Evidence of MIS 5 sea-level highstands in Gebel Mousa coast (Strait of Gibraltar, North of Africa)

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ABSTRACT

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The Last Interglacial is considered the most suitable episode from which to infer patterns of rapid sea-level change since its climatic conditions were similar to those of the present interglacial. However, specifying the true position of its sea level with high accuracy is very troublesome in the absence of sedimentological, erosional or even palaeontological markers. This study investigates the morphosedimentary evidence (beach deposits, cliff, notch and shore platform) of two highstands registered and dated during MIS 5 stage by U-series dating in the North of Morocco (Strait of Gibraltar). Bioerosive notches and mixed siliciclastic and carbonate deposits, high energy beaches with algal bioherms, were formed in coastal environments during MIS 5a. A sea-level height of +10 m asl can be inferred for this substage. The record of MIS 5e substage is less defined in the geomorphological record, consisting of backshore/foreshore deposits located at +13 to +15 m asl. A tectonic uplift rate of ~0.1 mm/yr has been estimated for the last 130 kyr. These data are consistent with models of coastal uplifting calculated for the Strait of Gibraltar.

1. Introduction

Evidence from a variety of sources in the field is required to accurately interpret sea-level changes in the geological record. In the last decades, depositional (Dumas et al., 2006; Bardají et al., 2009a; Muhs et al., 2011), geomorphological (Antonioli et al., 2006a; Hearty et al., 2007) and even archaeological markers (Auriemma and Solinas, 2009; Anzidei et al., 2011) have been used as indicators of sea-level rise during the Late Quaternary. For a correct interpretation of this evidence using a multidisciplinary approach to the study of sea-level history, independent confirmation of the age of the deposits through chronometric methods such us uranium-series or amino-acid racemization (AAR) geochronology is required (Hearty et al., 2007), whilst coastal and marine deposits linked to shoreline fluctuations can determine the hydrodynamic conditions and, indirectly, the eustatic changes. Conversely, a precise measure of the palaeo-sea level is very difficult to estimate in the absence of appropriate sedimentary structures (e.g. foreshore plunge-step; Dabrio et al., 1985) or specific sedimentary environments, such as tidal flats (Mauz and Bungenstock, 2007) or reflective and microtidal beaches (Dabrio et al., 2011). It is only in certain settings (e.g. wave dominated, small tidal range and carbonate coastal cliffs) where the integrated analyses of morphosedimentary complexes are useful tools for the precise reconstructions of the relative sea-level position during Quaternary highstands (Ferranti et al., 2006; Antonioli et al., 2007), and in this respect, bioerosional and tidal notches are precise indicators (+/− centimeters) of short-term sea-level positions (Stiros et al., 1992; Laborel et al., 1994; Antonioli et al., 2006a, 2006b; Ferranti et al., 2006; Hearty et al., 2007).

The Marine Isotope Stage (MIS) 5, and in particular the MIS 5e (or Last Interglacial), is considered the most suitable recent geological period for comparison with the present interglacial (e.g. see Tzedakis, 2003 and references therein; Rohling et al., 2008). Its duration was around 17–18 kyr, between ~133 and 116 ka, during which global sea level rose around 6 (±3) m above present sea level (e.g., Hearty and Kindler, 1995; Shackleton et al., 2002; Siddall et al., 2003; Lambeck et al., 2004). During MIS 5e, sea-level changes are characterized by intervals of transition and stability marked by abrupt shifts (Hearty et al., 2007). These circumstances make this stage a reliable episode from which to infer rapid sea-level change patterns even though its climatic conditions and global ice volumes were not

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exactly similar to the present ones, with a surface temperature around 2 °C warmer and the Greenland ice sheet more reduced than at present (Rohling et al., 2008). The number of highstands during MIS 5, and especially during MIS 5e, is still an issue and there is agreement on the number, timing and heights reached by the sea (e.g., Antonioli et al., 2004; Dorale et al., 2004; Hearty et al., 2007; Bardají et al., 2009a, among others).

Numerous papers have focused on MIS 5 deposits along the Spanish Mediterranean coasts using multidisplinary approaches (U-series dating, geomorphological and morphosedimentary analyses, palaeontological assemblages) in order to resolve this problematical issue, and focusing their interest on MIS 5e rather than MIS 5c and MIS 5a. MIS 5 presents four or five sea-level highstands along the Spanish coastline (Zazo et al., 2003). According to phreatic overgrowths studies in coastal caves located in Mallorca in the western Mediterranean, sea-level was ~1.5–3 m above present sea level (m asl) during MIS 5e and ~1–1.9 m asl during MIS 5a (Fornós et al., 2002; Tuccimei et al., 2006; Dorale et al., 2010). For the Rock of Gibraltar, Rodríguez-Vidal et al. (2007a, 2007b) described several marine terraces and coastal sedimentary deposits at heights between 1,5 and 5 m asl. More recently, Dabrio et al. (2011) described small-scale, short-lived fluctuations and rapid sea-level changes recorded during the second MIS 5e highstand in the southeastern coast of the Iberian Peninsula.

Similar studies are comparatively scarce for the north of Morocco, with the main ones dating to the 1970's, covering a brief description and chronological setting of marine terraces, with additional geomorphological and neotectonic interpretations (El Gharbaoui, 1977, 1978). Further to the southwest, the Quaternary littoral deposits are better studied, including the Ouljian regional stratotype which can be partially correlated with MIS 5 stage (Biberson, 1961; Texier et al., 2002; Rhodes et al., 2006). More recently, several studies describe the palaeoenvironmental evolution of this area during the Last Interglacial (Aboumaria et al., 2005; 2009), and try to correlate the age and altitude of marine terraces with adjacent travertines forming during warm and wet interglacial periods (El Kadiri et al., 2010). These last authors suggest an eustatic factor to explain the origin of the marine terraces, although they infer a significant tectonic influence on this region.

The main aim of this paper is to describe and date a hitherto undescribed bioerosive notch in northern Morocco, and other sedimentological sea-level markers, corresponding to Late Pleistocene highstands developed during the Last Interglacial in Cape Leona and the coast of Gebel Mousa (Northern Morocco) (Fig. 1). Secondly, we compare the data obtained with the pattern of tectonic uplift established for the western Mediterranean coast on the basis of marine terrace altitude.

2. Regional setting

The study area is located in the Tangier peninsula in the North Coast of Morocco. The coast is steep with a wave-dominated hydrodynamic regime. The Atlantic tidal wave enters the Mediterranean with an eastward progressive propagation. The average tidal range in this area is 50 cm and its range varies from a few centimeters during neap tides to 1 m during spring tides (Benavente et al., 2007).

