



UNRAVELLING LATE QUATERNARY COASTAL EVOLUTION THROUGH A MULTIDISCIPLINARY APPROACH: A CASE STUDY FROM SOUTHWESTERN SICILY (ITALY)

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ABSTRACT: We present new lithostratigraphic, micropaleontological, and chronological evidence for the Late Quaternary evolution of the Carboj River mouth along the southwestern Sicilian coastline. Field mapping, micropaleontological analysis, and luminescence dating reveal a narrow, elevated coastal landform, the Maragani relief, capped by a flat surface underlined by marine sands dated to ~77 ka (MIS 5a). This surface, perched at ~55 m a.s.l., overlies the Early Pleistocene Agrigento Formation, assigned to the middle Calabrian, establishing a vertical stratigraphy spanning nearly one and half million years.

Unlike the classic stepped terraces typical of the region, the Maragani relief lacks fluvial incision and shows no evidence of marine abrasion. Instead, its geometry, lithology, and tectonic context support interpretation as a relict wave-built mouth bar formed during a sea-level stillstand and later uplifted by regional deformation associated with the Sicilian Fold and Thrust Belt.

This study shows that even single localized coastal features can capture the combined effects of tectonic uplift and sea-level change. By focusing on the Maragani relief, we highlight how site-specific landforms, often overlooked, can offer valuable insight into Quaternary landscape evolution along the Mediterranean margins.

Keywords: coastal landscape; lithostratigraphy; micropaleontology; luminescence dating; central Mediterranean.

1. INTRODUCTION

Marine terraces along coastlines are key archives of Quaternary landscape evolution. They preserve signals of glacio-eustatic sea-level fluctuations modulated by regional uplift and crustal deformation (Bull, 1984; Dumas et al., 2005; Malatesta et al., 2022). Nowhere is this more evident than in the central Mediterranean, specifically along the Sicilian margin, where terrace sequences record the combined imprint of climatic oscillations and the structural dynamics of the Sicilian Fold and Thrust Belt (SFTB). These landforms offer critical constraints on rates of uplift, sedimentary response to sea-level highstands, and coastal evolution through the Middle and Late Pleistocene (Antonioli et al., 2006, 2025; Ferranti et al., 2006, 2007, 2021; Di Maggio et al., 2017; Pavano et al., 2016; Parrino et al., 2022, 2023; Agate et al., 2025).

Across Sicily, the marine terrace records are far from uniform. The Sicilian region spans multiple tectonic domains, and coastal uplift patterns change markedly along strike. In northeastern Sicily, MIS 5e terraces rise to more than +100 m, reflecting rapid vertical motions of the Calabrian forearc above the subducting Ionian slab

(Antonioli et al., 2006; Ferranti et al., 2007; Pavano et al., 2016). Along the northern margin, well-developed terrace flights show a clear eastward increase in uplift from the low-strain western sector into the actively rising Peloritani region (Antonioli et al., 2006; Ferranti et al., 2007; Pavano et al., 2016; Di Maggio et al., 2017; Parrino et al., 2023). By contrast, much of the southern coastline preserves no clear MIS 5e markers, likely reflecting limited accommodation space, erosion, and poor preservation potential (D'Angelo & Vernuccio, 1996; Antonioli et al., 2006; Ferranti et al., 2006).

Much of this regional work has focused on MIS 5e terrace surfaces, often recognised either near their quasi-eustatic reference elevation of ~5-6 m in tectonically stable Mediterranean settings, or at significantly uplifted positions along the Sicilian margin, ranging from ~2-14 m in the northwest to >100 m in the rapidly rising north-eastern sector (Antonioli et al., 2006, 2025; Ferranti et al., 2006, 2007; Sulli et al., 2013; Parrino et al., 2023). In several areas these surfaces are also identified by the warm-water marker fossil *Thetystrombus latus* (Gmelin, 1791) (= *Strombus bubonius* Lamarck, 1822). The distribution of this fossil, however, is highly uneven and notably absent along the southwestern coast, leaving terrace

