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Plio-Quaternary coastal uplift along the western Iberian Margin: insights from dated marine terraces (Peniche, Portugal)

Margarida P. Gouveia [a,b,*], Pedro P. Cunha [b,c], António A. Martins [d], Martin Stokes [e], Alberto Gomes [f], Christophe Falguères [g], Pierre Voinchet [g], Jean-Jacques Bahain [g], Telmo Pereira [h,i,j,k], Silvério Figueiredo [i,j,k,l], Qingfeng Shao [m], Olivier Tombret [g]

[a] Câmara Municipal da Figueira da Foz, Portugal
[b] University of Coimbra, MARE - Marine and Environmental Sciences Centre / ARNET, Portugal
[c] Department of Earth Sciences, Portugal
[d] ICT – Institute of Earth Sciences, Department of Geosciences, University of Évora, Portugal
[e] School of Geography, Earth and Environmental Sciences, University of Plymouth, UK
[f] CEGOT, Department of Geography, University of Porto, Portugal
[g] HNHP UMR 7194 - Histoire Naturelle de l'Homme Préhistorique, MNHN-CNRS-UPVD, Département Homme et Environment, Muséum National d'Histoire Naturelle, Sorbonne Université, France
[h] Universidade Autónoma de Lisboa, Portugal
[i] Polytechnic Institute of Tomar, Portugal
[j] Geosciences Center - Univ. of Coimbra, Portugal
[k] Uniarq - Centro de Arqueologia da Universidade de Lisboa, Portugal
[l] Portuguese Center of Geo-History and Prehistory, Portugal
[m] School of Geography, Nanjing Normal University, Nanjing, China

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ABSTRACT

This study presents a detailed geomorphological and geochronological analysis of a marine terrace staircase developed into the Peniche Peninsula (Portugal), a rocky headland of Jurassic carbonate bedrock located in the central sector of the Western Iberian passive margin. The marine terrace levels are described morphologically and sedimentologically, but also dated using ESR and U-Series methodologies. The marine terrace staircase comprises six emerged levels ranging from 4 m (above mean sea level, asl) (Tm6) to 24–28 m asl (Tm1), inset into a summit wave-cut platform at 29–45 m asl (Pm). The marine terrace sediments are composed of rounded boulders to cobbles and coarse sands. Dating results reveal that the marine terrace staircase spans ~900 ka across the Middle-Late Pleistocene. The terraces can be assigned to either a single sea-level highstand or a level that has been re-occupied by two sea level highstands. The staircase records very low uplift rates (0.04 to −0.02 m/ka; the longer-term mean rate for the entire Pleistocene staircase is 0.03 m/ka), typical of a passive continental margin. Regionally, coastal terrace staircases are typically found along the Western Iberian passive margin, with their configuration locally influenced by the underlying bedrock geology and tectonic history.

1. Introduction

Marine terraces are coastal landforms comprising an erosional bedrock surface (shore platform or wave-cut surface) overlain by coastal sediments from beach and/or shoreface origins, and sometimes buried by terrestrial deposits (aeolian, fluvial, slope) (e.g., Bradley, 1957; Anderson et al., 1999) (Fig. 1). Morphologically, marine terraces typically display a flat to gently dipping seawards surface unless buried by terrestrial sediments (e.g., Stokes and García, 2008). The sea level changes recorded by marine terraces reflect the interplay between

* Corresponding author. Câmara Municipal da Figueira da Foz, Portugal.
E-mail addresses: mariamporto@gmail.com (M.P. Gouveia), pcunha@dct.uc.pt (P.P. Cunha), aam@uevora.pt (A.A. Martins), mstokes@plymouth.ac.uk (M. Stokes), albgomes@gmail.com (A. Gomes), christophe.falgueres@mnhn.fr (C. Falguères), pierre.voinchet@mnhn.fr (P. Voinchet), bahain@mnhn.fr (J.-J. Bahain), telmojrpereira@gmail.com (T. Pereira), silverio.figueiredo@ipt.pt (S. Figueiredo), qingfengshao@njnu.edu.cn (Q. Shao), olivier.tombret@mnhn.fr (O. Tombret).

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spatially and temporally variable eustatic and tectonic drivers (e.g., Lajoie, 1986). Conceptually, shore platforms are developed during a rising sea level, with inland migration by a sea cliff notch (Bradley and Griggs, 1976). During a sea level highstand, beach sedimentation commences, followed by burial by terrestrial deposits as the sea level begins to fall. Uplifted coasts, either by sustained active tectonics or isostatic adjustments, are potentially able to record multiple marine terrace levels in a staircase configuration (e.g., Bull, 1985). Staircases are key geomorphological and stratigraphic markers as they can provide quantitative assessments of surface uplift rates, giving insights into coastal landscape development over a range of spatial and temporal scales (e.g., Lajoie et al., 1991). Uplift rate calculation requires knowledge concerning:

1) the elevation of the shoreline angle (landward limit of sea level highstand) for each marine terrace level;
2) a geochronological framework of the marine terrace levels which comprise a staircase;
3) the elevation and timing of a eustatic highstand unaffected by tectonic activity (Lajoie, 1986). Whilst all have inherent complexities and challenges (e.g., Pedoja et al., 2011), the geochronology of a terrace staircase is perhaps the most intricate. The dating limitations of marine terraces are widely recognized. For example, older approaches have often relied on relative stratigraphic techniques, matching terrace levels to their probable interglacial highstands (e.g., Zeuner, 1952). Early adopters of the numerical dating of marine terraces typically involved the U-Series technique (e.g., Hillaire-Marcel et al., 1996; Muhs et al., 1992). This approach provided the chronology for lower and younger terrace levels, especially those associated with the Late Pleistocene Marine Isotope Stage (MIS) 5e, but with poorer resolution for higher and older levels (Early-Middle Pleistocene, i.e. MIS 7 and older). Although new and updated methods are now commonly applied (e.g., U-Series: Zazo et al., 2003; OSL: Normand et al., 2019) age range and accuracy limitations still exist. Literature database modeling approaches have been used to overcome technical dating challenges, where better age-constrained lower and younger levels (e.g. MIS 5e, etc.) have been used to produce different uplift rate scenarios (e.g., Pedoja et al., 2011, 2014). Accordingly, these rates can inform on the timings of the higher-older levels via uplift rate extrapolation and integration with eustatic highstand elevations/timings. In other regions, such approaches suggest an acceleration of the Pleistocene global uplift rate (Pedoja et al., 2011) as well as providing deeper time (Neogene-Quaternary) perspectives on high elevation marine terrace levels and erosion surfaces (Pedoja et al., 2014).

The Pedoja et al. (2011, 2014) database approaches highlight: 1) a need for improved marine terrace age control spanning the entirety of a given staircase configuration, to avoid uncertainty issues for modeling approaches; and 2) a need to fill regional/geographical knowledge gaps concerning marine terrace staircases.

These issues commonly occur with low to moderate uplift rate coastlines, which often preserve marine terrace records but lack research attention compared to tectonically active high-uplift rate coastline regions (e.g., SW USA, Leeward Antilles islands, Mediterranean; Muhs et al., 2012; Karymbalis et al., 2022), where seismic hazard assessment requirements provide a more urgent need for marine terrace analysis (e.g., Hanson et al., 1994).

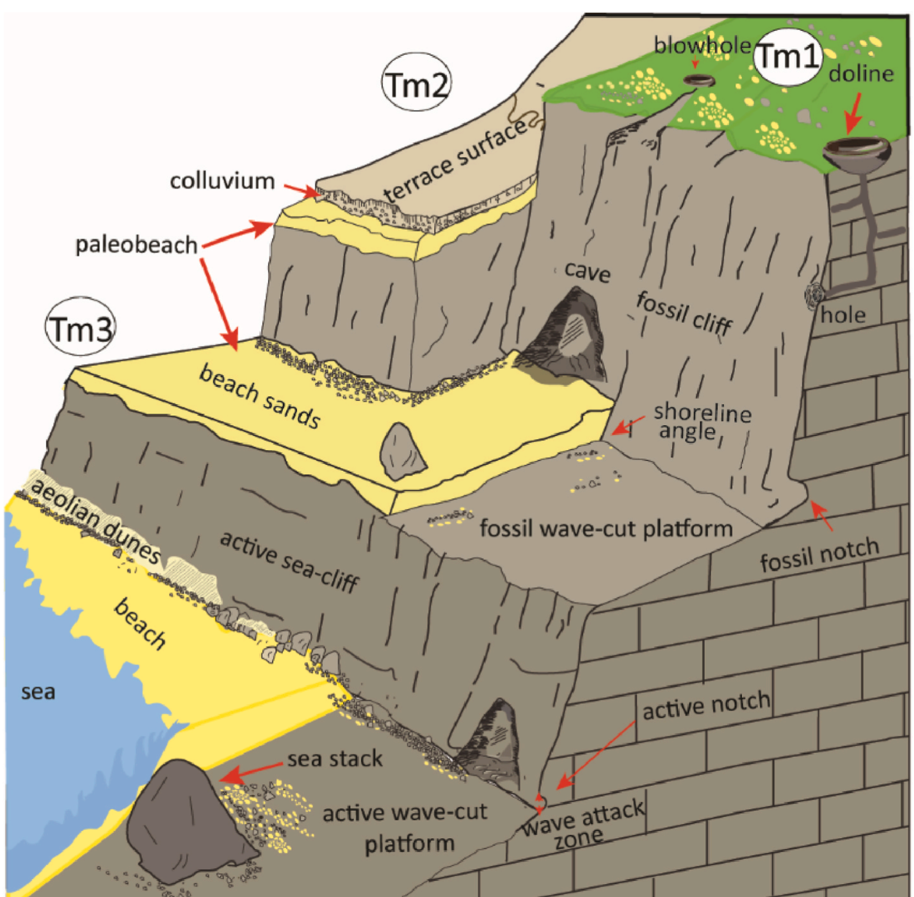

Fig. 1. Conceptual sketch of the component parts of a marine terrace staircase. Tm1 to Tm3 are the emergent marine terraces located above the modern wave-cut (shore) platform and associated beach deposits.

