deposit with calcareous and glauconitic nodules, and its top is covered by marine deposits.

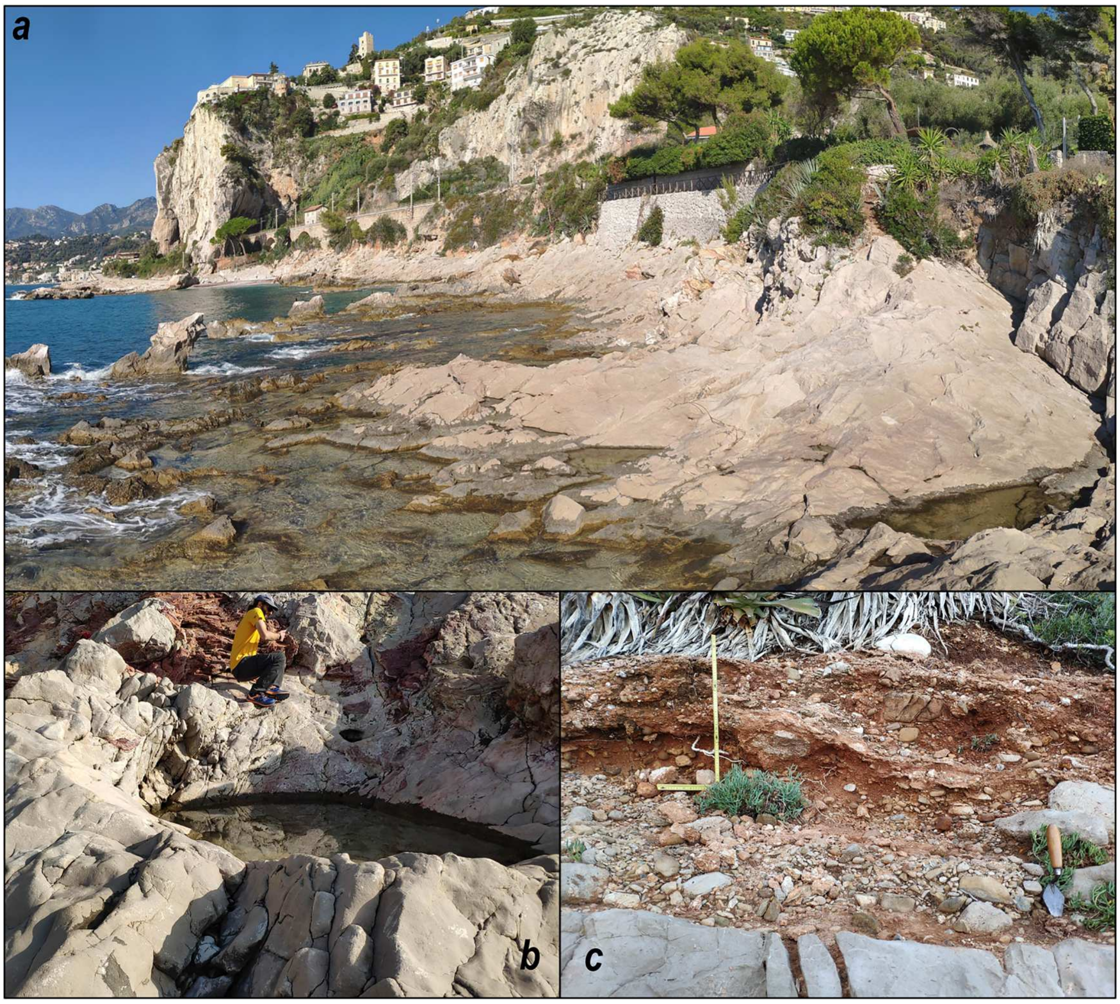

Figure 4. General view of the main coastal features in the study area (a), dominated by the ramp (a). Major rockpool of the pothole type (b), and relic spot of raised marine deposit, and (c) in the area of Punta Garavano.