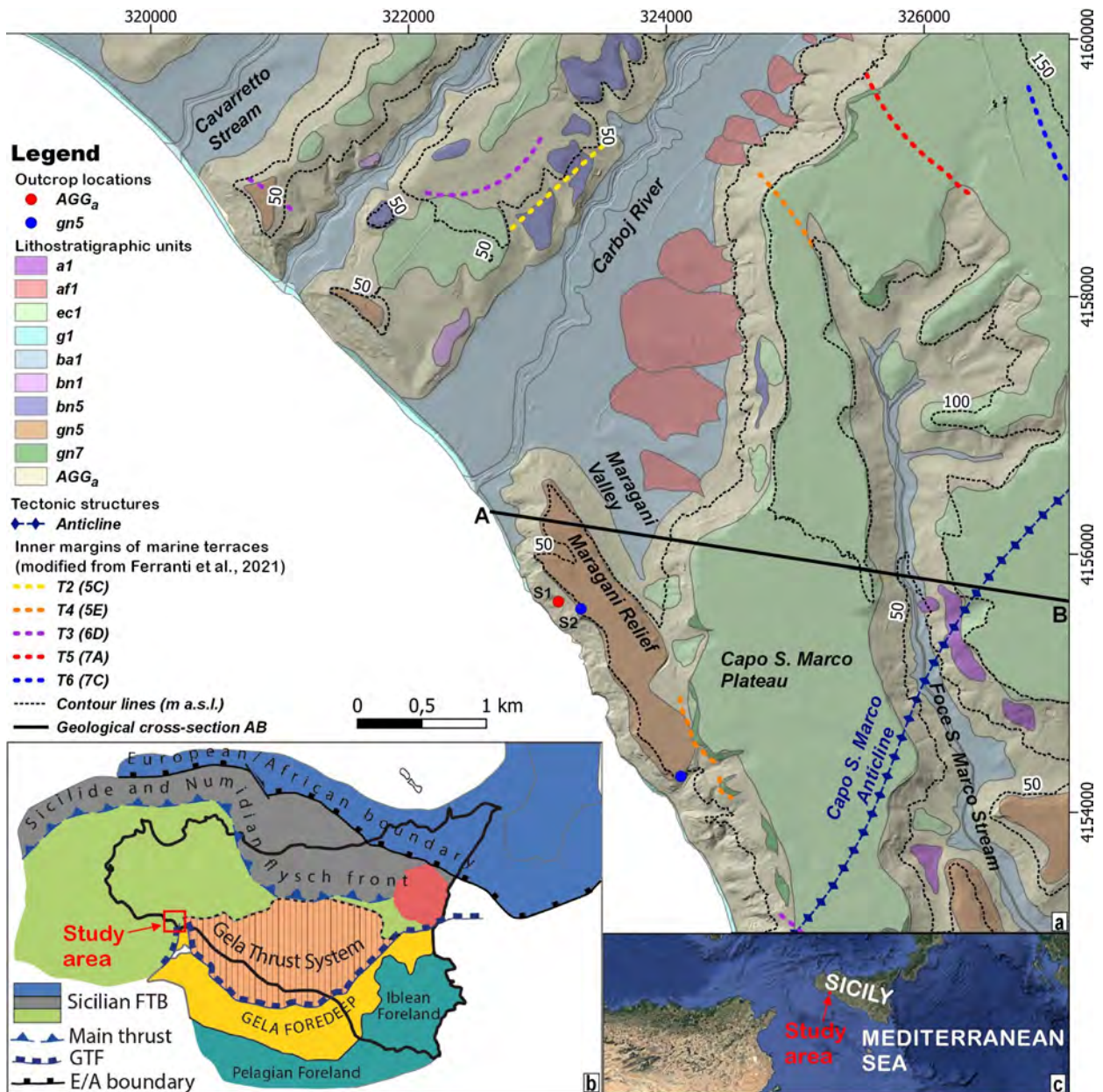


Fig. 1 - (a) Geological map of the Carboj River mouth region showing lithostratigraphic units, mapped tectonic structures, terrace inner margins, trace of the section (see Fig. 2) and sample locations. The stratigraphy includes Early Pleistocene deep-marine marls of the Agrigento Fm. (AGG_a), overlain by marine terrace deposits (gn5 to gn7), alluvial terraces deposits (bn1, bn5), transitional (g1), alluvial (ba1), and continental (a1, af1, ec1) units. Outcrop locations are marked in red (AGG_a) and blue (gn5), with S1 and S2 indicating the precise sampling points discussed in Figures 4 and 5. Dashed coloured lines trace the inner margins of stepped marine terraces (T2-T6), interpreted as MIS 5c to 7c features (modified from Ferranti et al., 2021). Black dashed contour lines (50 and 100 m a.s.l.) highlight the topography of the Maragani relief and surrounding landscape. (b) Tectonic overview map of southern Sicily, showing the main structural domains, including the Sicilian Fold and Thrust Belt (SFTB), Gela Foredeep, and Iblean and Pelagian forelands. The study area is indicated by the red box. (c) Location of the study area within the central Mediterranean Sea (modified from Google Earth).

chronologies in this sector historically less certain.

Within this broader framework, the southwestern margin remained poorly constrained until the work of Ferranti et al. (2021), who provided the first integrated mapping and luminescence ages for marine terraces spanning MIS 7 to MIS 5. Their study showed that uplift in the Menfi-Selinunte-Sciacca sector reflects both a

long-wavelength regional signal and shorter-wavelength deformation linked to active fold growth along the buried front of the SFTB. This work established the first quantitative terrace chronology for the area and clarified the structural controls on coastal emergence.

As these Sicily-wide and regional frameworks have become better defined, new questions have emerged at

finer spatial scales. One such question arises from field-based observations at the mouth of the Carboj River, where we identified a distinctive landform, the Maragani relief (Fig. 1), that diverges from the stepped marine-terrace pattern typical of the region. This narrow, elongated surface extends parallel to the coastline but is oriented perpendicular to the Carboj River mouth, a configuration not observed at adjacent, larger river systems. Its isolated expression, lack of upstream incision, and capping of marine sands suggest it is not the result of fluvial erosion or classic marine abrasion. This makes the Maragani relief a compelling case study for examining how sedimentary, hydrodynamic, and tectonic processes can interact in complex, site-specific ways that diverge from regional terrace models.

By zooming in on this particular landform and applying a multiproxy approach that integrates lithostratigraphy, micropalaeontology, and luminescence dating, we aim to show how landscape evolution in tectonically active settings is not only regionally coherent but also locally complex when examined at finer resolution. In doing so, we place the Maragani relief within the broader context of Late Quaternary coastal uplift in southwestern Sicily and refine the link between terrace formation, stratigraphic architecture, and active structures along the SFTB front.

2. GEOLOGICAL SETTING

The study area is located along the southwestern coast of Sicily, within the foreland domain of the SFTB. According to regional physiographic mapping (Amadei et al., 2000), the landscape transitions from "Terrigenous Hill Landscape with Plateaus" in the west to "Heterogeneous Hill Landscape with Plateaus" toward the east. This variation reflects the lithological complexity and structural heterogeneity of the region, shaped by Neogene compressional tectonics and overprinted by Quaternary coastal processes.

The coastal segment between Capo San Marco and the Carboj River mouth (Fig. 1) exposes a well-preserved suite of Middle-Late Pleistocene marine and continental deposits. Marine terraces, ranging in elevation from ~50 to 105 m a.s.l., are carved into the Early

Pleistocene (Calabrian) Agrigento Formation (AGG; Fig. 1a), a syn-tectonic regressive succession consisting of marly sands, sandy to silty clays (AGG_a), biocalcarenites, and biocalcirudites (AGG_c) (Catalano et al., 1998; Gasparo Morticelli et al., 2015; Montana et al., 2024; Pucci et al., 2023; Sulli et al., 2024).

The AGG deposits unconformably overlie deformed Meso-Cenozoic bedrock and related Miocene-Pliocene syn-tectonic covers, reaching thicknesses of over 500 meters (Fig. 2) in the western part of the study area (Sulli et al., 2024).

Moreover, even after the Agrigento Formation was deposited, this region was still affected by a compressive tectonic regime, which caused the folding of the succession after the Calabrian age, as evidenced by the presence of the Capo S. Marco anticline (Figs 1a, 2; Sulli et al., 2024).

Marine terrace deposits, mapped as gn5 and gn7 in Figure 1, unconformably lie on the AGG_a unit. They consist of sands and calcareous arenites and conglomerates, occasionally rich in rhodoliths and displaying shallow marine facies. Their elevations and morphologies correspond to established sea-level highstands during MIS 5 and MIS 7.

Above these marine units, two main types of surficial deposits are present. The fluvial terrace deposits (bn) comprise unconsolidated yellow-brown silty sands grading into poorly sorted, clast-supported conglomerates with rounded carbonate clasts (Fig. 2). These deposits typically occur between 35 and 70 m a.s.l. (Figs 1a, 2). Overlying and surrounding them, the transitional and continental covers include valley-floor alluvium (ba1), slope debris and landslide deposits (af1, a1), eluvial-colluvial sediments (ec1), and beach deposits (g1). These units are widespread and often discontinuous, blanketing terrace surfaces and valley margins (Figs 1a, 2).

The Maragani relief, positioned between the Capo San Marco plateau and the Carboj River mouth, fits into this stratigraphic framework. It is underlain by the AGG_a and mantled by Middle-Late Pleistocene deposits, integrating it structurally and stratigraphically into the broader terrace system. The geological cross-section A-B and the relative lithostratigraphic column,