The Tangier peninsula constitutes the southern margin of the Strait of Gibraltar (Fig. 1) within the Gibraltar Arc–Rif Range. The Betic-Rif mountains belt is the most westerly of the alpine mountain chains of Southern Europe and Northern Africa. The Rift Belt of North Africa is generally divided into three: the Internal Zone, an Intermediate Flysch Zones, informally known as the Flysch Nappes, and the External Zone (Wildi, 1983) (Fig. 1).

From the geological point of view, the study area is located in the northwestern end of this range where well developed staircased marine terraces are clearly observed in the landscape (Rodríguez-Vidal and Cáceres, 2005) (Fig. 2). These terraces are formed over the Mesozoic rocks of the Riffian Internal Zones that crop out extensively in this region: mainly carbonate rocks of the Tariquide Units that make up the more important reliefs of the region. The Flysch Unit is constituted by well stratified claystones, limestones and sandstones, which crop out in both sides of Gebel Mousa (Bel Younech town) and in front of Perejil Island (also known as *Leila* or *Taura Island*) (Figs. 1 and 2).

3. Material and methods

3.1. Sedimentology and palaeontology

Standard field techniques were employed in the investigation and sampling of the outcrops. Two stratigraphic sections were measured, logged and photographed to identify the main sedimentary structures and facies for palaeoenvironmental interpretations (Fig. 2). Furthermore, some petrographic samples of representative facies were collected and analyzed under transmitted, polarized light after preparation of polished cylinder and thin sections in order to determine textural components, microfossils and diagenetic

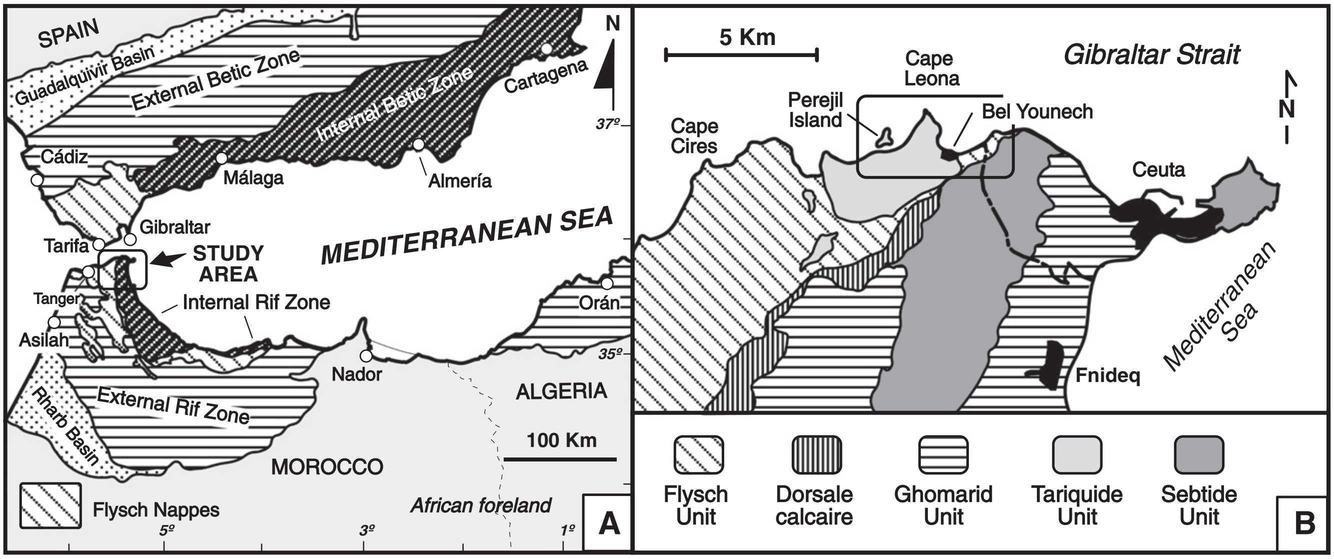

Fig. 1. A, location and geological sketch of Southern Spain and Northern Morocco. B, geological setting of the studied area.