Low to moderate uplift rate coasts are common along the passive margins of rifted oceanic basins (Pedoja et al., 2011, 2014, 2018). Within the Atlantic Ocean, the west-facing Iberian passive margin coastline of Portugal and Spain, about 800 km long, is an example of where marine terrace staircases are preserved in some locations along the entire coast. In this study area, early research was mostly descriptive and followed a classical marine terrace-climate cycle matching approaches assessing various coastal sites along the Iberian margin (e.g., Teixeira, 1979). This approach is still routinely used nowadays; for example, along the SW Iberian Martins et al. (2025) have used an assumed MIS 5e marine terrace that lacks direct age control to inform on spatial variations of surface uplift linked to active tectonics. Only

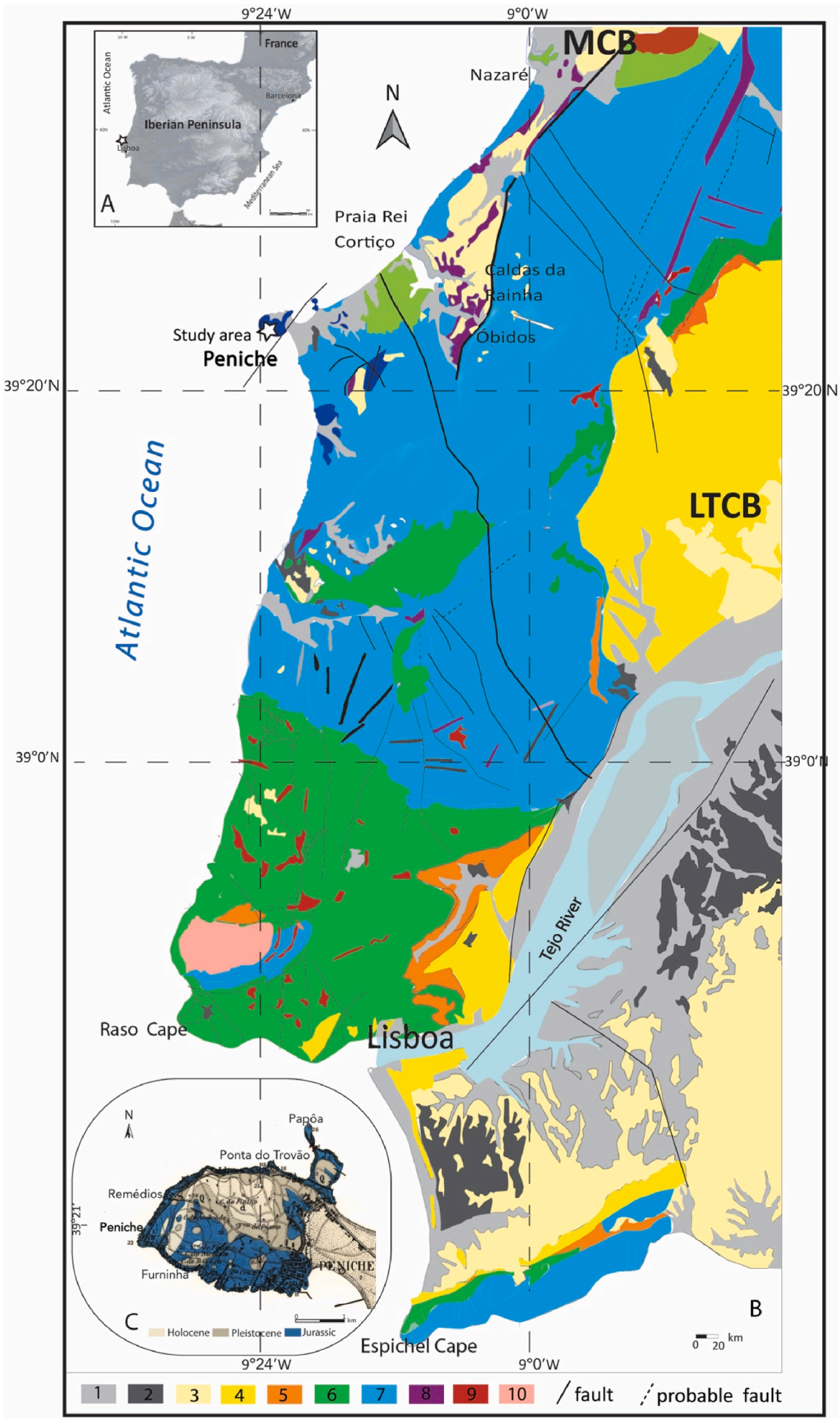

Fig. 2. A - Geographical setting of the study area (black star); B - simplified geological map (1/500,000) of central western mainland Portugal; C - geological map of Peniche (1/50,000 as the original scale). Legend: 1 - Holocene; 2 - Pleistocene; 3 - uppermost Zanclean to Gelasian; 4 - Miocene; 5 - Paleogene; 6 - Cretaceous; 7- Jurassic; 8 - Triassic; 9 - volcanic rocks; 10 - granite.

recently, have studies begun to apply dating methods – e.g., Radiocarbon (^{14}C), Thermo-luminescence (TL), Optically Stimulated Luminescence (OSL), Electron Spin Resonance (ESR), U-Series and Cosmogenic (TNC) – to marine terraces. Much of this dating work focuses on Late Pleistocene coastal sequences associated with the MIS 5e highstand (e.g., Alonso and Pagés, 2007) to inform on paleoenvironmental changes associated with climatic-eustatic variability. In westernmost central Iberia, Late Pleistocene marine terraces with MIS 5e and MIS 3 contexts have yielded important information concerning the early human (Neanderthal) coastal occupation and coastal resource exploitation (Aubry et al., 2005; Benedetti et al., 2009; Haws et al., 2010; Zilhão et al., 2020).

Some common themes emerge from marine terrace studies along the Iberian Atlantic passive margin: 1) during the 20th Century a large number of research studies have been chiefly descriptive; 2) dating studies are few, and where undertaken the temporal relationship to a given highstand is often the best estimate based on stratigraphic bracketing; for example, sediments dated to MIS 4-2 suggest that the underlying shore platform and any beach sediments are related to the MIS 5e highstand; 3) dating studies of marine terrace staircases, especially those that preserve levels older than MIS 5e are very rare. Where dating has been attempted, issues with the quality of the sampled material and the limitations of the dating technique often provide minimum ages or large age error bars that span multiple glacio-eustatic cycle(s) (e.g. Martins et al., 2025).

Considering the aforementioned issues associated with marine terrace research along the Iberian Atlantic continental passive margin, we describe and date an exceptional marine terrace staircase developed onto the rocky headland of the Peniche Peninsula (westernmost central Portugal; Fig. 2). The staircase spans the Early to Late Pleistocene, thus providing a unique and potential key reference site of passive margin coastal landscape development along the Western Iberian Margin. Firstly, we describe the staircase sequence using remote sensing and field-based mapping, surveying, and characterizing the marine terrace morphological and sedimentary components. Then, we apply ESR and U-Series dating techniques to the deposits of the terraces. Terrace elevation and geochronological data are then assessed alongside global Pleistocene eustatic highstand positions and timings. Finally, we use the collective results of the marine terrace staircase geomorphology, geochronology and the global eustatic curves to quantify temporal variations in tectonic uplift. We then consider these vertical movement rates according to local-regional Iberian marine terrace research in specific and to low-moderate uplift passive margin coastal landscape development in general.

2. Geological and geomorphological background

Marine terraces (Fig. 1) are developed intermittently along the length of the Iberian passive margin which forms a west facing Atlantic Ocean coastline that runs for ~800 km between ~37° and 43°N.

Geologically, this margin is dominated by Palaeozoic bedrock deformed during the Variscan orogeny, forming high mountainous relief (elevation up to ~2000 m elevation) to the north and inland, and a low elevation (~180 m) widespread planation surface across the south of mainland Portugal (Galve et al., 2019). Mesozoic-Cenozoic bedrock dominates the central-southern parts of the coastal margin, representing the aggradational and erosional remnants of large sedimentary basins (Cunha, 2019).

The culminant unit of the sedimentary Cenozoic basins in Portugal (the allostratigraphic unit UBS13) was dated to ~4 Ma at its base (CN12a biozone and $^{87}Sr/^{86}Sr$ ages 3.79 ± 0.27 Ma; Cachão, 1990, 1995; Gili et al., 1995; Silva, 1996; Diniz et al., 2016), 4.26 ± 0.29 Ma (TNC; Seal, 2017) and to 1.8 Ma at its top (ESR; Gouveia et al., 2020).

In SW Portugal, cosmogenic dating of this culminant sedimentary unit yielded the 26Al/10Be ages of 4.5 ± 0.3 Ma and 4.6 ± 0.2 Ma (Ressurreição, 2018); 2 Ma +0.3/-0.2 Ma (Figueiredo, 2015); and 1.96 ± 0.09 Ma (Seal, 2017).