4.7. Anthropogenic landforms

The whole area has been significantly reshaped by human activities. A major road known as the *Via Iulia Augusta*, constructed during the first century BC by the Emperor Augustus, stretches under the main cliff where the road to the archaeological museum and the path to Capo Mortola are now located. Throughout the Common Era, agricultural terraces were built to reshape the slopes where patches of colluvium rested. Terraces are supported by dry stone walls 1–2 m high. They are now mostly abandoned or integrated into modern retaining walls, in some cases supporting greenhouses.

The morphology of the cliff foothill was mostly modified through the construction of the railway around 1870. A deep trench dissected the scree slope, revealing some significant archaeological findings. The railway crosses the area in an east–west direction at a constant altitude of about 17 m a.s.l. The tracks rest on a ballast of indeterminate thickness. For most of its route the railway cuts the natural talus debris, with a couple of exceptions: in the central portion it cuts through the southernmost projection of the rocky relief with a tunnel about 100 m long, while further east (at Punta Garavano) it cuts a second rocky ledge with a trench about 60 m long and up to 9 m deep, isolating a modest rocky outcrop to the south from the rest of the relief.

In the past centuries, quarrying activities extensively occurred. Starting from 1883, private exploitation of the cliff rock to produce lime affected some of the caves as well as the archaeological deposits inside them. The Bausu da Ture cave was destroyed, and the platform west of the Spiaggia delle Uova, originally cut by the excavators along a fault plane, is now partly shaped by marine processes. The Barma Grande Cave was deprived of its mouth and eastern wall. Thanks to public and private interventions in 1898, the importance of the site was formally recognized and in front of the Barma Grande, a museum was built for the expositions of the retrieved archaeological materials, some of which were also showcased directly in situ.

A few buildings, including a brewery, were built to the fore of the cliff between the end of the nineteenth century and the beginning of the twentieth century. A panoramic elevator was active between the 1930s and 1960s along the cliff near the old archaeological museum, allowing easy movement between the middle