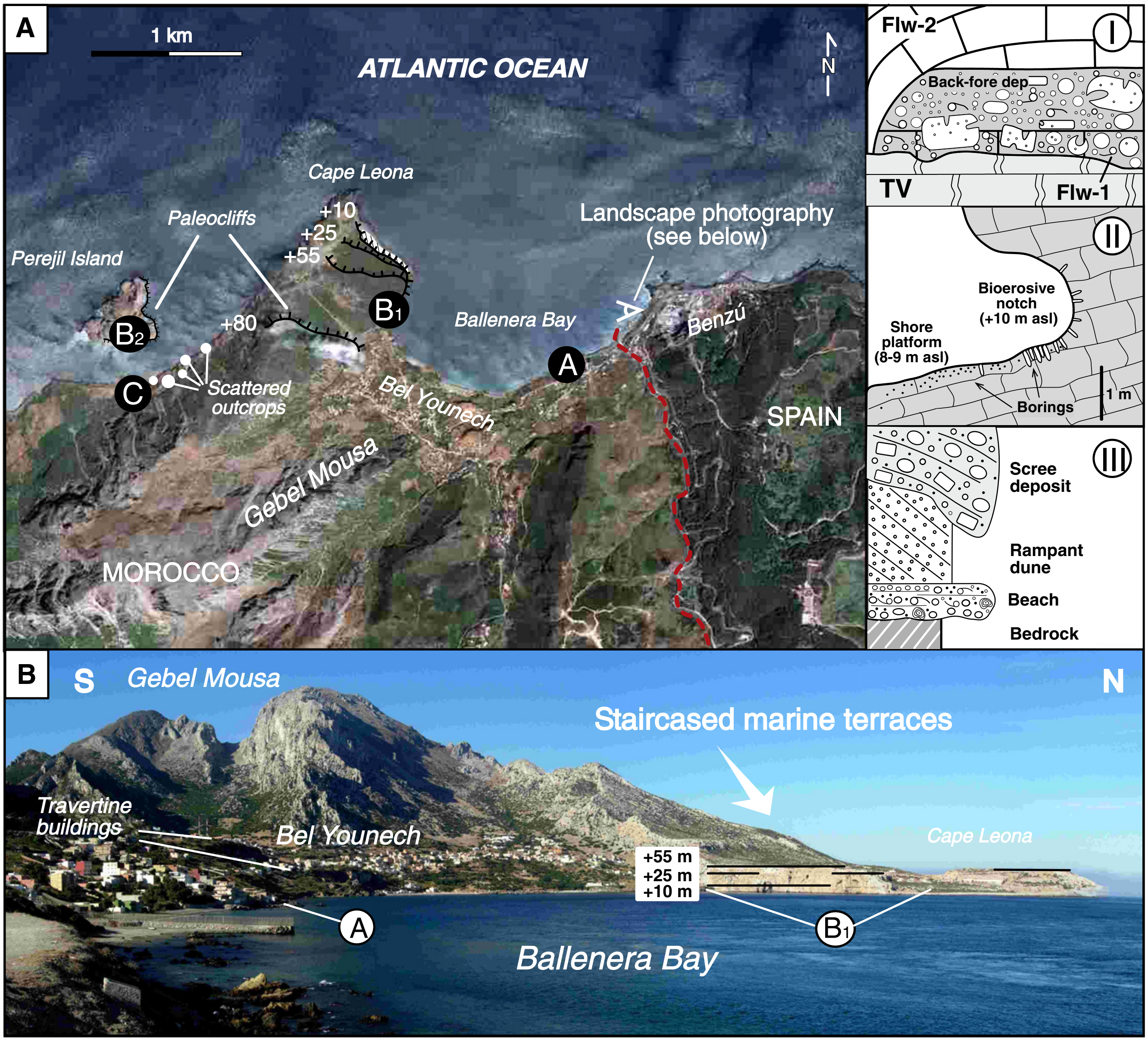

Fig. 2. A, location of the studied sections in Bel Younech Beach (Section A), Cape Leona and Perejil Island (Sections B_1 and B_2) and outcrops in front of Perejil Island (Section C). B, panoramic landscape photography of Gebel Mousa and Cape Leona. Location of field sections can be observed. TV, Travertine; Flw-1 and Flw-2, flowstone layers; Back-fore dep, Backshore/Foreshore deposit. The small sketches on the right of the figure indicate the main morphosedimentary evidence of MIS 5 observed in the studied section.

features. Spatial stratigraphic correlation between sections was not possible.

Bioerosive structures were found in Cape Leona (Fig. 2) linked to both notch development in Mesozoic limestones as well as in boulders/cobbles of coastal deposits. Relict borings were measured and classified in order to infer palaeoecological conditions and to define with accuracy past sea-level positions. Scattered specimens of macrofossils (red algae, bivalves and gastropods) found in different facies were identified at species level where possible. Other sub-samples were selected for microfossil analysis and washed through a 63-µm sieve and then dried. Benthic foraminifera were collected but no ostracoda were found.

3.2. Erosional features

Erosional littoral features (notch and shore platform) were analyzed, measured and mapped in the field (Sections B_1 and B_2; Fig. 2), with an additional analysis of aerial photographs (scale 1:5000) also undertaken in order to interpret MIS 5 sea-level changes. The topographic elevation of geomorphologic markers and deposits was measured by means of a high resolution altimeter, which was referenced to present mean high tide level. This level was then used as the 0 m datum. The altimeter was periodically recalibrated at sea level to correct barometric pressure changes. Finally, all the data were represented in geomorphological sketches (1:25,000) and longitudinal profiles.

3.3. Isotopic measurements

Both speleothem and marine samples were dated by U-series analysis (alpha spectrometry) in the "Laboratorio de Datación of the Departamento de Física Aplicada I, Universidad de Sevilla (Spain)." The U and Th electrodeposition was performed for 1 hour at 1.2 A onto stainless steel discs. The discs were measured by alpha spectrometry. This system was equipped with PIPS detectors and shows good stability over the 5–7 days counting time generally needed for each disc. The $^{230}Th/^{232}Th$ activity ratio was high

(Table 1: >20). Consequently, a detrital correction was not necessary although the error range may be higher than that desired. In any case, we consider that the ages given by the U-series dating are coherent and within the limits to attribute the MIS 5 stage to the studied deposits. However, it is acknowledged that the reliability and methodological problems arising from the use of U-series dating should be considered when applying this approach to dating coastal deposits (Bardají et al., 2009b; Mauz and Antonioli, 2009).

4. Occurrence of MIS 5 highstands evidence

Mixed carbonate-siliciclastic deposits crop out in two sections near the present coast. Section A is located in the Ballenera Bay, next to Bel Younech beach, and Section C is located in front of Perejil Island. Erosional and ichnological markers have been described in Cape Leona cliffs and Perejil Island (Sections B_1 and B_2) (Fig. 2).

4.1. Section A. Bel Younech Beach

Bel Younech Beach presents a staircased sequence of three travertine platforms. The lower (TV in Figs. 2A-I and 3A) contains at its base scattered coastal deposits located between +13 and +15.5 m asl that are preserved within large cavities generated in the travertine deposits. These sheltered deposits are formed by a heterogeneous level consisting of a group of sedimentary lenses of limited lateral continuity made up of 1–2.5 m thickness of conglomerates cemented by carbonates (Fig. 3B). Two different growth phases of flowstones have cemented these deposits (Flw-1 and Flw-2 in Fig. 2A-I). Both phases have been dated by U-series as MIS 5e-2 (sample MABE0604) and MIS 5a (sample MABE0603), respectively (Table 1). The term MIS 5e-2 has been used here to indicate the first highstand of MIS 5e (after Tuccimei et al., 2006).

In conglomerate facies both limestone and sandstone clasts are poorly sorted and show a heterometric distribution (long axis 2–25 cm). Their rounding ranges from well-rounded to angular although the abundance of higher textural maturity is predominant over the rest. Percentages of siliciclastic matrix are very variable and depend on the point of observation. In most cases, clast orientation is random and internal stratification is absent, although poorly defined subhorizontal beds have been observed. Near the base of some deposits low-angle parallel laminated bioclastic sand and gravel layers are present, containing scattered pebbles and cobbles with their long axes indicating seaward palaeocurrent directions.

Fossils are uncommon in this facies and only some well-preserved specimens of the gastropod *Patella ferruginea* Gmelin (1791) in natural position have been collected. Boulders and cobbles are extensively bored by *Gastrochaenolites* borings of variable diameter.

Following the outcrops landward, lateral facies transitions show more disorganized and texturally immature deposits. Fossil remains become scarcer, increasing the proportions of sandy and clay matrices and showing a characteristic reddish color. Rizoliths and bands of fenestral porosity (keystone vugs sensu Bain and Kindler, 1994) are frequent.

The petrographic analyses show that an important proportion of original calcite shells (mollusc, algae and echinoderm) have been dissolved. Skeletal grains are surrounded by thick crystals of botroyoidal and bladed marine cements growing on the red algal fragment, enclosed by a surrounding, later accumulation of irregular micritic matrix. Dissolution porosity is very extensive, with inter- and intraparticle pore spaces partly filled by a later mosaic of equant (micro-) sparite of meteoric origin that shows irregular and discontinuous growth (Fig. 4A and B).