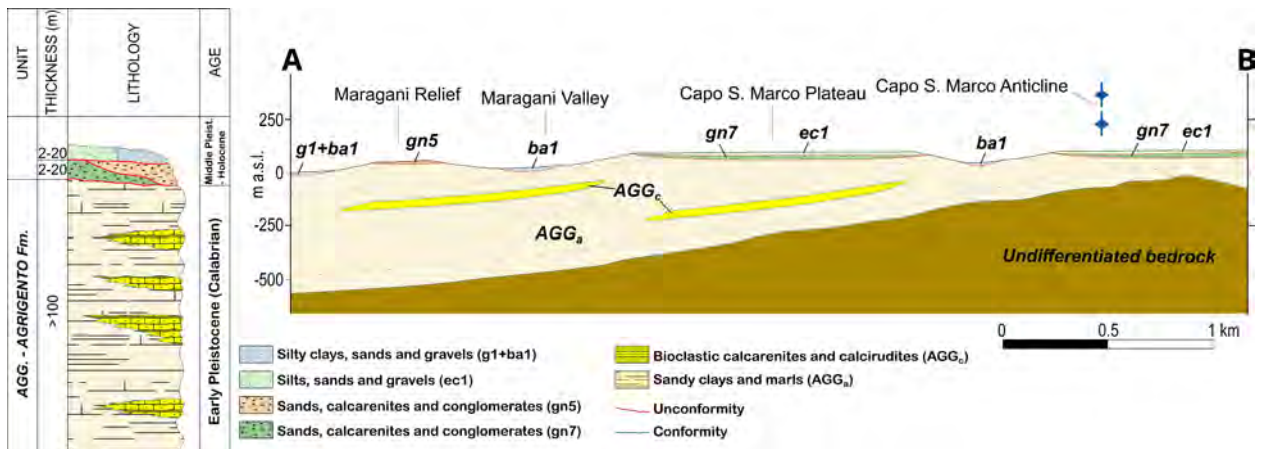


Fig. 2 - Composite lithostratigraphic column shown on the left illustrates the composition and the geometric relationship between the different outcropping units, as well as their average thickness. On the right, the geological cross-section A-B (modified from Sulli et al., 2024) is shown (trace in figure 1a). As regards the A-B section, the undifferentiated bedrock includes the deformed Meso-Cenozoic units of the Saccense domain and the overlying Middle Miocene to Pliocene syn-tectonic deposits (Sulli et al., 2024).

illustrate the stratigraphic architecture across the study area and highlights the persistence of AGG as the underlying unit beneath both marine and continental sequences (Fig. 2).

3. MATERIALS AND METHODS

3.1. Field Mapping

Geological mapping and field observations were conducted between 2021 and 2024 under the framework of the Italian national geological mapping initiative (CARG Project, Sheet 628 - "Sciacca"; Sulli et al., 2024). The survey focused on the Capo San Marco-Carboj River sector, with special attention to the Maragani relief and adjacent terraces. Terrace surfaces were mapped using high-resolution topographic data and field-verified through stratigraphic logging and lithofacies description.

The underlying stratigraphy, including the Early Pleistocene Agrigento Formation (AGG_a), was traced across multiple outcrops and logged in detail to distinguish marine (MIS 5 and MIS 7) and continental facies, as well as to characterize the stratigraphic boundaries.

3.2. Lithostratigraphy

Stratigraphic successions were identified through field analyses, by observing well-exposed outcrops and documenting facies information, thickness, stratal pattern, bedding attitudes, and detailed logs were subsequently obtained. Moreover, stratigraphic relationships between the different units and various boundary types were also examined to produce detailed lithostratigraphic logs (Nichols, 2009; Miall, 2022). Direct macroscopic observations of the grain size and distribution, mineralogical content, and fossiliferous content, served to obtain crucial compositional and granulometric data. Additionally, two sediment samples, labelled as S1 and S2, were collected and then subjected to laboratory processing and analysis. Granulometric analyses were conducted on these samples to estimate the dimensional distribution of the analysed sediments. Thereafter, by using a reflected-light optical microscope we determined the compositional features of the sediments (Besler, 2008).

3.3. Micropaleontological Analysis

One of the two collected samples (S1) was treated in the laboratory to study the micropaleontological content. In particular, a portion of this sample of about 80-100 g was oven-dried, disaggregated in a dilute solution of 10% hydrogen peroxide (H₂O₂) for about 24 h, and then washed using a 63 µm mesh sieve (Ayyad et al., 2025). The residue was then oven-dried at about 50-60 °C and weighed to obtain an estimate of its particle size distribution. Qualitative analysis of the planktonic and benthic foraminiferal assemblages was conducted on the size fraction greater than 125 µm of the residue (Caruso, 2004; Sabbatini et al., 2014; Bonfardeci et al., 2018; Ferraro et al., 2024). The biostratigraphic and chronostratigraphic assumptions were based on planktonic foraminiferal taxa, adopting the most recent biozonal scheme for the Mediterranean Sea (Lirer et al., 2019).

3.4. Luminescence Dating

To establish a chronostratigraphic marker for the Maragani relief, we collected a single Optical Stimulated

Luminescence (OSL) sample (S2-OSL) from a sandy horizon capping the surface. The sample preparation was carried out under low-intensity red light in the OSL/TL laboratory of the Department of Earth Sciences, IIT Kanpur. The outermost 3 cm of each sample was used to assess moisture content and calculate dose rates, while the inner, light-protected portion was used to determine equivalent doses (De). This inner material was sieved to isolate grains between 90 and 212 µm, then treated with 32% hydrochloric acid (HCl) to remove carbonates, followed by 30% hydrogen peroxide (H₂O₂) to eliminate organic matter. To prevent particle clumping, 0.01 N sodium oxalate (Na₂C₂O₄) was added. Fine-grained polymineral fractions (4-11 µm) were isolated by settling based on Stokes' law (Wintle, 2008; Mahan et al., 2023; Malik et al., 2024; Sharma et al., 2024; Srivastava et al., 2025).

For De measurement, continuous-wave OSL was recorded using a Risø TL/OSL reader equipped with blue (470 nm) and infrared (870 nm) LEDs and a ⁹⁰Sr/⁹⁰Y beta source. Post-IR IRSL signals were filtered through Corning 7-59 and Schott BG-39 filters. The fine grains were mounted on 9.8 mm stainless steel cups using a pipette with acetone suspension (~2 mg/ml). The post-IR IRSL Single Aliquot Regeneration (SAR) protocol (pIRIR₂₂₅) was used for De estimation (Buylaert et al., 2009, 2012; Thiel et al., 2011). Aliquots were preheated at 251 °C for 60 seconds, then stimulated twice with IR light for 200 seconds, first at 50 °C (IR signal), then at 225 °C (post-IR signal). A 200-second IR bleach at 290 °C concluded each SAR cycle to remove any residual signals. At least 20 aliquots per sample were analysed, and both recycling ratios and recuperation were assessed. The luminescence signal was derived from the first 2 seconds of stimulation, subtracting the final 50 seconds as background.

To determine the environmental dose rate, surrounding sediment was dried at 50 °C, sealed in airtight containers for over 21 days to allow radon-222 equilibrium with radium-226 and then analyzed via gamma spectrometry using a high-purity germanium (HPGe) detector to measure concentrations of ²³⁸U, ²³²Th, and ⁴⁰K. All luminescence data were processed using Risø Analyst software, and dose rates and final age estimates were calculated using the DRAC (Dose Rate and Age Calculator) version 1.2 (Durcan et al., 2015).

4. RESULTS

4.1. Field characteristics and overall stratigraphic architecture

Field mapping and sedimentary logging at the Carboj River mouth reveal a stratigraphic succession capping the Maragani relief, bounded by the Capo San Marco plateau to the southeast and the present coastline to the southwest (Fig. 1).