This culminant unit (UBS13), in western and southern mainland Portugal, comprises alluvial fan and fluvial deposits inland, changing to deltaic and shallow marine deposits near the coast. The same culminant unit and surface is also represented in the SW of Spain and North of Morocco, at least exposing the widespread wave-cut platform of its base (e.g., Araújo, 1997; Ramos-Pereira, 2004; Cunha et al., 2017; Gouveia et al., 2020; Gutierrez-Mas and Mas, 2013; Hssaine and Bridgland, 2009). The global sea level at 4 Ma (Middle Pliocene) is considered to be ~22 m (Miller et al., 2020).

The fill of the Cenozoic basins forms low elevation undulating landscapes with localized elevated hills linked to Alpine tectonics, separating different basin domains. Marine and fluvial terrace staircases tend to develop better in association with these elevated fault bounded topographies that are commonly associated with stronger rock strengths (eg., rocky headlands).

The Peniche study area is a rocky island of resistant Lower Jurassic limestones attached to the mainland by a sand spit. It is located some 75 km North of Lisbon, in the uplifted Western Mesozoic Reliefs, which separated the Cenozoic Mondego and Lower Tagus basins (Fig. 2B; Galve et al., 2019). (Fig. 2B). The main active tectonic structures located near the study area include the NNE-SSW trending Pombal – Leiria - Caldas da Rainha fault zone, conjugated with the NW-SE Ferrel fault (Cabral, 2012), and a NE-SW fault to the SE of the Peniche Peninsula (Fig. 2B).

With 10 kms of perimeter, the peninsula (a former island) is bordered to the North, West and South by 5–30 m high steep cliffs (Fig. 3). It has a diverse range of Mesozoic lithologies composed of Lower Jurassic marine carbonates of the Cabo Carvoeiro Formation. Across the peninsular, these are mainly calcarenitic limestones, with an occurrence of the Papôa Cretaceous volcanic breccia in its NW sector (França et al., 1960; Duarte and Soares, 2002).

The culminant shore platform has its surface varying in elevation from 29 m asl in the West to 45 m asl in the East (Fig. 4). In the Peninsula the culminant shore platform ranges from 29 to 34 m asl, restricted to a small area around the westernmost Cape Carvoeiro headland. The altitude of this culminant shore platform is consistent with the regionally extensive uppermost Zanclean shore platform and its overlying Piacenzian to Gelasian deposits that are widespread across the mainland Portugal landscape (e.g., Gouveia et al., 2020). Inset into the summit shore platform is a staircase of marine terrace remnants, comprising shore platforms with variable widths, sea cliff notches, and a coastal sediment cover that forms altitudinally levels positioned between 4 m and 24–28 m asl (Fig. 4). Cave karst is commonly developed into the sea cliffs around the island margins. On the southern island flank is the entrance to a passageway at ~16 m asl that opens out into the Furninha cave. This is an important site with dated Late Pleistocene sediments, fossils, and Middle Palaeolithic to Neolithic artefacts (Delgado, 1884; Raposo, 1995; Zilhão, 1997), which provides some significant paleoenvironmental context for the marine terrace focus of this study. The eastern Peninsula margin comprises Holocene aeolian sands that link Peniche to the mainland. Inland, the topography progressively rises in a stepped staircase configuration of coastal terrace levels developed between 6 and 9 (T5f) and 35–45 m asl (Pf), cut into Jurassic bedrock (Fig. 4).

Regarding climate, the Pliocene was characterized by global warming and high sea levels (Vieira et al., 2018). According to Dowsett et al. (2013), global sea surface temperatures (SST) during the Pliocene warm period around 3 Ma were 2–3 °C higher than in the 20th century.

Interglacial periods across the last 1 Ma show the SST close to 20 °C, contrasted by intervening glacial periods, which comprise widely recognized extremely cold stadial events across Western Iberia (Rodrigues et al., 2011, 2017). During the Middle and Late Pleistocene, the SST in the Western Iberian Margin fluctuated between 6 °C and 21 °C, with the warmest temperatures occurring throughout interglacials MIS 5e and MIS 19c. Climatically, MIS 11 represents the

Fig. 3. View, toward NE, of the Peniche Peninsula (photo by Daniel Despont). The main relevant sites are indicated.

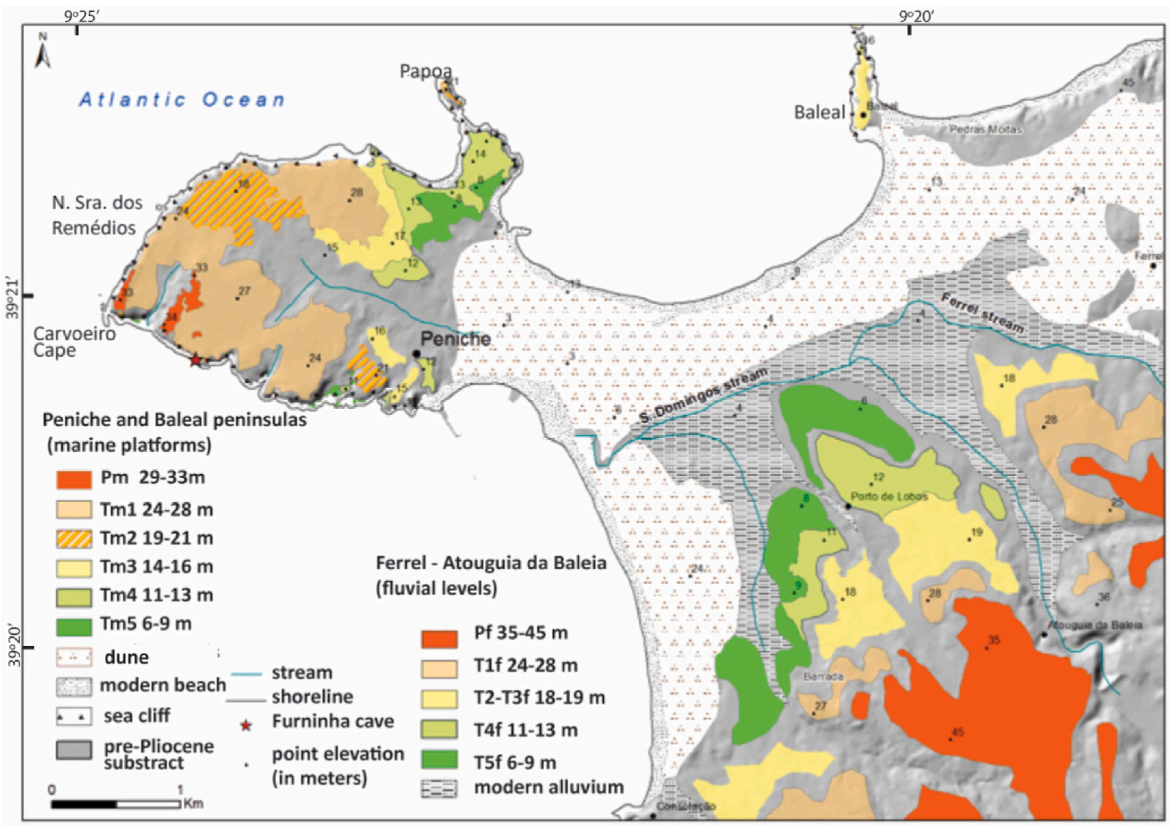

Fig. 4. Spatialization of the surface of the culminant shore platform, terraces, aeolian sands and modern beach sedimentary units across the Peniche Peninsula study area and its landwards connection, highlighting key shore platforms and coastal levels. The Tm6 cannot be represented on this figure due to its small witdth.

warmest sea surface temperatures of a recent interglacial, followed by MIS 9 with the highest sea levels. The coolest interglacial (17 °C) was MIS 23 (Rodrigues et al., 2011, 2017).

3. Materials and methods

3.1. Geomorphology

The Peniche marine terraces were firstly investigated by remote sensing and field-based mapping and surveying. Geomorphological mapping was undertaken at 1/10,000 scale using a municipal topographic base map in conjunction with (30 cm/pixel) LiDAR derived DEM dataset (DGT, 2011) to characterize the broad morphological configuration of the peninsula. A 1/50,000 geological map (França et al., 1960) was used to establish relationships between the peninsula morphology and its underlying bedrock geology (lithology, stratigraphy and structure). Coastal cliff areas with well-developed marine terrace levels (e.g., Furninha site) were documented by drone aerial photogrammetry and field based differential GPS survey. The GPS surveying used real-time kinematics with a GNSS Epoch 50 RTK system for cm-scale location and elevation accuracy. Survey data from less accessible vertical cliff sections were supplemented with handheld tape measure values. The mapping and surveying results established a relative stratigraphic framework of marine terrace levels, providing context for detailed analysis of the geomorphology, stratigraphy, sedimentology, but also geochronological sampling of the component levels. Special attention was given to the elevations of the innermost shore platform edges and shoreline angles of each terrace level, since these components provide key data inputs into uplift surface quantification (e.g., Lajoie, 1986).

The maps were made in ArcGIS Pro, combining the geological and topographic cartography; tables were created using Microsoft™ Excel® and the drawings were made using Adobe Illustrator.

3.2. Sedimentology

The Peniche marine terraces are expressed by sedimentary covers that vary in distribution, thickness, and sediment type (Fig. 5). Sediment distribution and thickness were recorded through field mapping and survey (section 3.1). Sediments were then described in terms of lithological, textural and compositional characteristics to inform the marine terrace depositional setting and targeting geochronological sampling (section 3.3).