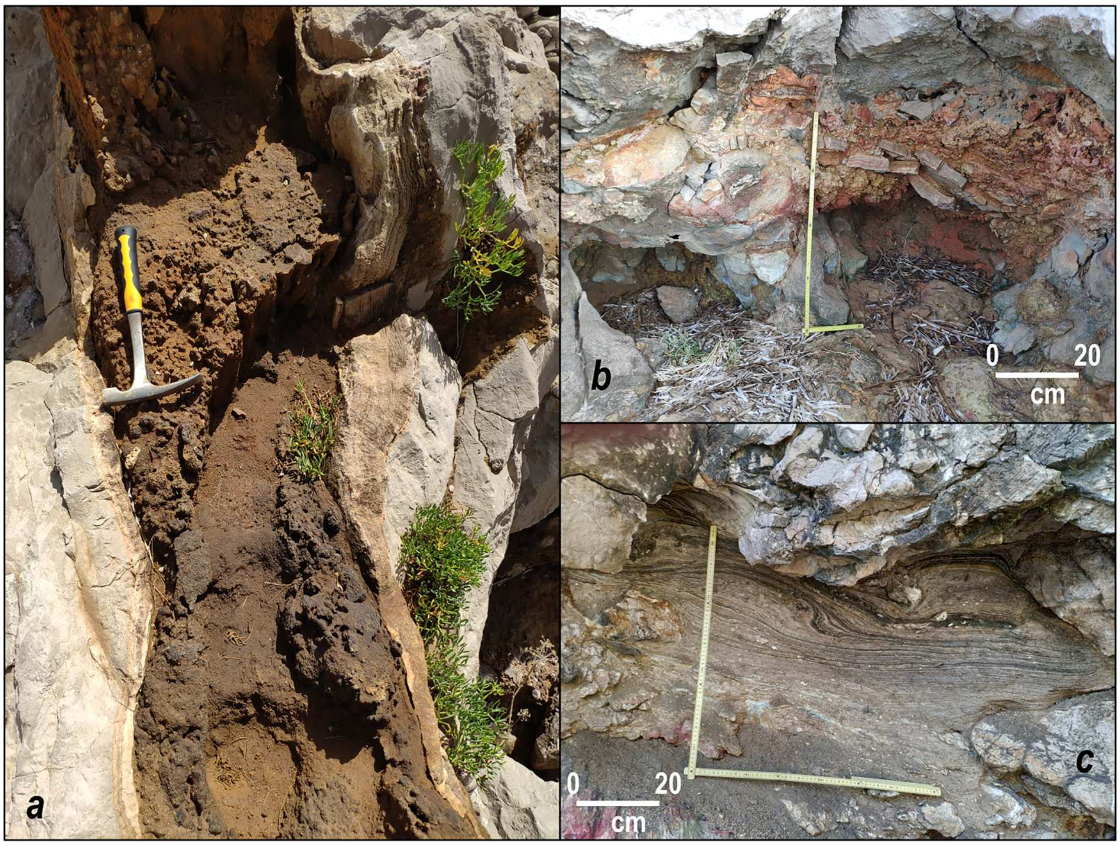

Figure 5. Karst-related deposits distributed along the Punta Garavano promontory: sediments from ancient lateritic soils sandwiched by calcitic flowstones (a); clastic sediment with fragments of flowstone in a reddish matrix (b); cemented laminated deposit (c).

and bottom of the cliff. During World War II, a military bunker was built along the coastal roadbed. Most of the buildings were damaged or destroyed during World War II by the Allies' bombings and by the explosions along the railway line that were caused by the escaping German troops. Among these, there was a resort with a casino in the western part, which, following the war, was demolished. More recently, a block of apartments (in the 1960s) and the new museum (in the 1990s) were built on top of a reworked marine terrace.

The main road is the Grimaldi-Mentone road, stretching above the cliff top between 70 and 90 m of altitude, which borders the mapped area to the north. The road seems to rest on the rocky substrate, possibly exploiting a natural ledge/shelf. To the south (and seaward) is the access road to the modern prehistoric museum and its parking lot between 6 and 9 m a.s.l. The road continues eastward from the museum, unpaved, to Spiaggia delle Uova beach and then proceeds as a pedestrian path towards the agricultural terraces above Punta Garavano.

5. Geomorphological evolution

The current geomorphological setting in the Balzi Rossi area is the result of different physical and chemical processes shaping the bedrock under different climatic conditions and consequent sea-level modifications beginning within the Cenozoic and continuing during the Quaternary. The tectonic setting of the area has been the main driver of geomorphological processes. The high and steep cliff, which represents the iconic feature of the landscape in this coastal stretch, is the consequence of major fault line activity intersected by a secondary order of discontinuities along which karst dissolution produced caves.

Karst (limestone) dissolution has not only produced large cavities but has also contributed to their infilling through karstic precipitation products, as well as conveying inside the caves the residual products of surface karst dissolution. It also fostered the production of speleothems and the cementation of terrigenous, and occasionally anthropogenic, deposits inside the caves, facilitating their preservation. Climate fluctuations have alternatively promoted dissolution and cementation processes, producing a complex pattern of relic warm and cold climate-related features. Similar patterns have been extensively observed in karstic caves with preserved traces of Palaeolithic settlement along the coasts of the Tyrrhenian Sea (e.g. Isola et al., 2024; Marra et al., 2020; Moroni et al., 2019; Pieruccini et al., 2022; Villa et al., 2020).