The relief itself stretches over 2 km in a NW-SE direction and is constructed from a basal unit of laminated sandy clays and marls, several tens of meters thick, assigned to the Early Pleistocene (AGG_a) (Fig. 3). This unit is unconformably overlain by well-stratified reddish-brown sands and weakly cemented calcarenites, up to ten meters thick (unit gn5; Fig.s 2, 3), which define the key morphosedimentary expression. The relief terminates abruptly to the northeast at the Maragani valley, an incised linear depression notably lacking any visible upstream catchment or channel incision. This valley

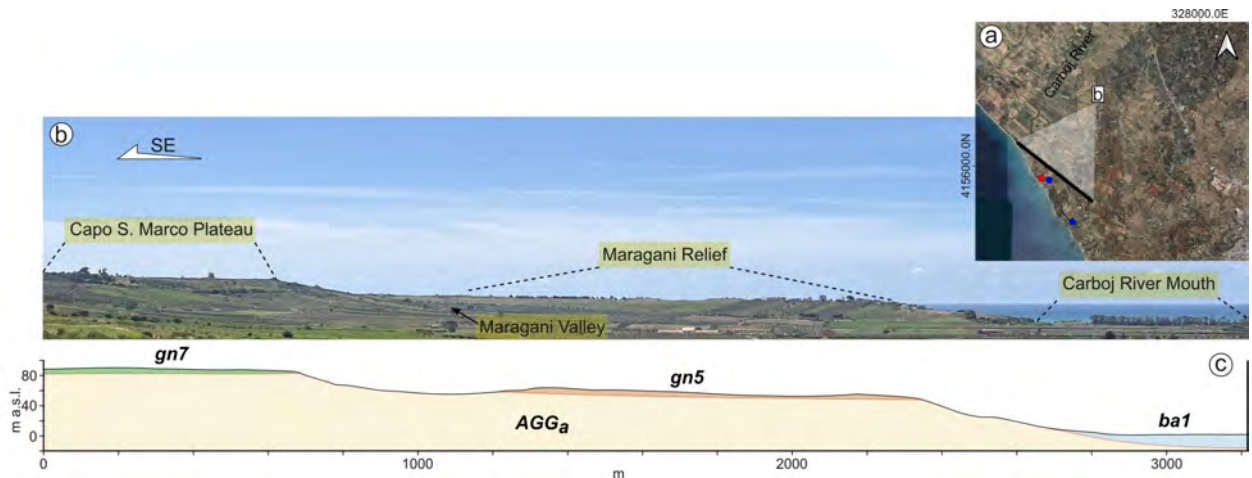


Fig. 3 - (a) Location of the point from which the photo was taken. The black line represents the topographic profile trace along with outcrop locations in red (AGG_a) and blue ($gn5$); (b) Panoramic view of the Carboj River Mouth (on the right), Maragani Relief, Maragani Valley and Capo S. Marco Plateau (on the left); (c) Topographic profile derived from the DEM, corresponding to the panoramic view shown in figure b. Additionally, the corresponding lithologies and their geometric relationships have been reported below the topographic profile.

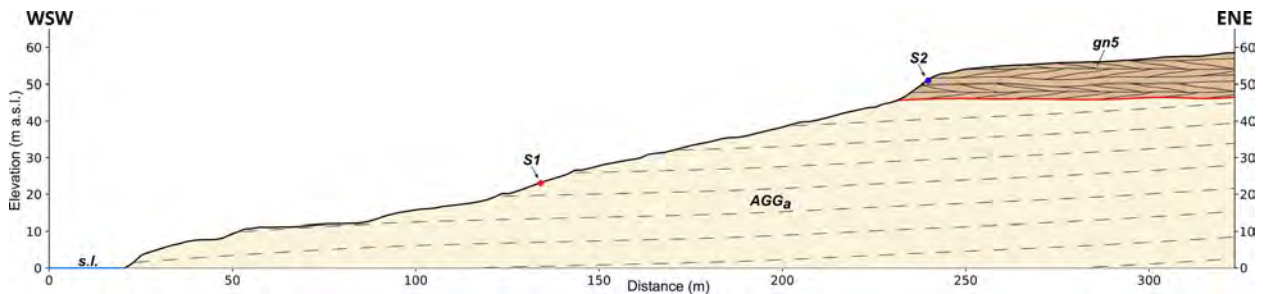


Fig. 4 - Lithostratigraphic sketch of the sampled outcrops from the Maragani relief. Here sample S1 refers to the grey-brownish marls and clays of the Agrigento Fm. (AGG_a) and S2 to the well-stratified, reddish-brown calcarenites of unit $gn5$, organized in sub-parallel to moderately cross-bedded layering.

separates the relief from the Capo San Marco staircase. On its southern edge, the relief is bounded by low-lying alluvial deposits (unit $ba1$) that extend to the present-day shoreline.

4.2. Micropalaeontology and sedimentology of the AGG_a unit (Sample S1)

Two sediment samples were analyzed from the Maragani sequence (Fig. 4). Sample S1, collected from the lower AGG_a unit, showed a fine-grained matrix dominated by clay and marl, with minor sandy silt (Fig.s 4, 5a, b). Micropaleontological analyses revealed a rich and well-preserved planktonic foraminiferal assemblage including *Globigerinoides ruber*, *G. elongatus*, *G. tenellus*, *Globoconella inflata*, *Neogloboquadrina pachyderma*, and *Neogloboquadrina incompta* (Tab. 1; Fig. 5c).

Benthic taxa include *Hyalinea balthica*, a marker for the middle Calabrian (Azzaroli et al., 1996; Caruso, 2004; Cita et al., 2008; Montana et al., 2024). On the basis of the planktonic foraminifera biostratigraphy, sample S1 was attributed to the middle part of the MPl1 zone "*Globigerina cariacensis* Interval Zone" (Lirer et al., 2019). Therefore, the occurrence of *Hyalinea balthica* and the evidence on planktonic foraminiferal assemblage point to a middle Calabrian age (Emilian sub-stage) for this sample.

The sample also contained quartz, calcite, pyrite, and mica fragments, as well as abundant bioclasts, in-

cluding mollusc, echinoderm, and ostracod valve fragments (Tab. 1).

4.3. Stratigraphy, Sedimentology, and OSL Chronology of the $gn5$ Deposits (Sample S2)

The reddish-brown calcarenite outcrops of the marine terrace deposits (unit $gn5$), which unconformably overlie the Early Pleistocene marls and clays of the AGG_a (Fig.s 5a, 6a), are organized in well-stratified, centimetre-thick beds showing sub-parallel to moderately cross-bedded stratification (Fig. 6b). Closer inspection of the outcrop (Fig. 6c) reveals alternating sets of planar and cross-laminated beds, with clear evidence of herringbone structures, as well as storm-generated erosional surfaces truncating previously deposited layers (Fig. 6d). Some beds show weak channelisation, suggesting deposition in a nearshore environment shaped by the combined action of tidal currents and moderate wave energy. The dip directions of the strata and laminae observed in the cross-bedded and herringbone structures are oriented towards NE and SW.