4.2. Section C. Western side of Cape Leona

On the steep coast facing Perejil Island (Section C, Fig. 2) there is a regular slope with coarse conglomeratic, cemented scree deposits overlying a thick rampant coastal dune formed by recent fine-grained and well-sorted sands, both probably developed during MIS 3–4 (Fig. 3C and D). In this area, conglomerate and bioclastic sand deposits outcrop at +10 m asl grading seaward to algal limestone and calcarenite deposits at +8 m asl (scattered outcrops next to Section C in Fig. 2).

The higher deposits are comprised of a clast-supported polymodal conglomerate bedset (Fig. 3D) with a thickness ranging from under 100 to 150 cm. Facies are very bioclastic and very scarce in the siliciclastic matrix. Lateral variations in depositional thickness, bedding geometry and grain-size are common. This bed overlies an erosive surface that truncates the underlying units and presents locally some important erosional relief. Although sedimentary structures are difficult to observe in the field, this facies show normal graded bedding and very diffuse, gently parallel-inclined planar bedding. Facies include some interbedded levels (<10 cm thickness) of bioclastic, medium to coarse sands with parallel lamination. Clast shape is angular to rounded and their size ranges from granules to rare occurrences of cobble-sized clasts. Borings of *Entobia* and *Gastrochaenolites* are very common in limestone clasts.

The bioclasts include fragments of gastropods (*Patella*, *Bittium*, *Conus*), bivalve pectinids, serpulids and very abundant skeletal elements of echinoids (plates and spicules). Debris of red algae is also especially frequent, probably originating from the break-up of larger individuals (Fig. 3E). Rhodoliths of red crustose coralline algae show very diverse diameters and exhibit broadly spheroidal shapes with radial branches. Species-level taxonomic identification of algae has not been possible in these facies.

The petrographic analysis of thin sections shows echinoderm spicules and red algae rhodoids lined by micrite crusts. A poorly developed generation of turbid, thin isopachous calcite cement surrounds the skeletal grains. This first generation of probably marine origin cement is followed by thick crystals of equant spar with irregular edges and mosaics that fill the pore space (Fig. 4C and D). Occasionally, a second generation of irregular micrite coating has been observed bounding the equant sparite.

Scattered outcrops located seaward at +5 to +8 m asl can be easily correlated with previous facies some tens of meters away. In these outcrops carbonate facies are deposited on top of the erosional surface formed directly in Mesozoic limestone bedrock intensely bored by *Entobia* isp., without intermediate conglomerates. They consist of massive packstone-limestone with a lower proportion of coarse detrital elements, although calcarenite deposits have been also sporadically described. Facies are constituted mainly by rhodoliths of calcareous algae (mainly *Lithophyllum* sp. and *Melobesia* sp.; sensu Braga et al., 1993 and Braga and Aguirre, 1995) that represent more than 75% of the sediment volume. The U-series of the calcareous algae corresponds to MIS 5a substage (84.4±3.3 ka) (Table 1).

Patch-like growths are not directly observed due to bad outcrop conditions but, in some cases, red algae forming laminar structures

Table 1

A synthesis of U-series dates from Bel Younech Beach and Cape Leona samples. (*) After Tuccimei et al. (2006).

Sample code	238U	234U	230Th	234U/238U	230Th/234U	230Th/232Th	234U/238U	T (ka) σ	MIS*	Elevation* m asl
MABE0604	17.6±0.4	22.7±0.5	16.6±0.4	1.290±0.014	0.727±0.022	50.1±2.9	1.418±0.020	131.2±7.4	5e-2	1.5–3
MABE0603	25.1±0.6	32.4±0.7	18.4±0.3	1.291±0.012	0.566±0.016	259.0±24.0	1.372±0.016	87.0±3.7	5b/a	–20
MABE1005	8.4±0.2	9.3±0.2	5.1±0.1	1.115±0.011	0.547±0.015	32.9±2.1	1.145±0.015	84.4±3.3	5a	1.9

Fig. 3. A, Lower travertine platform at Bel Younech Beach (Section A) where conglomeratic facies interpreted as backshore/foreshore deposits have been found at heights between +13 to +15 m asl. B, Close up of bioeroded boulders deposited during MIS-5e stage into travertine cavities. Two different growth phases of flowstone (Flw-1 and 2) cover these facies allowing to pre-date and post-date them. C, Late Pleistocene sedimentary succession overlying Tertiary substrate in Section C. D, Beach facies in Section C where graded conglomerate overlies an erosive transgressive surface formed onto Flysch Unit. E, Close-up of bioclastic conglomerate in Section C. Reworked algal limestone, rhodoliths, and fragments of branching red algae are very common in shoreface deposits.

have been preserved. The spherical shapes are less common than fragmented forms in rhodoliths beds. The rhodoliths range in mean diameter from 0.5 to 6 cm but small-size specimens prevail, exhibiting dense branching patterns. Some specimens show evidence of secondary encrustation by serpulids and bryozoans, whilst other also shows borings of internal bioeroders, mainly *Entobia* sp. Some specimens of benthic foraminifera (mostly *Elphidium advenum*) were collected from detrital matrices of weakly cemented deposits, with *Cibicidoides* sp., *Quinqueloculina* sp. and *Haynesina depressula* as secondary species. Bivalves, serpulids, echinoderms and gastropods are very rare.

Thin section analyses of these facies show how partly dissolved grains are surrounded by poorly developed isopachous rims of equant calcite cement of possible meteoric origin. Primary micrite matrices can be observed between partly dissolved red algae debris (Fig. 4E and F).

4.3. Sections B_1 and B_2. Cape Leona cliffs and Perejil Island

Erosional markers associated to MIS 5e-2 highstand have not been described in Sections B. Most of the limestone coast of Gebel Mousa