In terms of impact on the present-day landscape, gravity-driven landforms are the most outstanding. The detachment of debris from the cliff, which is still active, and the related displacement at its base must have been an ongoing process throughout Pleistocene climate fluctuations. Together with it, the extensive reworking of *Terra Rossa*-type paleosoil material, representing the matrix of scree deposits, has massively impacted on the formation of the most extended feature – the scree slope –, and favoured the preservation of the archaeological deposit. The thick talus produced (Figure 3) has been only partly explored through archaeological excavations and anthropic activities, represented by constructions of roads and buildings since the Roman age up to the present. Available data (Cremaschi et al., 1993; Douka et al., 2012) suggest that processes other than gravity have contributed to its formation in the past, e.g. periglacial processes. In the Provençal area, stratified talus slopes are a recurring feature and have been extensively described (Raynal, 1973; Van Steijn, 2011). Although missing robust geochronological constraints, those studies revealed that the layering within the scree reflects accumulation during alternating moist and dry climatic conditions. The latter have most likely been in phase with the advance of glaciers documented in the neighbouring Maritime Alps (Federici et al., 2017; Tremblay et al., 2019). In the Balzi Rossi site, thus, the scree slope currently mantling the cliff bottom represents an invaluable archive of climatic changes occurring since the end of the last interglacial, and a repository of human evolution evidence. Although the deposit has been extensively removed by multiple human activities, this map testifies that patches of it are still unexplored or destroyed only at their top, and a dedicated, detailed survey is still possible.

Other than the few raised outcrops of cemented marine deposit along Punta Garavano, the features associated with marine-driven formation represented in the map, both along the coast and on the seafloor, are all related to ongoing processes. Traces of at least 3 sea-level high stands onshore, though, have been reported in the area since the late eighteenth century (De Saussure, 1780; see Ryan et al., 2024 for full reference), including depositional and erosional features. The latter correspond to notches and lithophaga hole bands. Notches actively shaped along the ramp represent an excellent modern analogue to infer the position of the raised paleo features relative to the mean sea level at the time of their formation. Marine deposits found inside some of the caves beneath deposits characterized by Palaeolithic archaeological material are now extremely rehandled (e.g. Barma Grande and Ex Birreria) or completely removed (e.g. Price of Monaco Cave and Ex Casinò). The latter was unearthed, removing the bottom of the scree slope during the construction of some buildings on top of the flat surface in the westernmost tract of the coastal strip. Vicino (1974), who excavated the site, described a sandy marine deposit with molluscs belonging to the so-called 'Senegalese fauna' containing *Thetystrombus latus*. This faunal assemblage is considered the biomarker of MIS 5e in the Mediterranean (Asioli et al., 2005). Unfortunately, human activities, including building and road construction and archaeological investigations, have almost completely removed all the marine deposits in situ, the record of which remains in the literature and in some samples preserved in repositories and museums (Costanzo et al., 2024). At the bottom of the subaerial cliff near Punta Garavano, conversely, minor patches of the original deposit are diagnostic of the interplay between gravity-driven and marine processes, both of which are preserved. It must have been active in those phases when sea level was lapping onto the cliff bottom, i.e. most likely at the end of the 5e substage of the Last Interglacial (Federici & Pappalardo, 2006; Ryan et al., 2024). The morphology of the currently submerged part of the ramp represents a potential modern analogue of the feature described by Vicino (1974), the preservation of which is also favoured by regional uplift (Morelli et al., 2022). However, as reported in the map, the seafloor is extensively mantled by terrigenous and biogenic deposits associated with seagrass (*Posidonia*) development, and its morphology can be only broadly detected through a traditional bathymetric survey. Recently, though, in front of the new museum building, five possible cave entrances were identified by scuba divers at the toe of the ramp (Stefano Costa, personal communication), the exploration of which is ongoing.

6. Conclusions

The very large-scale (1:1000) geomorphological map of the Balzi Rossi archaeological area and of its shallow seafloor is functional to the high-resolution detection of the geomorphic features of an area of outstanding archaeological relevance, having been a major crossroad of Palaeolithic populations along the shorelines of the northwest Mediterranean Sea. Our detailed mapping of landforms is aimed at providing a fundamental tool to support: (i) the reconstruction of the landscape at relevant time frames during prehistory as well as its diachronic evolution; (ii) the comprehension of the specific sedimentary and geomorphic processes that contributed to the formation of the archaeological deposits of each site located along the Balzi Rossi complex; (iii) the production of documentary materials supporting territorial planning and cultural services in this area, because a proper recognition as an outstanding geocultural value of the site is still missing (Bollati et al., 2025).