Sedimentological analyses of the terrace deposits were performed to characterize sedimentary processes. Sand grain-size analyses were carried out in the Department of Earth Sciences of the University of Coimbra (DCT-UC). The carbonate cement of sandstones was dissolved using HCl (10 %). Grain-size analyses were then performed using a sieve stack with ½ Φ increments. Sand grain sediment composition analyses used binocular microscope observation (50x) and X-ray powder diffraction using a Panalytical Analytical Aeris XRD diffractometer with a Cu tube in a 2θ range, at a scanning rate of 3° min −1, 40 kV and 15 nA. The mineralogical composition of non-oriented subsamples was obtained using HighScore Plus analytical software. Sand subsamples were prepared according to the standardised Panalytical backloading system, which provides near-random particle distribution.

3.3. Geochronology

The timing of marine terrace formation was primarily determined using the ESR technique. The marine terraces sediments and their quartz and feldspar sand grains are buried. The minerals then accumulate electrons within their crystal lattice structures through particle bombardment by radioactive decay. The ESR technique exposes the target mineral(s) to high-frequency electromagnetic radiation, exciting the trapped electrons and causing them to resonate. The resonance is proportional to electromagnetic adsorption, reflecting the number of trapped electrons and thus age. ESR dating offers opportunities for dating Late-Middle Pleistocene or older marine terrace levels and highstands.

Terrace levels Tm1 (highest) to Tm5 (lower) were sampled by collecting ~50 × 50 cm blocks of sandstones. Three samples were taken from Tm3, taking advantage of its better preservation to provide greater insight into the timing of marine terrace formation. No samples were obtained from the lowest Tm5 and Tm6 levels, because they lacked sufficient sediment cover.

ESR dating was applied to the Tm1 to Tm4 levels (6 samples). The sampled blocks were disaggregated under controlled laboratory conditions involving extraction of the 250-180 μm fractions of quartz. Grains were then subjected to different laboratory protocols to calculate the Paleodose (De) and natural (annual) Dose (Da) rate parameters required for age calculation. For the De measurements, a multi-aliquot additive (MAA) dose procedure was employed. The Da measurements used the 250-180 μm grain fractions, which were etched and measured using high-resolution low-background gamma-ray spectrometry with the dose-rate conversion factors of Guérin et al. (2012). Full details of the ESR preparation, measurement and age calculation steps are provided as Supplementary Information.

Some travertine deposits occur at the top of two marine terraces in the Furninha area. These deposits provide an alternative means to age bracket the marine terrace development, complementing the primary ESR dating. The U-series decay chain methodology (Bateman, 1910) was first used in studies of sea-level change by dating corals from continental passive margins and in tectonically uplifted reef complexes (Chappell, 2002; Muhs et al., 2002). Travertines generally behave as closed systems to uranium uptake after calcite precipitation. They will achieve secular equilibrium, with the number of radioactive decay events in the decay series being equal to that of the long-lived uranium parent isotope, whereby the measured age can be regarded as real (Normand et al., 2019). Travertine formation is typically associated with warmer and wetter climatic conditions, constraining the time of interglacial high sea-level stands (e.g., El Kadiri et al., 2010).

In the Furninha site, one sample of travertine was collected from topmost part of the Tm3 deposits (Fig. 5G) and another from the Tm4 top. Full details about the analytical procedures, sample preparation, laboratorial measurements and age modeling are described in Supplementary Materials.

Fig. 5. Field sections from the Furninha area, roughly parallel with the modern shoreline, from where most of the geochronological samples were collected. A – Tm1 wave-cut platform; B – Tm2 wave-cut platform; C – Tm3 wave-cut platform D – Tm4 wave-cut platform; E – shore angle of the Tm4 wave-cut platform. F – Tm5 wave-cut platform; Furninha cave entrance; G – *in situ* dose rate measurement; H – sample Pen1 being collected from Tm3 deposits.

3.4. Paleosea level highstands and calculation of surface uplift

The resulting ESR ages of the terraces dated were compared to global eustatic cycles (ages given by Lisiecki and Raymo, 2005) and the sea level data supplied by Spratt et al. (2016), since they are based on 57 globally distributed oxygen isotopic records). This allowed the marine terraces to be assigned to different sea level highstands and their respective MISs. The inferred corrected uplift rate, as defined by Bull (1985), involves subtracting the present marine terrace shoreline angle altitude from the shoreline angle altitude of the global paleosea level at the considered age. The corrected height is then divided by the age of the marine terrace. So, for each terrace level, the shoreline angle elevation (E), the age of its beach sediments (A) and the global sea level height at the time of terrace formation (e) were used to quantify the surface uplift rate (U) using equation (1) of Lajoie (1986).

$$U = \frac{(E - e)}{A} \tag{1}$$

4. Results

4.1. Marine terrace stratigraphy, geomorphology and sedimentology

Six marine terrace levels (Tm1 to Tm6: highest to lowest) were identified by field survey across the Peniche peninsula (Fig. 6). These levels are positioned between 24 and 28 to 4 m asl, inset into the uppermost Zanclean marine erosion surface (age data in section 2) that occurs between 29 and 34 m asl in the peninsula. Tm1 is the most spatially extensive terrace level occupying elevations ranging from 24 to 28 m asl and dominating the southern area. Tm2 (19–21 m), Tm3 (14–16 m) and Tm4 (11–13 m asl) occur across Peniche but have particularly well-developed inner platforms and sea notches along the southern coast. Tm5 (6–9 m) and Tm6 (4 m) are only developed locally at some coastal cliff margins.

The Tm1-Tm6 terrace staircase is best developed along the southern coastal cliff sector of the Furninha Cave site (Figs. 7 and 8). Each level typically comprises a shore platform, a shoreline angle and an overlying sediment sequence dominated by cemented siliciclastic sands with

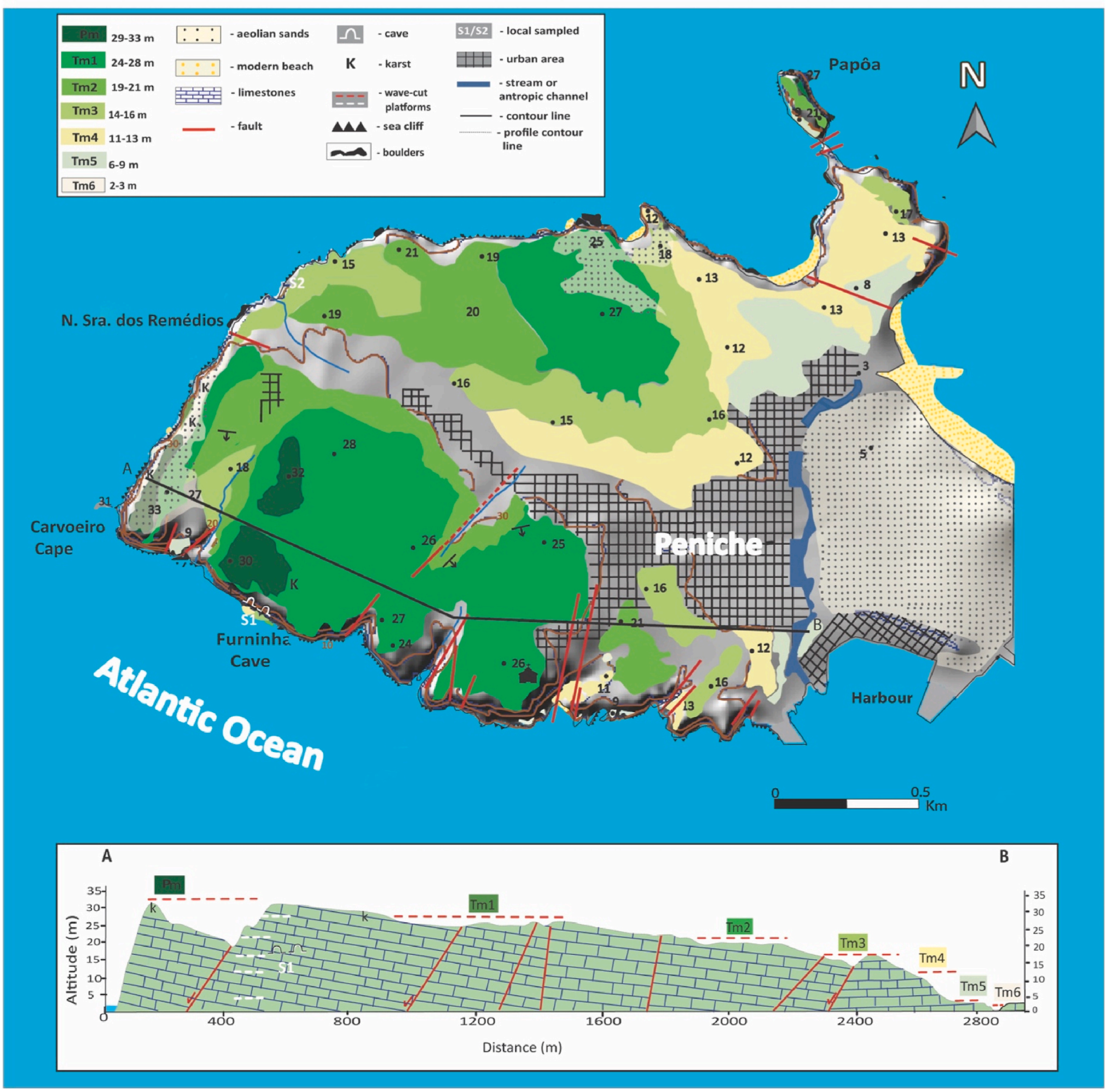

Fig. 6. Simplified geomorphological map and geological section of the Peniche peninsula, showing the main shore platforms (note: Tm6 is too small to be represented at this scale) and other geomorphological information. ESR sample sites: S1 = Furninha site, samples Pen2 (Tm3), Pen3 (Tm3), Pen4 (Tm2) and Pen5 (Tm1); S2 = ~500 m NE of N. Sra. dos Remédios, sample Pen1 (Tm3).