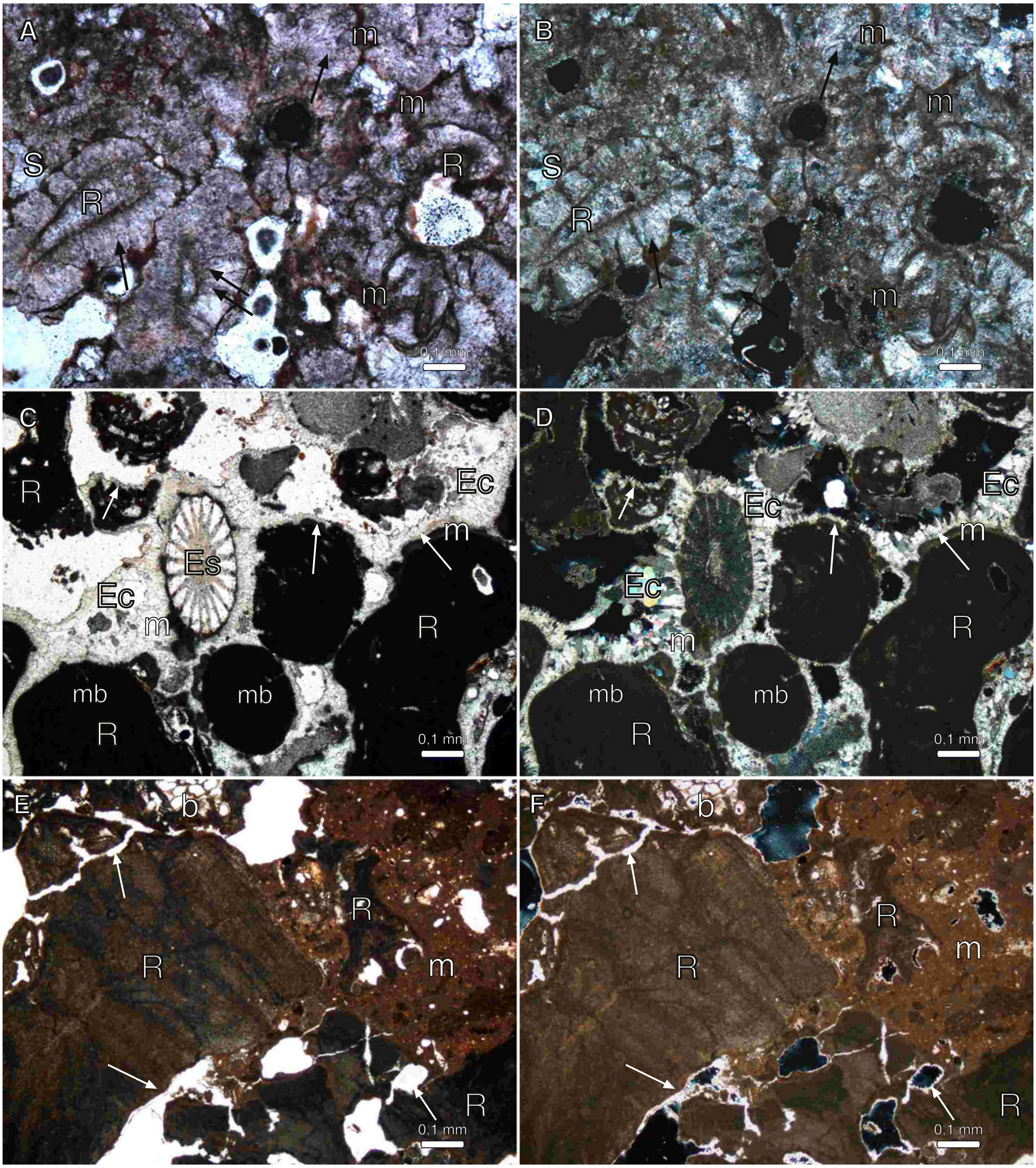

Fig. 4. Thin section photographs with parallel (left) and cross (right) nichols of coastal facies in Sections A and C. A and B) Botryoidal and bladed (black arrow) cement around bioclast (mainly micritized red algae) in backshore deposits of section A. Micrite matrices and calcite equants fill the pore space produced by extensive subaerial solutions of grains. C and D) Cementation phases of littoral deposits on samples taken in Section C. A first generation of micritic crust followed by a rim of thin isopachous, bladed (marine-origin?) cement (white arrow) can be observed around the skeletal grains. The equant fresh water calcite spar is filling the pore space. E and F) Packstone of red algae in scattered outcrops laterally correlationable with Section C. In these samples, interparticle isopachous rims of equant calcite cement are very scarce (white arrow) although micrite matrices can be observed between red algae debris. Skeletal grains are partly dissolved and broken. R, red algae; m, micrite; s, microspar; Ec. Equant calcite; Es, echinoid spicule; mb, boring; b, bryozoans.

presents a clear, pervasive and laterally continuous collection of bioerosive markers at +10 m asl (Fig. 5A). The best outcrops are located in Cape Leona cliffs (Section B_1, Fig. 5E) and Perejil Island (Section B_2, Fig. 5C and D), with a well-developed marine notch (base of the floor at +10 to +11 m asl) over 500 m-long and a broad shore platform at +8 to +9 m asl (Fig. 2), both carved in Jurassic limestones. The amplitude of the notch is 210 cm and its depth of concavity is less than 25 cm, presenting a smoothed shape. Its height, shape and dimensions do not change significantly along the outcrop (Fig. 5A). These markers can be spatially correlated according to topographic elevation and directly in the field with the nearshore deposits of MIS 5a, as described in Section C.

Two ichnogenus have been identified in these outcrops (*Gastrochaenolites* and *Entobia*), both corresponding to the boring activity of endobenthic bivalves and clionid sponges, respectively. In many cases, these ichnocenoses have been protected from coastal erosion due to the development of speleothems in crusts that covered the notch walls. Unfortunately, biological organisms have not been preserved, thus preventing the notch from being dated. The shore platform has experienced an intense karstification process and shows a gentle topographic slope seaward.

The *Gastrochaenolites* borings are flask-shaped and slightly elongated, with varying sizes between 10–65 mm long and 5–25 mm wide. They are always arranged perpendicular to the vertical/subvertical palaeocliff