At the northwestern end of the Maragani relief (Fig.s 1a, 4, 6a, 6d), where the same unit ($gn5$) is also exposed, we collected sample S2. The outcrop at the sampling site shows well-stratified, centimetre-thick reddish-brown weakly cemented calcarenites alternating with moderately sorted fine sands. The sediments were subsequently examined under reflected-light optical

| Sample | Elevation (m a.s.l.) | Lithology | Lithic fragments | Bioclasts | Biostratigraphic markers | Biozone | Chronostratigraphy |
|--------|----------------------|---|--|---|---|---------|--------------------------------------|
| S1 | 23 | Clays and marls with minor sandy silts | Quartz, calcite, pyrite, and micas | Mollusc, echinoderm and ostracod shell fragments, and foraminiferal tests | Planktonic foraminifera (<i>Globoconella inflata</i> , <i>Globigerinoides tenellus</i> , <i>Neogloboquadrina pachyderma</i>); benthic foraminifera (<i>Hyalinea balthica</i>) | MPlé1 | Early Pleistocene (middle Calabrian) |
| S2 | 51 | Moderately sorted fine sands and weakly cemented calcarenites | Calcite, quartz, crystalline carbonate fragments, minor pyrite, glauconite, and gypsum | Foraminiferal tests | - | - | Late Pleistocene (77±6.1 ka) |

Tab. 1 - Multi-disciplinary information of collected samples from the Maragani relief.

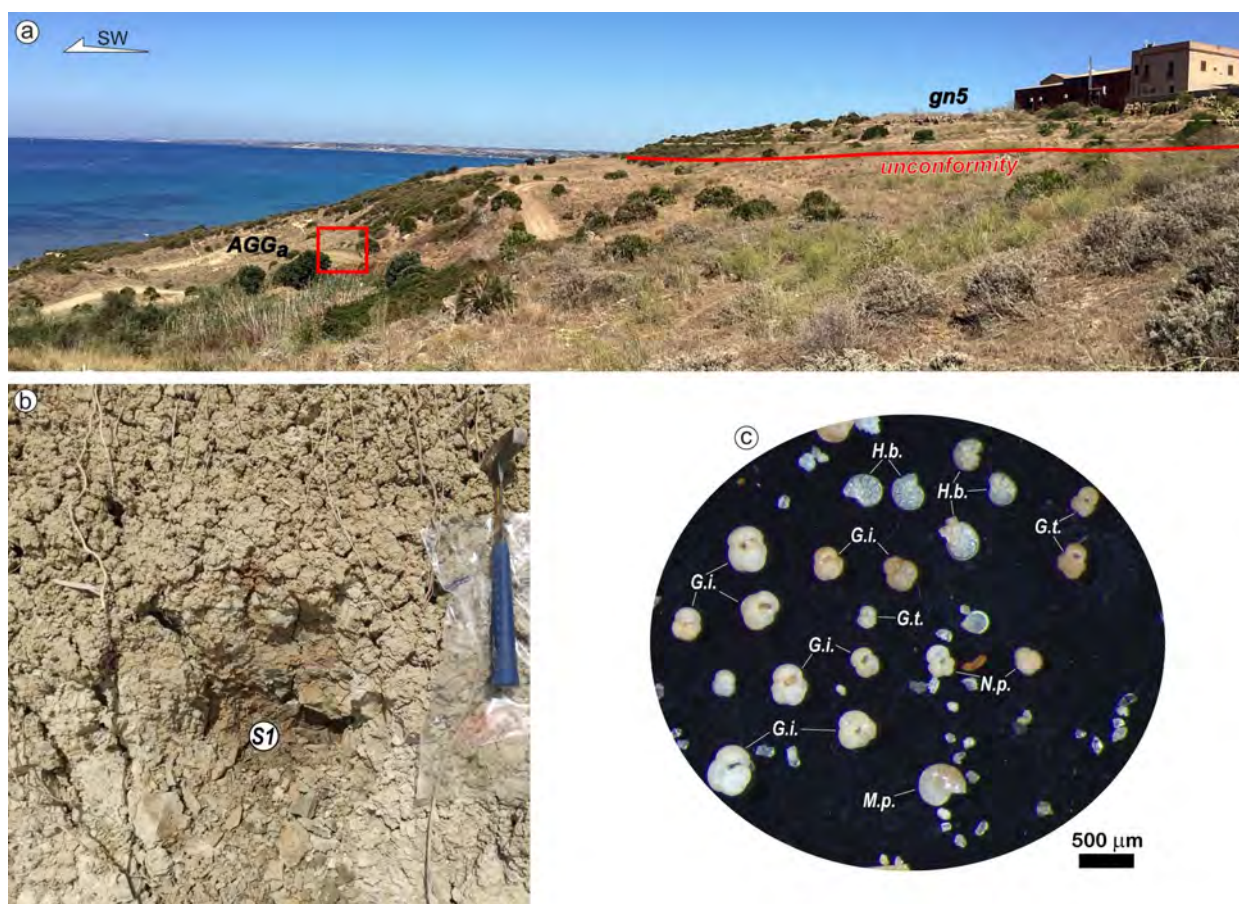


Fig. 5 - (a) A section on the Maragani relief showing the Agrigento Fm. (AGG_a) unconformably overlain by the marine terrace deposits (gn) of the Maragani relief. The red square indicates the site where sample S1 was collected; (b) Detail of the grey-brownish marls and clays of the Agrigento Fm. (AGG_a) is shown, with the indication of the sampling point S1; (c) Microphotograph of sample S1 taken with a reflected-light optical microscope (fraction larger than 125 µm) revealing the main planktonic and benthic foraminiferal taxa identified. The genus and species of the various planktonic and benthic foraminifera taxa are indicated by white labels. Planktonic foraminifera: G.t.= *Globigerinoides tenellus*; G.i.= *Globoconella inflata*; N.p.= *Neogloboquadrina pachyderma* (left coiling). Benthic foraminifera: H.b.= *Hyalinea balthica*; M.p.= *Melonis padanum*.