The detailed geomorphological mapping is thus necessary to visualize each archaeological site within its geomorphological context (e.g. within its landscape) and to highlight the relationship between landforms and settlement sites within the Balzi Rossi complex, offering an effective tool to elucidate the Late Quaternary evolution of the area and the response of human communities. Indeed, since the beginning of investigations and even in recent times, the focus of archaeological researchers in the Balzi Rossi area has been on retrieving information on the stratigraphy of the archaeological deposits preserved in a cave or in a rock shelter, thus considering each archaeological evidence as a self-standing site (Ryan et al., 2024). Conversely, our geomorphological investigation suggests that they are parts of the same cultural landscape and thus each archaeological evidence belongs to a complex settlement system, where human groups arranged the space available below the cliff so that it could be exploited for different functions or by different human groups at the same time. Geoarchaeological research in progress is performing radiometric dating of natural and anthropogenic sediments to create a more robust chronological framework to boost archaeological and paleoenvironmental reconstructions.

This map also offers fresh insights into the future planning of touristic itineraries along the Balzi Rossi cliff, aimed at increasing awareness of the tight relationship between archaeological heritage and geodiversity (*sensu* Brandolini et al., 2019). Moreover, in this direction, the geomorphological map could represent the base layer to produce a simplified version of the map (e.g. Bollati et al., 2020), suitable for dissemination to the general public to make it familiar with geomorphological dynamics and paleoenvironmental conditions featuring the area.

Indeed, our approach further increased our understanding of the evolution of the area by comparing subaerial and submerged evidence. A critical aspect of landscape reconstruction in near-shore locations is the presence of landforms today submerged because of sea level rise that, conversely, have been long-lasting features of the Palaeolithic cultural landscape (Harff et al., 2016). Ongoing research is aimed at reconstructing the currently submerged portion of the landscape where our ancestors thrived. In such a context, the critical point is the creation of topo-bathymetric DEMs. Here, we tested an innovative approach aimed at overcoming this issue, based on the use of a common datum for terrestrial and marine elevations and on the use of the French dataset LITTO3D© that provides a 3D model acquired with the same LIDAR instrument across the shoreline, and thus simultaneously above and below sea level. The very large scale of this map permitted testing the accuracy of the topo-bathymetric model and validating the methodology to be used in future investigations. Moreover, the detection of modern analogues of past sea-level indicators has been a further outcome of this work, supporting future reconstructions of paleo-sea-level change in human-settled landscapes.

Software

All data were processed and analyzed with Agisoft Metashape Professional 1.5.5, CloudCompare 2.12.4, SAGA 8.1.1, QGIS (versions from 3.16 to 3.28) and QField 2.4.4 software. The main geomorphological features on the seafloor were interpreted using 3D visualization by means of Global Mapper software supplemented by long slope profiles created with QGIS tools.

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Author contributions

CRediT: **Marta Pappalardo:** Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Supervision, Writing – original draft, Writing – review & editing; **Alessandro Perego:** Data curation, Formal analysis, Investigation, Software, Visualization, Writing – original draft; **Gabriella Raffa:** Data curation, Formal analysis, Investigation, Methodology, Software, Visualization; **Matteo Vacchi:** Conceptualization, Investigation, Supervision; **Alessio Rovere:** Conceptualization, Funding acquisition, Investigation, Methodology, Software; **Elisa Casella:** Software, Visualization; **Deirdre D. Ryan:** Data curation, Writing – review & editing; **Luca Forti:** Software, Visualization; **Andrea Pezzotta:** Software, Visualization; **Irene M. Bollati:** Conceptualization, Formal analysis, Writing – review & editing; **Manuela Pelfini:** Conceptualization, Writing – review & editing; **Elisabetta Starnini:** Conceptualization, Data curation, Investigation, Supervision; **Andrea Zerboni:** Conceptualization, Data curation, Funding acquisition, Investigation, Resources, Supervision, Writing – original draft.

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Data availability statement

All data and materials supporting the results of this paper are available from the corresponding author upon reasonable request.

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