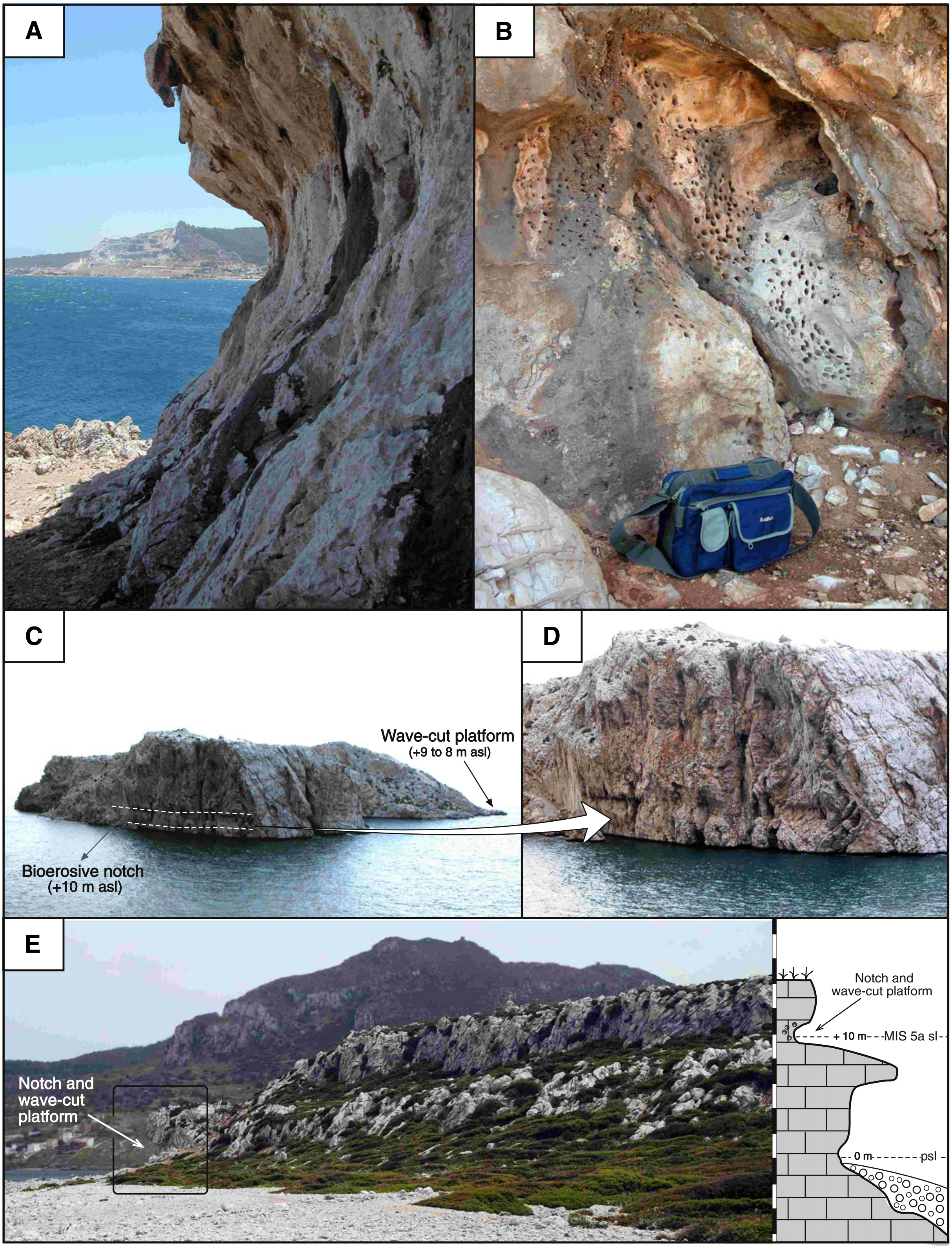

Fig. 5. Erosive and palaeoichnological markers. A, Bioerosive notch at +10 m asl in Cape Leona (Section B_1). B, Horizon of occurrence of *Gastrochaenolites* borings near the retreat point of the notch in Section B. C and D, Pervasive, laterally continuous notch in Section B_2 (Perejil Island) at +10 m asl and shore platform attached (+8–9 m asl). E, Photography and interpretative sketch of Cape Leona Beach (Section B_1). Highstand palaeocliff attached to small extension shore platform generated during MIS 5a can be observed.

surface. Oval apertural shape, a neck region markedly compressed and a circular cross-section indicate that the studied traces correspond to the ichnospecies *Gastrochaeonolites torpedo* (Kelly and Bromley, 1984). Although *G. torpedo* appear scattered along the outcrops at various heights in Section B_1, the larger borings are concentrated mainly in a horizon located between the base and the retreat point of the notch profile from +9 to +10 m asl (Fig. 5A and B). Unfortunately, it was not possible to identify the *Entobia* ichnospecies. Although *Entobia* borings have been described associated to *G. torpedo* at the base of the notch (+9 m asl), its distribution pattern in the outcrop is much more diffuse than *G. torpedo*. Therefore *Entobia* borings appear along Section B_1 at lower heights than the *G. torpedo* horizon, a few meters below the notch.

5. Interpretation and discussion

5.1. Facies analysis

The internal structure and palaeontological record of the coastal facies of Section A (Bel Younech Beach) denotes mainly backshore depositional environment during MIS 5e-2 in this zone, although the occurrence of the gastropod *Patella ferruginea* in their natural position (Porcheddu and Milella, 1991; Templado, 1997; Hawkins et al., 2000) on boulders bioeroded by *Gastrochaenolites* (e.g. Bromley and Asgaard, 1993) could indicate mesolittoral environments attached to a rocky shoreline exposed to high energy waves. In outcrops located seaward, sandy and gravelly facies with horizontal/low-angle parallel lamination and clast imbrications can be interpreted as the upper intertidal zone -or foreshore- of a conglomeratic beach (e.g. Dabrio et al., 1985; Hiroki and Terasaka, 2005). These last deposits were probably formed very close to the MIS 5e sea-level highstand. In landward outcrops the higher proportions of clay matrix, very scarce fossils and the well development of fenestral porosity observed in conglomerate facies are common features in backshore zone of beaches exposed to storms actions, where the mixture of terrestrial and coastal sediments takes place by the action of high-energy waves (Bain and Kindler, 1994; Hearty et al., 1998). Very similar deposits have been described in washover zones of progradational gravel beach sequences in the Pleistocene uplifted marine terraces of the outer Apeninic belt (Massari and Parea, 1988).

The poor development of isopachous and bladed calcite cement in these facies can be interpreted as a possible record of early marine cementation phase. Dissolution vugs, micrite crusts, equant spar in irregular rims and mosaic filling pores and meniscus fabric suggest long-term prevailing subaerial exposure and meteoric-phreatic diagenesis (Longman, 1980).

The environmental interpretation and dating of flowstones that cemented the backshore facies have allowed us to reconstruct the sequence of sedimentary and karst processes that took place between 130 and 85 ka in Section A (Fig. 6). During MIS 5e caves and shelters were developed within the lower and pre-existing travertine accumulation some meters above the palaeosea-level. The age of these travertine units has been estimated by El Kadiri et al. (2010) through U-series dating to between 225 and 98 ka, with a probable configuration consisting of a triple staircase waterfall (Chalouan et al., 2008). After the caves and shelters were formed, high-energy storm waves filled them with boulders, coarse detrital material and shells derived from adjacent beaches. The bottom of the cavities and conglomeratic facies were then covered by flowstones (Fig. 6A) that cemented them and prevented the erosional processes. A very similar process takes place every year in the neighboring town of Ceuta, when spring tides combined with high-energy waves associated to storms surges, produce the erosion and ejection of boulders, pebbles, and sands onto roads located up to 5 m asl (Abad et al., 2010). A new phase of precipitation of speleothems took place around 100 ka in MIS 5a/b substages (Fig. 6B) during a lower sea-level stage. The water flowing over the previous deposits and walls of caves produced the formation of a new flowstone generation that filled the remaining space. At present, a similar scenario is observed in Bel Younech beach, where recent cemented deposits originated by storms can be found embedded within the travertine accumulation very close to sea-level.