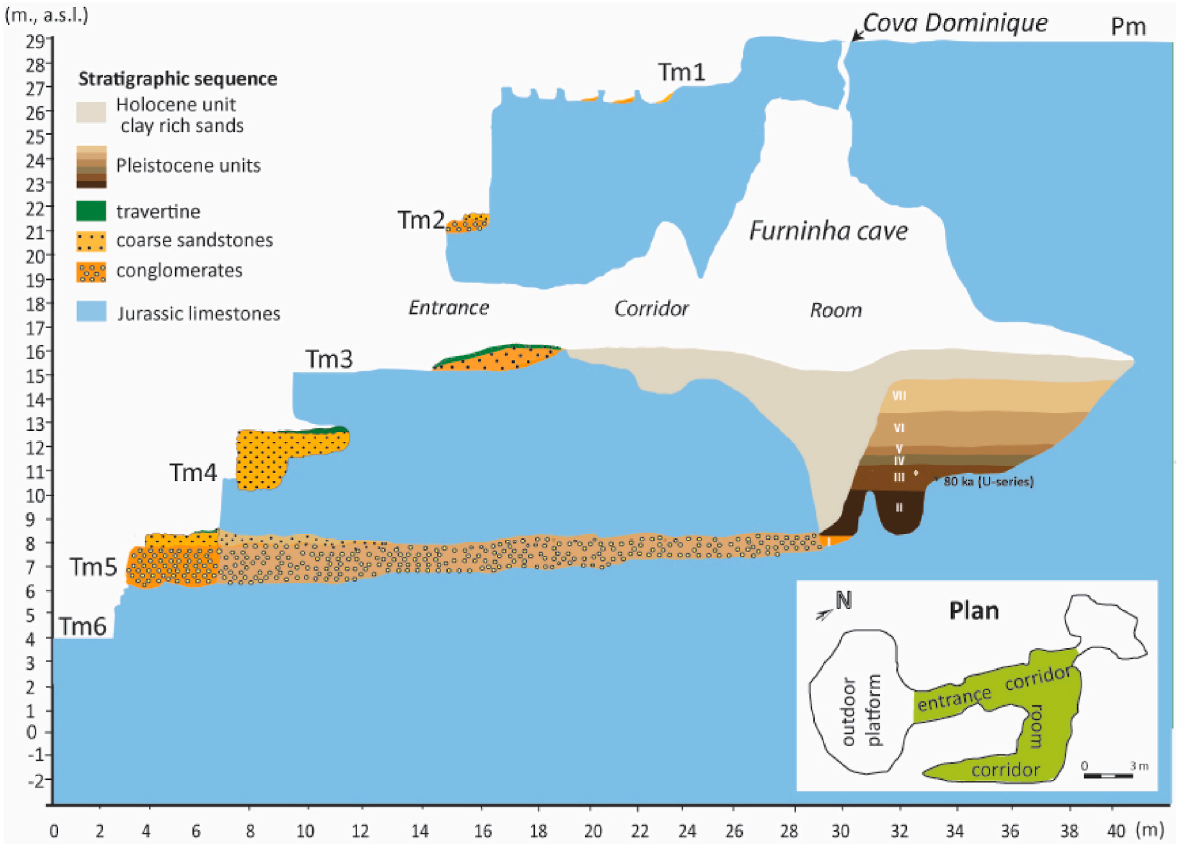

Fig. 7. Schematic representation of the marine terrace staircase and cave-karst system of the Furninha site (see Fig. 6 for cave location). Pm = culminant wave cut surface); Tm (1–6) = wave-cut platforms and associated marine deposits (the Pleistocene unit comprises a lower marine conglomerate (I) and upper layers of aeolian sands (II to VII); the Holocene unit comprises clay-rich sands). In the late 19th century, the Pleistocene and Holocene units were completely excavated (Delgado, 1884).

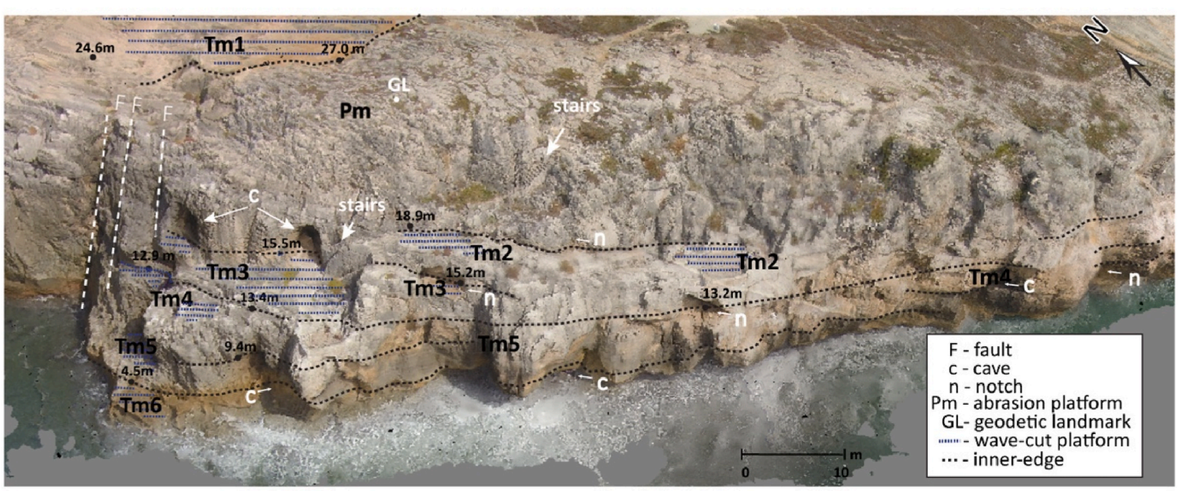

Fig. 8. Drone acquired 3D model of the coastal terrace staircase within the Furninha site, located ~850 m SE of Cape Carvoeiro. Marine terraces Tm1 to Tm6 and other relevant geomorphological elements are indicated.

carbonate shells, but often comprising gravels with rounded boulders as a basal layer.

Within the Furninha site, Tm1 comprises an ~18 m wide shore platform developed into Jurassic limestones with a shoreline angle positioned at 26.9 m. The platform surface comprises a ~1.0 m plus karst topography of poorly sorted medium-coarse sands with occurrences of marine shells. The sands were sampled for ESR dating (Pen 5) ~6.0 m from the shoreline angle.

Tm2 comprises a narrow, 4.0 m wide wave-cut surface with a shoreline angle at 20.7 m. The deposits comprise a basal 0.5 m thick layer of gravels with cobbles and boulders, capped by 1.0 m of very coarse to coarse sands, sampled for ESR dating (Pen 4) ~0.5 m from the shoreline angle.

Tm3 is a very well-developed wave-cut surface that can be traced along the length of the southern coastal cliff region. In the Furninha site, this surface is up to 16.0 m wide with an outer edge at 13.5 m and a shoreline angle at 15.5 m. Up to 3.0 m of marine sediments overlie this surface, comprising a basal unit of conglomerate with well-rounded boulders set within a gravelly-sand matrix that grades up into yellow coloured coarse-medium sands with carbonate shells and bone fragments at its top. A thin, 0.2 m thick, travertine layer caps the sands. Samples for ESR dating were collected from the base (Pen2) and top (Pen3) of this terrace in the Furninha site, whilst a further sample was taken from the base of Tm3 sands (Pen1) that outcrop along the northern coastal cliff area for chronological validation purposes.

Tm4 comprises a well-developed but narrow, 6.0 m wide wave-cut surface with an outer edge at 10.0 m and a shoreline angle at 12.9 m. The platform is capped by up to 2.5 m of basal cemented gravels and coarse sands, covered by a thin travertine layer. An ESR sample (Pen8) was taken from sands at 0.5 m above the base.

Tm5 comprises an 8.0 m wide wave-cut surface with an outer edge at 5.0 m and a shoreline angle at 6.4 m. This wave-cut surface is capped by 2.0 m of pebbly gravels (1.4 m) and a pebbly coarse sandstone (0.6 m), overlain by a thin (0.1 m) travertine. A sample (Pen7) was taken from the pebbly coarse sandstone unit.

The lowermost Tm6 unit comprises a narrow wave-cut surface with a shoreline angle at 4.0 m. No sediments were found on this level and thus, age data is lacking.

4.2. *Marine terrace geochronology*

4.2.1. *ESR dating of optically bleached quartz grains*

The samples, technical data and age results for the Peniche marine terraces are presented in Tables 1 and 2, and Figs. 9 and 10. The ESR ages form a stratigraphically coherent sequence where marine terrace levels become younger in concert with successively lower altitudinal positions (Fig. 9).

Furthermore, the multiple samples taken from Tm3 appear to be spatially and temporally coherent regarding marine terrace aggradation.

The age data were compared to global eustatic trends and MISs. Tm1 (883 ± 120 ka) presents a wide error; so, it could correspond to the MSI 19 (more probable; at the transition Early to Middle Pleistocene) or to MSI 21 (less probable; Middle Pleistocene). Tm2 (707 ± 32 ka) can be clearly linked to MIS 17 highstand (earliest Middle Pleistocene). Tm3 (598 ± 160 to 490 ± 44 ka) spans highstands across MIS 15 and MIS 13 (early Middle Pleistocene), whilst Tm4 (315 ± 48 ka), clearly indicates the MIS 9 interval (late Middle Pleistocene). Tm5 and Tm6 lack age control from this study, but stratigraphic bracketing suggests a likely MIS 7 and MIS 5 association (earliest Middle to early Late Pleistocene), respectively. Within the studied staircase it appears that the MIS 11 is not represented by a marine terrace.