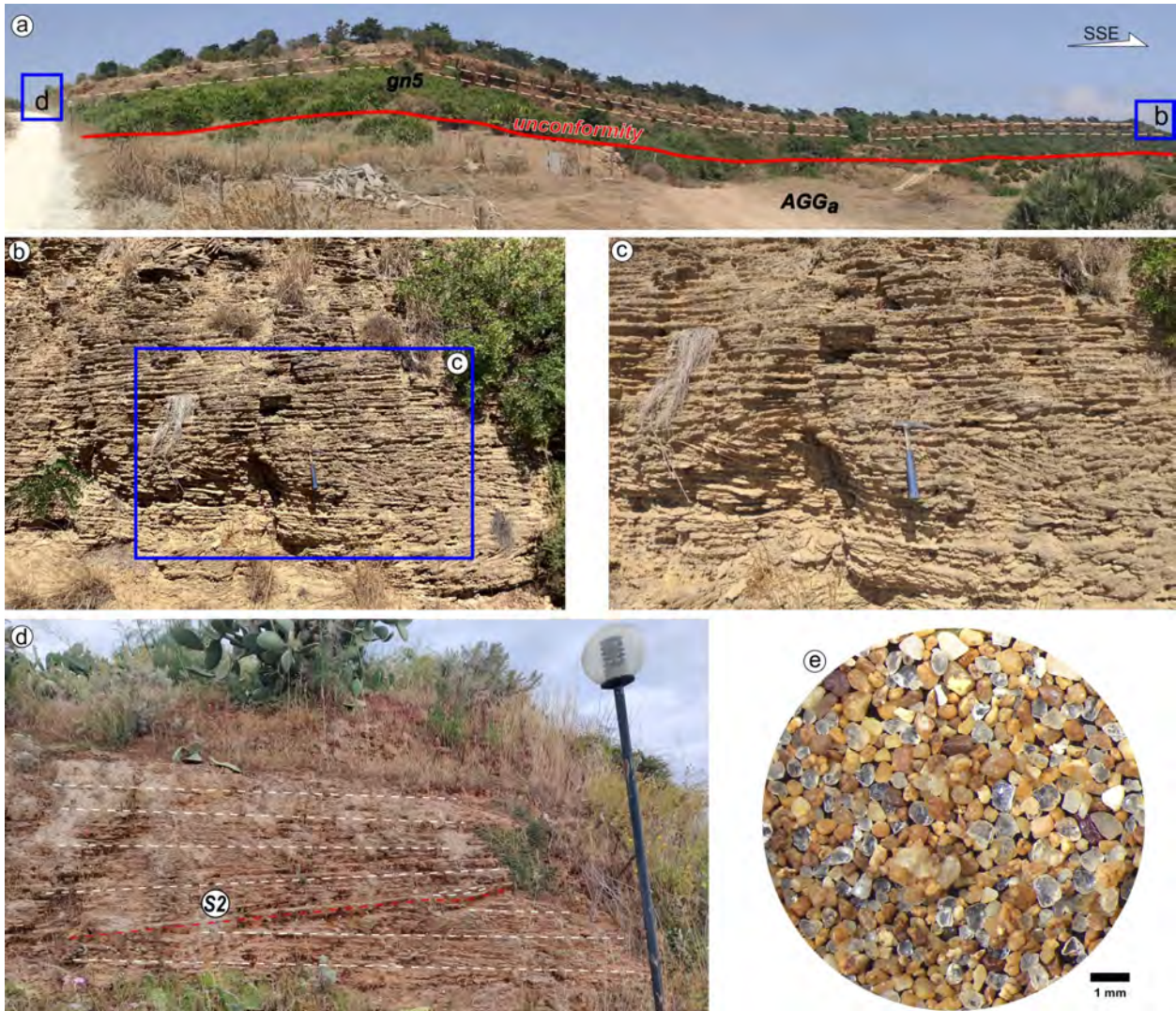


Fig. 6 - (a) Outcrop view of the Maragani relief showing marine terrace deposits (gn) unconformably overlying the Early Pleistocene Agrigento Formation (AGG_a). The unconformity is traced by the red line. Sample S1 (AGG_a) lies at its base. (b) Close-up of the outcrop showing well-stratified, reddish-brown calcarenites of unit gn5, organized in sub-parallel to moderately cross-bedded centimetric layers. (c) Detail from the same outcrop highlighting alternating sets of planar and cross-laminated beds, with evidence of herringbone structures indicative of tidal influence. (d) Lateral view of the same stratigraphic interval showing internal bedding, weak channelization, and storm-generated erosional surfaces (red dashed line), with the sample S2 location. (e) Reflected-light optical micrograph of the S2 sample (fraction >63 μm) displaying moderately sorted fine sands composed of angular to sub-rounded grains of calcite and quartz, along with bioclasts, pyrite, crystalline carbonate fragments, and accessory glauconite, and rare gypsum. The sedimentary features point to a tide- and wave-influenced nearshore depositional setting.

microscopy (Fig. 6e). The sample reveals moderately sorted fine sands composed predominantly of angular to sub-rounded grains of calcite and quartz, followed by crystalline carbonate fragments, minor pyrite, and trace amounts of glauconitic grains and rare gypsum. Notably, the sample includes bioclasts, both reworked planktonic and benthic foraminifera (Tab. 1).

The OSL sample (S2-OSL), taken from the same stratigraphic level as S2, yielded an age of 77 ± 6.1 ka, placing the deposit within MIS 5a (Fig. 7). This result provides a minimum age for the formation of the Maragani surface and is consistent with its elevation relative to other dated marine terraces in the region.

5. DISCUSSION

5.1. Origin and depositional setting of the Maragani relief

The Maragani relief illustrates how broad tectonic and sea-level patterns, well documented along the southwestern Sicilian coast, can manifest in distinctive ways at the local scale. While studies such as Ferranti et al. (2021) and Pucci et al. (2023) have mapped and dated classic stepped marine terraces in the Menfi-Selinunte-Sciacca sector, our observations at the Carboj River mouth reveal a coastal landform that does not conform to the canonical model of terrace formation through marine abrasion or progradation. In this respect,