In Section C bioclastic conglomerate and sands deposits have been interpreted as shoreface facies of microtidal, high-energy beaches deposited during the substage MIS 5a. In the coastal setting, polymodal, graded bedding, gently inclined stratified conglomerates with scarce matrix and interbedded layers of laminated bioclastic sands have been described in upper shoreface/foreshore facies (Massari and Parea, 1988; Martini et al., 1995; Armitage et al., 2004) (Fig. 7).

The biofacies described in these outcrops, constituted by reworked red algae rhodoliths of *Lithophyllum*, serpulids, echinoids, and molluscs is very similar to the “Lithophyllum incrustans and ursins” assemblage described in present rocky substrate of the Strait of Gibraltar (Bermejo and Melado, 2009). This assemblage lies on hard cliffs and large rocks in high-energy, wave-dominated coasts of clear light waters, at depths that range from a few centimeters to 7–8 m. In this sense, the *Gastrochaenolites-Entobia* assemblage described in bioeroded limestones clasts correspond to the Entobia ichnofacies (Bromley and Asgaard, 1993) recorded from shallow-marine rocky shores of low sedimentation rates with high-energy hydrodynamic conditions.

At topographically lower positions, rhodolith-rich facies described in scattered outcrops laterally equivalent to Section C that record a more external (seaward) and deeper shoreface environment (or even shallow marine zones), where probably (para-) autochthonous patch growths of encrusting calcareous algae prevailed. The highly fragmented nature of several rhodoliths and their close association with rocky-shore conglomerate beds indicate they were deposited in a moderate to high-energy shallow marine setting (Perry, 2005). Living rhodoliths commonly occur on calcareous sediment with a high content of dead fragments in areas where light is adequate for growth and water motion is enough to inhibit burial by sedimentation (Foster, 2001). In the present coast of the Strait of Gibraltar, lower shoreface zones are characterized by the predominance of the *Lithophyllum* and *Melobesia* red algae, and other epifaunal species, over other sessile and endolith organisms, the later being much more widespread in shallower mesolittoral and upper infralittoral environments such as that described in Section B_1. Poor development of red algae biogenic accumulations can be explained by very rapid sea-level rise inhibiting continuous superposition of coeval red algae colonies (Laborel et al., 1994).

On the other hand, *Entobia* borings described on rhodoliths and carbonate substrate in the scattered outcrops next to Section C record the imprint of endolithic sponges. Similar borings are produced at present by several species of *Cliona*. In the western Mediterranean, *Cliona* is not exclusive of coastal environments although this taxon lives usually in infralittoral rocky zones ranging from mean sea-level down to a depth of 25–35 m associated to bioconstruction of the red algae *Mesophyllum alternans*, densely populated by other encrusting and boring organisms (Laborel et al., 1994; Templado et al., 2009). So, the isolated occurrence of *Entobia* traces is not a good indicator of sea level, although its ecological distribution partly fits well with the environment deduced for (para-) autochthonous algae accumulations, where lower shoreface or shallow marine conditions have been inferred.

In the same way, benthic foraminiferal assemblages described in this algal facies allow us to infer a very shallow-marine to transitional palaeoenvironment (<10 m water depth), with gravelly sand bottom, under the influence of freshwater (Curzi et al., 1996; Hayward et al., 1997). The occurrence of epifaunal species (e.g. *Elphidium advenum*) suggests the presence of a substrate densely vegetated by algae and sea grass (Pérez-Asensio and Aguirre, 2010).

5.2. Sea-level erosional markers vs. ichnofossil record

The Mediterranean basin can be considered a tideless sea, with an atmospheric tidal range that hardly surpasses 0.5 m, so the topographic

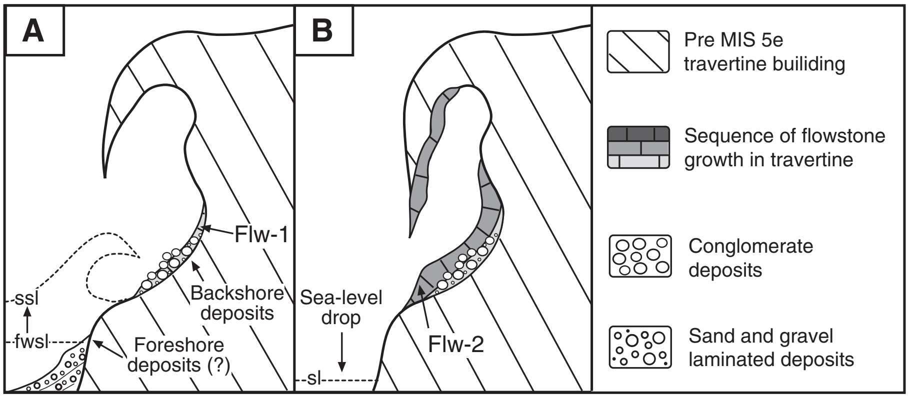

Fig. 6. Interpretative sketch showing the probable origin of storm deposit and flowstone layers into lower travertine formation (Bel Younech Beach, Section A). A, during MIS 5e (~130 ka) high-energy waves produced the infilling of caves and shelters generated in travertine near the shoreline. At the same time, the bottom of the cavities and conglomeratic facies enclosed in travertine were covered by a first generation of flowstone (Flw-1). B, a new phase of speleothem (Flw-2) took place during MIS 5a/b (~85 ka), when water flowing over the previous deposits and wall of caves produced the formation of a new flowstone episode. Fwsl, fair weather sea-level; ssl, storm sea-level. The position and height of beach deposits in A) is hypothetical.