4.2.2. *U-series dating of travertine levels*

A sample of the travertine level located at the topmost deposits of the Tm3, was collected at the Furninha Cave entrance. Sub-samples have been analysed by U-series in both the Paris and Nanjing laboratories. The uranium content ranges between 90 and 115 ppb according to the heterogeneity of the analysed sample (Table 3). Isotopic ratios agree for both laboratories at 1–2 %. The $^{230}Th/^{232}Th$ ratio is higher than 41 from the Nanjing laboratory analysis showing that the sample is free of exogenous thorium. The measurement performed in Nanjing with MC-ICP-MS is expected to be more accurate and the obtained age (>620 ka) can be used without any correction.

Another travertine sample was collected from the topmost deposits of the Tm4 at the Furninha Cave terrace staircase, providing an age (19 ± 0.5 ka; Table 4) much younger than the Tm4 terrace formation.

Fig. 9 shows a compilation of the main results of this study, namely the topographic position of each marine reference in this staircase, the obtained ESR and U-series ages, and correspondence with the probable MISs. Fig. 10 plots of the altitude *versus* the respective age of each dated terrace and the global mean sea level curves.

5. Vertical displacement rates

Uplift rates and the data used for their quantification are summarized in Table 4, following the Lajoie (1986) method (Section 3.3). From Tm3 three ESR ages were obtained, spanning MIS 15 to MIS 13. Therefore, we used the average age value to calculate the uplift rate. For the terrace staircase, the obtained uplift rates are very low. During the Middle Pleistocene, between ~900 and ~250 ka, the uplift rate is always 0.04 m/ka, but thereafter (early-late Pleistocene to Holocene) it decreases a little (0.06 m/ka) and later decreases more (−0.02 m/ka; weak subsidence).

6. Discussion

6.1. *Regional consideration of marine staircases along the western Atlantic margin*

The marine terrace staircase at Peniche displays a sequence of six levels inset into the ~4 Ma (latest Zanclean) wave-cut platform at 29–45 m asl in the region (Fig. 2), spanning an altitudinal range of 28 to 4 m asl with narrow spacings of 2–5 m (Figs. 6, 8 and 9).

Peniche is located in the uplifted Western Mesozoic Reliefs, which separated the Cenozoic Mondego and Lower Tagus basins (Fig. 2B; Galve et al., 2019; Cunha, 2019). Here, the layered Mesozoic limestone geology forms a resistant substrate that concentrates wave energy that is conducive for shore platform development, with local fault networks likely playing a key passive role in shaping the peninsula and its adjacent rocky headland coastal landscape morphology.

This configuration also occurs elsewhere in other staircases along the Western Atlantic Margin, but with differences in the numbers of terrace levels, their altitudinal ranges and spacings between them. These differences relate to variations in the substrate lithology, structure, and tectonic history highlighting the importance of bedrock geology for controlling coastal landscapes. However, the coastal landforms on passive margins may be mainly controlled by new formed faults or pre-existing faults reactivated due to intraplate tectonic stress and related onshore uplift (Vicente et al., 2008; Cabral, 2012).

In the Western Portuguese Margin, the regional differentiation of the uplift rates is due to several tectonic structures that have generated marked changes in the vertical movements of the crust. Some examples are summarized below:

Table 1
Sample information, external β and γ dose rate, cosmic dose and bleaching. External α was considered negligible. The water content (W.C.) for the burial time was estimated based on the field water content and the saturation water content.

Marine terrace	Sample code	Estimated W.C. (%)	External β dose rate (Gy/Ka)	External dose rate (Gy/Ka)	Cosmic dose rate (Gy/Ka)	Bl (%)
Tm1	Pen5	5 ± 2	318 ± 27	211 ± 31	169.1 ± 8.4	61.0 ± 1.3
Tm2	Pen4	11 ± 5	460 ± 22	279 ± 25	177.7 ± 8.8	46.0 ± 8.8
Tm3	Pen3	11 ± 5	352 ± 25	231 ± 29	163.1 ± 8.2	44.0 ± 2.9
Tm3	Pen2	5 ± 2	385 ± 26	249 ± 30	177.7 ± 8.8	53.0 ± 6.6
Tm3	Pen1	15 ± 5	705 ± 29	469 ± 33	163.1 ± 8.2	42.0 ± 5.0
Tm4	Pen8	10 ± 2	456 ± 29	280 ± 34	180.5 ± 9.1	50.0 ± 2.3

Table 2
Dosimetry and ESR age in Al, Ti–Li centres of sedimentary samples collected from the marine terraces. The depth from which sample were taken is given in (m) below each sedimentary sequence top.

Sample code	Tm1 terrace	Tm2 terrace	Tm3 terrace (top)	Tm3 terrace (base)	Tm3 (base)	Tm4 terrace
	Pen5	Pen4	Pen3	Pen1	Pen2	Pen8
Depth (m)	0.8	0.5	0.2	0.1	0.2	2
Elevation (m)	26.9	18.5	16.5	15.0	15.0	13.1
Grain size (µm)	250–180	250–180	250–180	250–180	250–180	200–100
^{238}U (ppm)	0.55 ± 0.07	0.76 ± 0.06	0.59 ± 0.06	1.49 ± 0.08	0.92 ± 0.06	1.07 ± 0.07
^{232}Th (ppm)	1.73 ± 0.45	2.12 ± 0.40	1.89 ± 0.43	4.18 ± 0.55	1.68 ± 0.48	1.90 ± 0.52
^{40}K (%)	0.31 ± 0.02	0.53 ± 0.01	0.35 ± 0.01	0.79 ± 0.02	0.39 ± 0.02	0.45 ± 0.20
D_a (total) (µGy.a^{-}	706 ± 42	987 ± 36	756 ± 38	1716 ± 60	821 ± 42	941 ± 45
D_e Ti centre (Gy)	585 ± 30	687 ± 77	384 ± 76	927 ± 51	431 ± 33	281 ± 49
Adj. Square	0.99-	0.99	0.97	0.99	0.99	0.98
D_e Al centre (Gy)	582 ± 59	716 ± 38	356 ± 38	486 ± 50	437 ± 45	338 ± 31
Adj. Square	0.98	0.98	0.98	0.99	0.99	0.98
Ti–Li centre Age (ka)	896 ± 350	696 ± 82	508 ± 103	684 ± 43	525 ± 47	298 ± 54
Al centre Age (ka)	859 ± 54	709 ± 36	548 ± 87	545 ± 43	588 ± 60	366 ± 37
Mean Age (Al and Ti–Li)	883 ± 120	707 ± 32	490 ± 44	598 ± 160	563 ± 63	315 ± 48

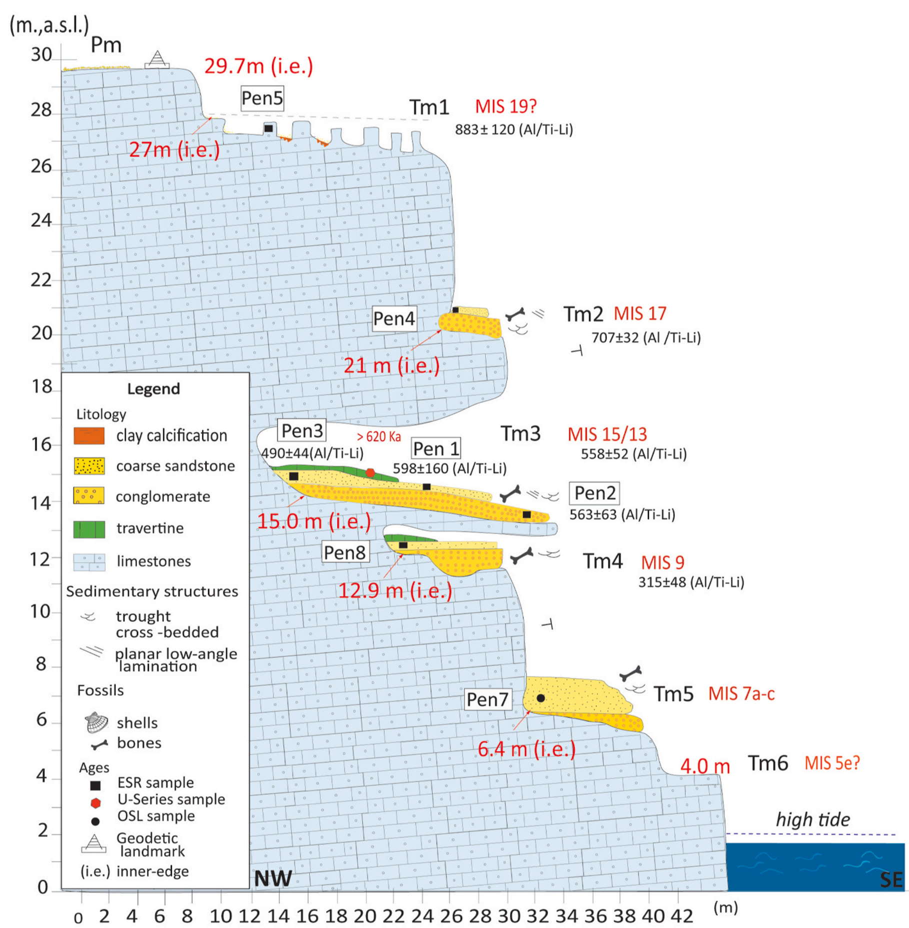

Fig. 9. Schematic geological section of the marine terrace staircase at the Furninha site, presenting the topography, lithostratigraphy and the ages obtained of each marine terrace (wave-cut surface and sedimentary deposits) (Tm1 to Tm6).