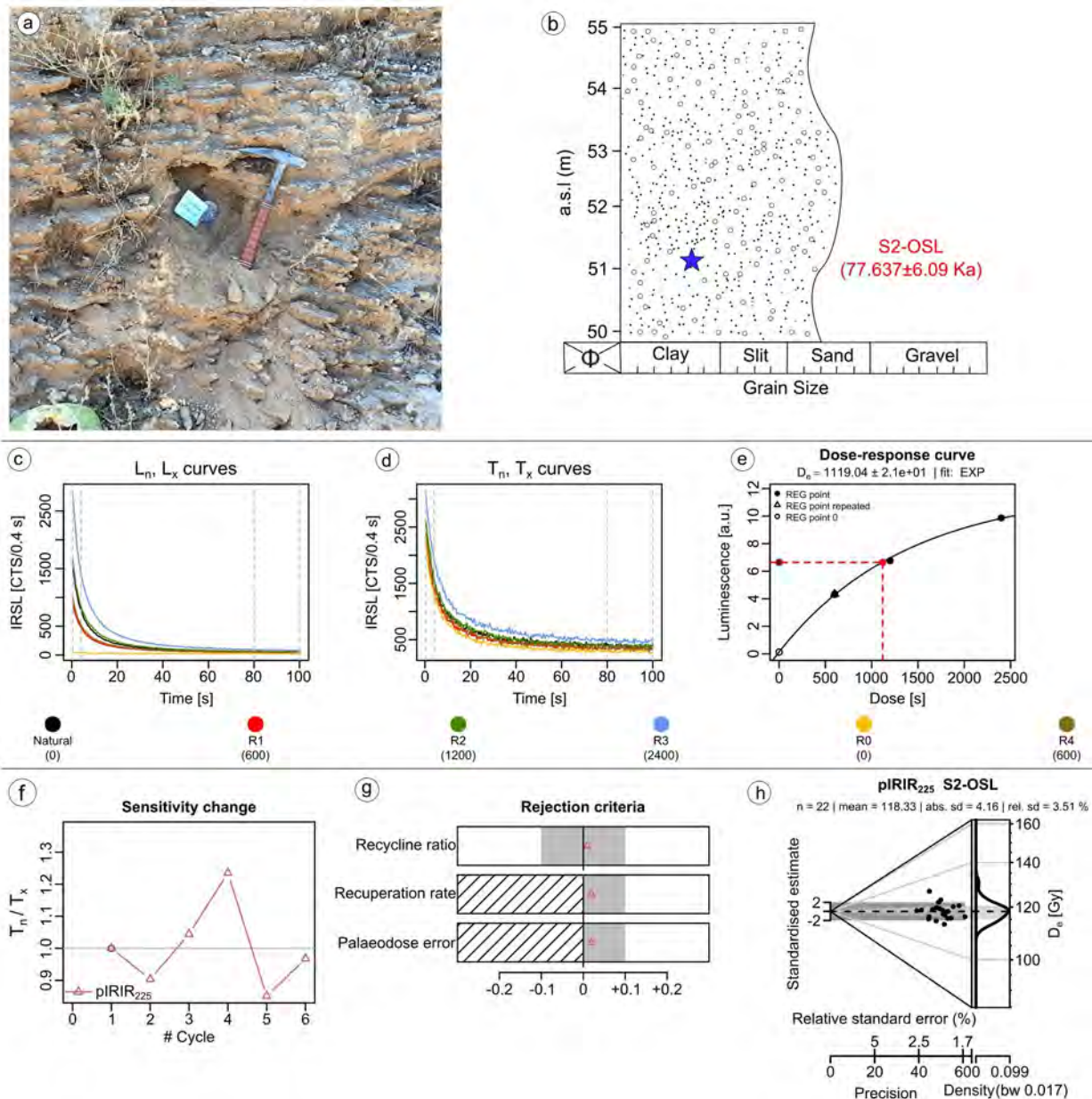


Fig. 7 - (a) Sampling of the sandy unit (gn5) from the Maragani relief for luminescence dating (sample S2-OSL); (b) Grain-size distribution of the sampled horizon; (c-d) Natural and regenerated luminescence decay curves (L_n , L_x ; T_n , T_x) obtained from the post-IR IRSL (pIRIR₂₂₅) Single Aliquot Regeneration (SAR) protocol; (e) Dose-response curve used for equivalent dose (D_e) determination; (f) Sensitivity change between SAR cycles; (g) Quality control parameters showing recycling ratios, recuperation rates, and palaeodose errors within acceptance limits; (h) Abanico plot of individual aliquot D_e values; the calculated age is 77.64 ± 6.09 ka, placing the deposit within MIS 5a.

our interpretation diverges from previous reconstructions of terrace architecture in the region, which largely emphasise planar abrasion platforms and progradational foresets. Instead, the Maragani relief represents a geomorphic anomaly that complements, rather than contradicts, the broader regional framework.

The geometry is the first clue, as the Maragani relief is a narrow, elongated feature perched at approximately 55 m a.s.l., oriented parallel to the coastline but perpendicular to the Carboj River mouth. The adjacent Maragani valley exhibits no upstream catchment, no

incision, and no evidence of channelized fluvial processes. This rules out a fluvial origin and points instead to a coastal depositional environment.

Micropaleontological and lithostratigraphic analysis of the two sampled units, S1 from the AGG_a and S2 from the overlying marine terrace deposits (gn5), reveals a stark contrast in depositional settings and ages. The lower AGG_a unit comprises clay-rich marls with a well-diversified planktonic and benthic foraminiferal assemblage including *Globigerinoides ruber*, *G. elongatus*, *Globoconella inflata*, *Neoglobobquadrina* spp., and *Hya-*

linea balthica, the latter indicating a middle Calabrian (Emilian) age. These assemblages point to upper-bathyal, open-marine sedimentation on a tectonically active slope within the SFTB foredeep. The absence of coastal indicators confirms deposition well offshore prior to any emergence of the Maragani relief.

In contrast, the overlying calcarenites of unit gn5 show well-stratified, moderately cross-bedded layers with alternating planar and cross-laminated sets and herringbone structures typical of tidal environments or under wave influence in shallow water (foreshore/upper shoreface) settings, hinting at an alternately paleocurrent direction of NE and SW (Nichols, 2009; Van Den Berg and Martinus, 2024). Weak channelisation and moderate sorting further support deposition within a mixed-energy nearshore system, consistent with a wave- and tide-modulated mouth bar (Walker & Plint, 1992; Cole et al., 2021). This facies arrangement differs from the classic terrace facies described by Ferranti et al. (2021), highlighting that not all elevated coastal surfaces in this region originated from the same geomorphic mechanism.

The unconformity separating the AGG_a and gn5 units marks a significant break in depositional history, recording burial, deformation, exposure, and truncation of the AGG_a marls prior to renewed highstand sedimentation. This transition integrates tectonic uplift, relative sea-level change, and coastal dynamics operating over >1 Myr. Similar stratigraphic discontinuities have been inferred regionally, but our section provides a rare outcrop-based example along the southwestern Sicilian margin.

5.2. Sea-level history and uplift rates along the Sicilian margin

The OSL age of approximately 77 ka from the gn5 calcarenites places the highstand deposition in MIS 5a. Although MIS 5e, around 125 ka, is commonly used as the principal highstand marker in Sicily, the Maragani relief stands at a comparable elevation despite its younger age. This yields a long-term uplift rate of approximately 0.9–1.0 mm yr⁻¹, which is consistent with the uplift values reconstructed by Ferranti et al. (2021) for the Menfi-Selinunte-Sciaccia sector. Thus, our uplift estimate aligns with regional patterns and indicates that MIS 5a highstands can reach elevations similar to MIS 5e under sustained uplift. In terms of reconstructed sea-level oscillations and uplift rates, our results therefore corroborate previous regional interpretations, even though the geomorphic expression at Maragani differs from classic terrace flights.

This relationship also highlights an important methodological contrast. Many previous uplift reconstructions across Sicily rely on MIS 5e indicators dated through faunal markers or lower-precision age methods, such as amino acid racemization (AAR), electron spin resonance (ESR), or U/Th on *Cladocora caespitosa* (Linnaeus, 1767) and molluscs, as summarised in Antonioli et al. (2025). These approaches often assign a nominal MIS 5e age and may underestimate uplift where highstand correlation is uncertain. Our OSL age provides a higher-precision constraint for this sector and demonstrates the value of integrating luminescence dating into coastal uplift studies along the Sicilian margin. In this sense, our results are methodologically distinct but broadly consistent with existing uplift frameworks, while helping to refine the timing and elevation of younger highstands.

5.3. Local morphodynamics and evolutionary model

What makes the Maragani relief distinctive is its isolation and the absence of similar features at other nearby river mouths. A likely explanation is that, during MIS 5a, the Carboj River entered a locally subsiding or flexurally warped coastal sector, possibly along a frontal splay of the SFTB. In such a setting, low fluvial discharge combined with local bathymetry would have allowed wave and tidal processes to dominate sediment redistribution and promote mouth-bar formation near sea level. The preservation of this feature at elevation reflects subsequent regional uplift.

Further support comes from the alignment of the relief and the sedimentary structures, which indicate southeast-to-northwest longshore transport during the highstand. These directions differ from the modern setting and likely reflect different bathymetric configurations, wave-refraction patterns, or the influence of now-submerged barriers (Micallef et al., 2013; Lodolo et al., 2023). Circulation features such as the Adventure Bank Vortex underscore how sensitive local hydrodynamics are to bathymetric changes, especially during different sea-level stands (Omrani et al., 2016; Borzi et al., 2022; Spatola et al., 2023).

Alternative origins, including fault-controlled basins or catastrophic flooding, can be dismissed. There is no evidence of major reverse faulting, and no chaotic breccias or debris-flow deposits are present. Instead, the sedimentary architecture and fossil assemblages support a long-lived shallow-marine system modulated by relative sea level and uplift (Parrino et al., 2023; Srivastava et al., 2023; Agate et al., 2025).

The conceptual model in Figure 8 outlines this evolution in four stages. During Stage 1, the AGG_a unit accumulated in a deep marine setting during a period of regional subsidence, establishing the structural and stratigraphic base of the Maragani relief. Although a terrace associated with MIS 7 is not preserved in the logged section, Stage 2 likely corresponds to relative sea-level fall and regional uplift during MIS 6. This resulted in partial erosion, deformation, and preparation of the substrate for renewed deposition.