- In the more elevated mountainous Palaeozoic basement bedrock coastal areas in the north of mainland Portugal, uplift estimates are low (mean = 0.05 m/ka) based upon values derived from the entire six-levels staircase (Carvalhido et al., 2014).
- To the north of Peniche, at Cape Mondego, there are at least four coastal terrace levels below the UBS13 platform (Ramos et al., 2012). It has a long-term uplift rate reaching ~0.06 m/ka, over the last ~4 Ma (258-22 m/4 Ma) and an uplift rate of ~0.017 m/ka for the Pleistocene terraces. However, this staircase of coastal terraces is not fully studied.
- Immediately north of Peniche, the geology changes into a less resistant bedrock geology. At Praia Rei Cortiço (Fig. 2B), marine terraces with bedrock platforms and overlying beach sediments are almost absent. Instead, a thick coastal sediment sequence comprising

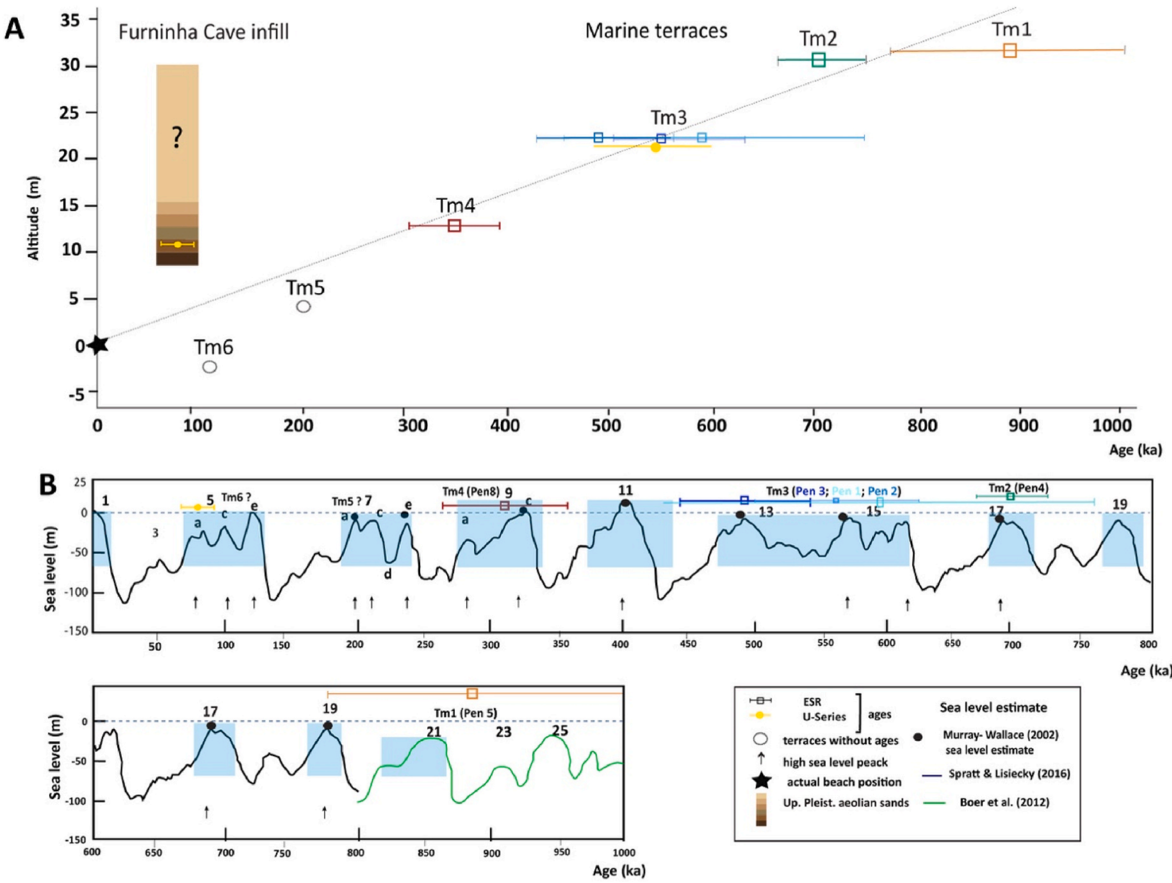

Fig. 10. A - Plot of the altitude *versus* the respective age of each dated terrace from the Peniche staircase (elevations are corrected for eustatic changes). B - Global mean sea level, mean ESR and U-series ages obtained, and the most probable age of the sedimentary deposits of the terraces indicated in blue shading. Black circles indicate the Murray-Wallace sea level estimates; the black and green curves are those proposed by Spratt et al. (2016) and Boer et al. (2012), respectively. Terraces (Tm) are displayed with the respective altitudes of their inner edges. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 3
U content (ppb), isotopic ratios and age without correction of the Furninha Cave Tm3 and Tm4 travertine samples.

Sample	^{238}U (ppb)	^{232}Th (ppb)	^{234}U/^{238}U	^{230}Th/^{234}U	^{230}Th/^{238}U	^{230}Th/^{232}Th	Age (ka)
Tm3 travertine **(Paris)**	114 ± 1.50	29.9 ± 0.39	1.05 ± 0.01	1.02 ± 0.02	1.08 ± 0.03	13 ± 0.30	>438
Tm3 travertine **(Nanjing)**	92 ± 0.08	7.23 ± 0.02	1.03 ± 0.00	1.02 ± 0.00	1.05 ± 0.00	41 ± 0.15	>620
Tm4 travertine **(Paris)**	465.0 ± 9.6	28.10 ± 0.57	1.143 ± 0.024	0.160 ± 0.004	0.182 ± 0.004	9.00 ± 0.10	19 ± 0.5

aeolian sands and estuarine muds prevails (Benedetti et al., 2009), configured into a linear coastal landscape morphology.

- South of Peniche, Cape Raso (Fig. 2B) has four terrace levels below the UBS13 wave-cut platform; a long-term uplift rate of ~0.02 m/ka, over the last ~4 Ma (100-22 m/4 Ma) and an uplift rate of ~0.07 m/ka for the Pleistocene terraces were calculated (Martins et al., 2025).
- Also to the south, the Cape Espichel (Fig. 2B) staircase has eleven Middle to Late Pleistocene terrace levels below the UBS13 shore platform. A long-term uplift rate of 0.05 m/ka over the last ~4 Ma (220-22 m/4 Ma) was calculated. Using the marine terraces has geomorphic references, uplift rates of 0.13–0.11 m/ka from ~900 to ~200 ka were calculated, but later of 0.06 m/ka (very low uplift) to −0.01 m/ka (subsidence) were obtained (Martins et al., 2025).
- For the Pleistocene marine terraces of the SW sector of the Western Iberian margin, vertical displacement rates of 0.007–0.038 m/ka (Ressurreição, 2018) and of 0.015 m/ka to −0.030 m/ka (Goy et al., 2024) were estimated, the latter based on a staircase of surprising fifteen marine terraces.

6.2. *Terrace chronology and eustatic relationship*

The Peniche marine terrace staircase is inset into the Middle Pliocene summit wave-cut surface (~4 Ma; section 2), comprising a numerically dated and temporally coherent sequence that spans the transition of the Early to Middle Pleistocene (Tm1) and the entirety of the Middle Pleistocene (Tm2 to Tm5). These are the first published ESR ages of marine terrace formation and correlated sea level highstands along the Iberian passive margin coast of the North Atlantic. Although some other OSL ages exist from some Western Iberian passive margin coastal landscape studies, terrace-beach materials close to the shoreline angle are usually not directly dated and the sea level highstand age is instead indirectly acquired from the dating of the overlying aeolian or fluvial/slope deposits, i.e. using a stratigraphic bracketing approach (e.g., Carvalhido et al., 2014). Furthermore, existing chronologies based on overlying deposits are temporally restricted to the latest Pleistocene-Recent, notably spanning MIS 4-2 (e.g., Carvalhido et al., 2014). This restricts any understanding of marine terrace staircase development to the MIS 5e highstand at best, with no meaningful

Table 4
Relative uplift rate calculation, taking into account the altitude of the shoreline angle (inner edge) and the respective paleo-sea level. WCN- wave cut notch; IE-inner edge; *sediment thickness at the shoreline angle; altitude at the shoreline angle (E ± ΔE); assigned Age (A); relative uplift rate (U =). The following sea level peaks were used: +22 m for ~4 Ma (Middle Pliocene) (Miller et al., 2020); for the Pleistocene MISs, we used the ages given by Lisiecki and Raymo (2005) and the sea level data supplied by Spratt et al. (2016), since they are based on 57 globally distributed oxygen isotopic records, so they lack any regional component.

Marine level code	Assigned MIS	Probable eustatic paleo-sea-level (m)	Type of marker	Sediment thickness* (m)	Relative altitude of shoreline angle (m)	Assigned age of terrace (ka)	Uplift rate U (m/ka)
Pm	**–**	**22**	Wave-cut platform	0	45 - (+22) = 23	~4 Ma	0.006
Tm1	**MIS 19?**	**−5**	IE	0.8	26.9 - (−5) = 31.9	875 ± 130 (ESR) 790-780 (MIS 19?)	0.04
Tm2	**MIS 17**	**−10**	IE	0.5	20.7 - (−10) = 30.7	707 ± 65 (ESR) 697-682 (MIS17)	0.04
Tm3	**MIS 15–13**	**−7**	WCN	0.8–2.5	15.5 - (−7) = 22.5	598 ± 160 to 490 ± 44, (ESR) 572-486 (MIS15-13)	0.04
Tm4	**MIS 9**	**0**	IE	2.5–3.0	13.5–0 = 13.5	359 ± 37 (ESR) 331-315 (MIS9)	0.04
Tm5	**MIS 7a-c**	**4.5**	IE	2.0	8.0 - (4) = 3.5	214-190 (MIS7)	0.02
Tm6	**MIS 5e**	**6.5**	IE	0	4.0 - (6.5) = −2.5	126 (MIS5e)	−0.02

chronological information on the higher older terrace levels (i.e. MIS 7, MIS 9, etc). Benedetti et al. (2009) have numerous MIS 4-3 ages and isolated MIS 5e-6 ages, but collectively these are derived from thick coastal sediment sequences that lack clear marine terraces and staircase morphological contexts due to their Cenozoic Mondego Basin location.

The age data of the Peniche marine terraces was compared to global eustatic trends and MISs. Tm1 (883 ± 120 ka) presents a wide error; considering its mean and age error bars it could correspond to either MSI 19 (more probably, at the transition of Early to Middle Pleistocene) or to MSI 21 (less probable; Middle Pleistocene). Tm2 (707 ± 32 ka) can be clearly linked to the MIS 17 highstand (697-682 ka, earliest Middle Pleistocene). Tm3 (598 ± 160 to 490 ± 44 ka) spans highstands across MIS 15 and MIS 13 (early-Middle Pleistocene), whilst Tm4 (315 ± 48 ka), clearly indicates the MIS 9 interval (late-Middle Pleistocene). Tm5 and Tm6 lacks age control from this study, but stratigraphic bracketing suggests a likely MIS 7 (214-190) and MIS 5e (126-119 ka) association (latest Middle to early-Late Pleistocene), respectively.

The chronology of this staircase could be explained by an interplay between uplift rate and global eustasy. The notion that consecutive marine terrace levels correspond to successive interglacial peak highstands (i.e. terrace counting and interglacial highstand matching) has been employed in many classical studies on the formation of marine terrace staircases (section 1). The ESR chronology from this study spans almost 900 ka, encompassing the transition of the probable Early to Middle Pleistocene through to earliest Late Pleistocene (MIS 19? to MIS 5e). Whilst some terrace levels show clear associations with one specific interglacial (e.g., Tm1 = 19?; Tm 2 = MIS 17; Tm4 = MIS 9; Tm5 = MIS 7), one terrace seems to comprise a chronology that spans two interglacials (Tm3 = MIS 15 to Tm13). The chronology of this staircase could be explained by an interplay between uplift rate and global eustasy. Under a very low uplift rate, the positions of global sea levels are primarily a function of ice volume with local modifications linked to wave dynamics and local coastal shelf bathymetry (section 3). So, could be difficult to assess the detailed timing of a terrace formation. This is further complicated due to some Middle-Late Pleistocene interglacials are polyphase, i.e., comprising two highstands (e.g., Bradley and Griggs, 1976; Pedoja et al., 2014). The Peniche Tm3 terrace, that probably span two interglacials, are likely to reflect situations where sea level peaks re-occupy the same level over two interglacial cycles. This is a widely reported phenomenon (e.g., Muhs et al., 2002; Zomenia, 2012) and is especially common for low uplift rate coasts (section 6.3, uplift discussion).

6.3. *Uplift of a passive margin coastal landscape undergoing compression*

The mechanism that causes regional surface uplift of this passive continental margin is an increased lithosphere compression of Iberia due to plate interactions, namely the North Atlantic seafloor spreading and the Iberia-Nubia Alpine plate convergence (e.g., Vicente et al., 2008; Cabral, 2012).

For Peniche, the fact that a marine terrace staircase exists means that the landscape has been subjected to continuous uplift. However, the uplift rates for the Peniche marine terrace levels are broadly very low. The shorter-term means that vertical movement rates for individual terrace levels span 0.04 to −0.02 m/ka, whilst the longer-term mean rate for the entire Pleistocene staircase is 0.03 m/ka. This range of values is broadly in keeping with, but at the lower end of the marine terrace staircases developed along a range of passive margin settings worldwide (Pedoja et al., 2014). Regarding this type of low-active tectonic coasts with such low vertical movement rates, the role played by GIA could also be a possible driving factor.

We consider that is the differential uplift promoted by the NE-SW vertical geological fault, located at the connexion between the Peniche Peninsula and the inland territory (Fig. 2B), that likely causes the vertical displacements of the Peniche peninsula.

Of global significance is the MIS 5e highstand as it forms the most widely preserved marine terrace level of coastal landscapes across a range of tectonic settings (e.g., Pedoja et al., 2011). For passive margins in general, the mean vertical movement rate using the MIS 5e level is 0.06 m/ka but varies from 0.12 m/ka (uplift) and −0.02 (subsidence) (e.g., Pedoja et al., 2011). For this study, the MIS 5e geomorphic level records a vertical displacement rate of −0.02 m/ka, indicating a very small subsidence for the last 126 ka. However, this value should be read with some caution, considering that there is still some debate about the position of sea level during MIS 5e: (1) having oscillated between +5 and + 9 m; or (2) having fluctuated with peaks between +2 and + 3 m (Benjamin et al., 2017; Dutton and Lambeck, 2012; Rohling et al., 2008b; Kopp et al., 2009; Hearty et al., 2007; O'Leary et al., 2013).

7. Conclusions

The low relief coast of the Peniche peninsula records a culminant shore platform inset by a staircase of marine terraces. The culminant wave-cut platform relates to the ~4 Ma (late Zanclean) regionally extensive marine incursion. The inset configuration of the six marine terraces that comprise the Peniche staircase is a consequence of multiple Pleistocene eustatic sea-level highstands, under a context of surface uplift.

The resulting ESR and U-Series ages occur in a consistent stratigraphic order from highest-oldest sequentially down to lowest-youngest. Taking into consideration both the dating error bars and information about global eustatic highstand positions, the: Tm1 shore platform is likely to correlated to MIS 19 (sea level peak at 790-780 ka); Tm2 correlates to MIS 17 (sea level peak at 697-682 ka); Tm3 correlates to MIS 15 - MIS 13 (long sea level high stand at 572-486 ka); Tm4 correlates to MIS 9 (sea level peak at 331-315 ka); and Tm5 probably correlates to MIS 7a-c (sea level peak at 214-190 ka). The lowest wave-cut platform at 4 m (Tm6), likely correlates to the MIS 5e (sea level peak at 126-119 ka).

The paleogeographic evolution of the Peniche peninsula, since the beginning of the incision stage on the culminant sedimentary unit (dated as ~4 to 1.8 Ma), can be explained by the development of several marine shorelines across different sea level highstands within a very low uplift rate. The Quaternary coastal landscape development in the study area has therefore been driven by an interplay between eustatic and uplift forcing mechanisms.

The Western Iberian Margin is a region where active tectonics plays an important role in the geomorphic expression and distribution of Quaternary marine terraces, recording in many cases vertical ground motions (uplift/subsidence) superimposed onto global sea-level oscillations. At Peniche, the shoreline angle and wave-cut platform altitudes, together with ESR ages, were used to calculate vertical displacement rates.

The culminant wave-cut platform is a key geomorphic reference. It's 4 Ma age coincides with an estimated global sea level highstand of ~22 m. The modern 45 m asl elevation of this culminant surface suggests a long-term uplift of 0.006 m/ka was obtained. During the Middle Pleistocene, between ~900 and ~250 ka, the vertical displacement is always 0.04 m/ka (uplift), but after (early Late Pleistocene to Holocene) it decreases a little (0.02 m/ka) and later even more (−0.02 m/ka; weak subsidence). These range of values indicate a setting with very low uplift rates and even little subsidence during the last 126 ka. This temporal pattern agrees with a passive margin setting undergoing some intraplate compression. Comparison of this study with the uplift rates obtained for other marine terrace staircase sites along the Western Iberian Margin suggests that the minor vertical displacement variations are controlled by active faults (differential uplift).

We must conclude that the ESR dating is suitable and useful to date upper marine terraces and the culminant unit, from ~200 ka (the lower dating limit for ESR technique) to ~3 Ma (upper limit). However the old ESR ages can have large error bars. The used U-series method only can date fresh water travertines and so their ages are quite limited in the temporal framework of a terrace staircase. In a future research improved age control could be provided by pIRIR (OSL on K-feldspar) the four lower emerged marine terraces (Tm6 to Tm3). This luminescence technique could date siliciclastic marine terraces up to ~500 ka (before the pIRIR OSL signal reaches saturation). By improving the temporal framework of a terrace staircase, the interpretation will be more robust and complete. We this on mind, our aim is to date other complete marine terrace staircases in Portugal and abroad.

CRediT authorship contribution statement

Margarida P. Gouveia: Writing – original draft, Investigation, Formal analysis, Data curation. **Pedro P. Cunha:** Writing – original draft, Supervision, Methodology, Investigation, Conceptualization. **António A. Martins:** Writing – original draft, Methodology, Investigation. **Martin Stokes:** Writing – original draft, Investigation. **Alberto Gomes:** Writing – original draft, Software. **Christophe Falguères:** Writing – original draft, Software, Methodology, Investigation, Data curation. **Pierre Voinchet:** Methodology, Investigation, Data curation. **Jean-Jacques Bahain:** Methodology, Data curation. **Telmo Pereira:** Writing – original draft. **Silvério Figueiredo ,:** Writing – original draft. **Qingfeng Shao:** Methodology, Data curation. **Olivier Tombret:** Data curation.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.quaint.2025.109954.

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