Stage 3 marks the MIS 5a highstand, during which the Carboj River mouth occupied a shallow, wave- and tide-influenced embayment. Here, the gn5 calcarenites were deposited as a mixed-energy mouth bar, shaped by alternating tidal flows, wave reworking, and southeast-to-northwest longshore transport. These deposits now preserve a clear record of highstand shoreline dynamics.

Finally, in Stage 4, regional uplift along the SFTB gradually raised the entire depositional surface to its current elevation, approximately 55 m above sea level, isolating it from further reworking. The juxtaposition of the S1 and S2 horizons, which respectively record deep marine and shallow coastal processes, shows how even a single relief can encapsulate more than a million years of stratigraphic and tectonic history.

6. CONCLUSION

This contribution puts forward a new hypothesis for understanding landscape evolution along a key stretch of the southern Sicilian coastline with just recent information on the uplift rate. The staged conceptual model we present (Fig. 8) integrates geomorphological, stratigraphic, and chronological evidences. This showcases

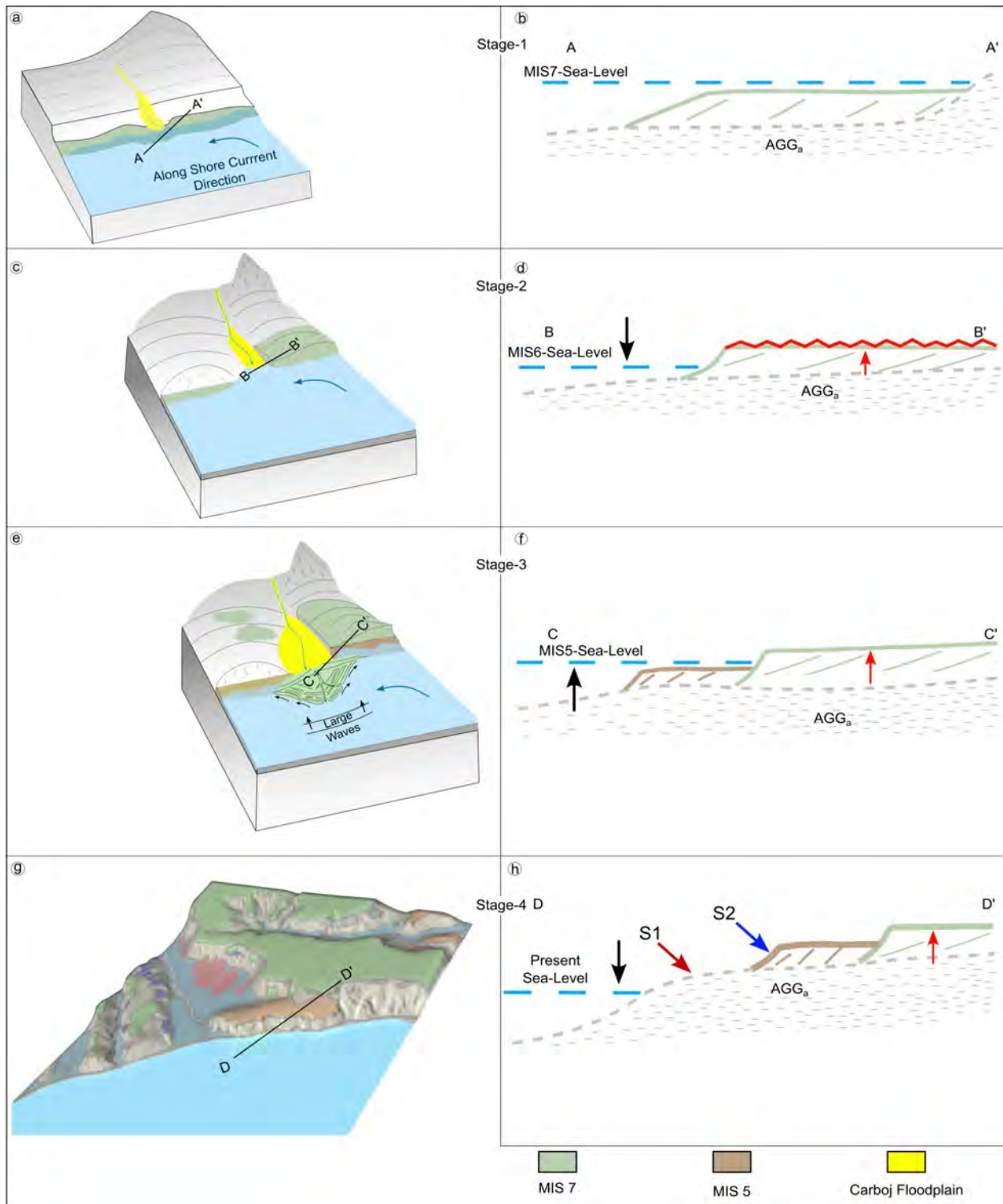


Fig. 8 - Conceptual model illustrating the proposed evolutionary stages of the Maragani relief: (a-b) Stage 1 (MIS 7 highstand): deposition of shallow-marine calcarenites overlying the Early Pleistocene marls and clays of the Agrigento Fm. (AGG_a) under alongshore current influence; (c-d) Stage 2 (MIS 6 lowstand): after relative sea-level fall, valley incision, and initial tectonic uplift of the coastal margin; (e-f) Stage 3 (MIS 5 highstand): formation of a wave-dominated sand bar at the Carboj River mouth under high-energy conditions in the Sicily Channel, followed by continued uplift; (g-h) Stage 4 (recent): present-day morphology with the Maragani relief capped by MIS 5a marine sands (sample S2) overlying the Agrigento Fm. (sample S1).

how local coastal features, like the Maragani relief, record the interplay of regional tectonic uplift driven by the Sicilian Fold and Thrust Belt and global sea-level fluctuations during the Late Quaternary, and how these signals compare with previously reconstructed terrace frameworks and uplift patterns along the Sicilian margin.

What this study highlights is that coastal evolution is not just a story of rising or falling seas. It's also about whether sea-level highstands align with stable surfaces and sufficient sediment supply or miss their window entirely. The Maragani relief, with its unusual geometry and depositional history, stands as a clear example of how these factors can converge to produce coastal landforms that don't fit neatly into regional models, but still hold the imprint of broader geodynamic trends. At the same time, our uplift estimate is derived from a single OSL-dated shoreline unit; although it is consistent with values reported for the Menfi-Selinunte-Sciacca sector, it underlines the need for additional, high-precision dating across southwestern Sicily to test and refine these interpretations.

While further quantitative modelling would enhance this interpretation, the stratigraphic and morphotectonic evidence provided here establishes a solid framework for future tectono-sedimentary investigations in the region. Building on the still sparse but growing body of dated coastal records from the Sicilian margins, this knowledge is essential not only for advancing geological understanding but also for informing sustainable coastal management strategies aimed at preserving the cultural and environmental heritage of the Mediterranean landscape.

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Author contribution: AS, MA, and MGM oversaw the overall research. ES, NP, and AB conducted fieldwork, analyzed and interpreted the data, developed the landscape model with figures, and drafted the manuscript. FC, PB, and AM contributed to visualization and review of the manuscript. ES, MD, and JNM supervised and assisted with the analysis and interpretation of the luminescence data.

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