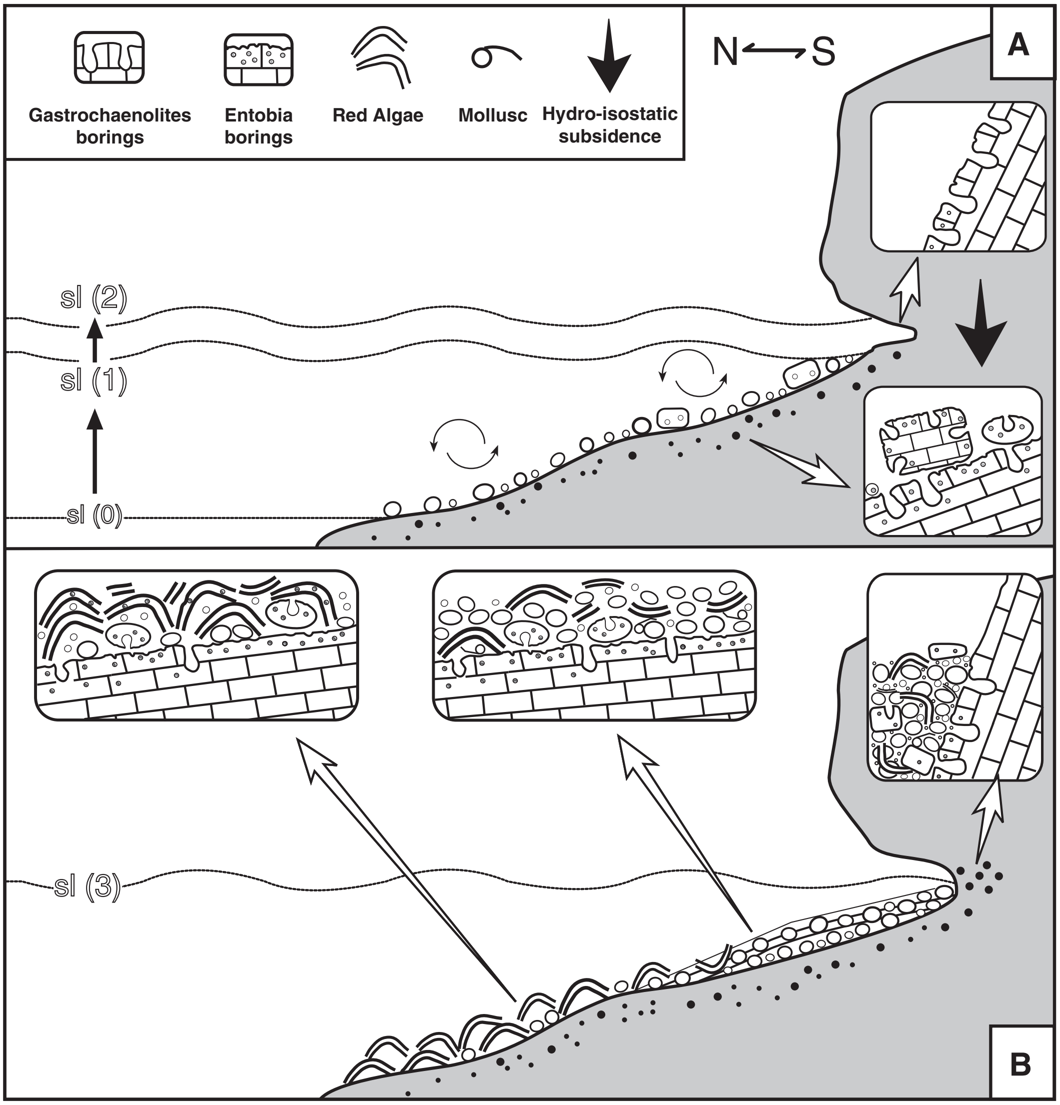

Fig. 7. Conceptual model of the sedimentary evolution of Sections B and C at the end of MIS 5a. A, ending of the trangressive process between MIS 5b/5a substages when erosional processes prevailed and the formation of notch and shore platform onto limestone rocky coast began (Sl-0 and Sl-1). In this initial phase the ichnocenoses are poorly recorded and overlapped due to the continuous rise of the sea-level. Slow sea-level rise caused by hydro-isostatic subsidence conditions in MIS 5a should be considered to explain the occurrence of smooth notch (Sl-2 to Sl-3). B, the conglomerate beaches and red algae bioherms were deposited in shoreface zone under stillstand sea-level conditions (Sl-3). Bioerosional activity of organisms continued in this phase onto cliff wall and boulders although borings of endobenthic bivalves (*Gastrochaenolites torpedo*) are concentrated in horizons at heights very close to the sea-level. Location of red algae bioherm in B) it is assumed and not directly observed in the field. Sl, sea-level. See explain in text.

elevation measured in the raised morphostratigraphic units could be considered close to the real value (Datum). The heights of the MIS 5a marine notch have been measured at +10 m asl in its middle to lower part, where boreholes of large dimensions are concentrated. Borings belonging to the ichnogenus *Entobia* and, mainly, *Gastrochaenolites* have been found through the walls of the notch morphology, although also scattered at lower altitudes along Mesozoic limestones outcrops of Sections B_1, B_2 and C.

Gastrochaenolites torpedo borings are attributed to the bioerosion of the mytilid bivalve *Lithophaga lithophaga* into calcareous substrate. In the present study area, this is very common in the infralitoral zones of rocky shores exposed to the waves together with sponges, cirripids, bryozoans and coralline red algae although this bivalve can be found in deeper environments (Templado et al., 2009). Furthermore, some investigations carried out in other Mediterranean coasts have confirmed the value of high-density occurrence of *Gastrochaenolites* borings at the same topographic height linked to erosional markers made during sea-level stillstands as a very useful tool to deduce water depths between 0 and 2 m (Stiros et al., 1992). Therefore, the indirectly dated bioerosive notch and shore platform in Gebel Mousa coast (Sections B_1 and B_2) can be considered as good indicators of the sea-level for MIS 5a substage and a very useful tool to estimate vertical tectonic movements rates (e.g. Pirazzoli, 1998; Kershaw and Guo, 2001; Antonioli et al., 2007; Hearty et al., 2007). On the other hand, the isolated occurrence of *Entobia* traces by itself cannot be used as an indicator of past sea-level.

The ichno-association described in marine notch (*Entobia* ichnofacies; Bromley and Asgaard, 1993) has been observed in Neogene and Quaternary rocky coasts and present-day shallow-marine zones with long time exposure and non significant sedimentation rates (e.g. MacEachern and Pemberton, 1994; Gibert and Martinell, 1998; Rodríguez-Vidal et al., 2007a; Santos and Mayoral, 2009), in many cases recording transgressive frameworks (e.g. Gibert et al., 1998) when the sea flooded extensive rocky areas, which were bored and encrusted by endolithic and epilithic organisms.

Therefore, the borings described in Section B can be considered not only as the marker of the MIS 5a highstand but probably also as the ending of the transgressive process which occurred between MIS 5b and MIS 5a stages, when the continuous rise of sea level produced the overlapping of successive coastal ichnocenosis (Sl-0 to Sl-1, Fig. 7A). Erosional processes prevailed at this time whereas the formation of notch and shore platform onto limestone rocky coast occurred during stillstand conditions (Sl-2, Fig. 7A). On the other hand, a new transgressive phase could have taken place at the end of MIS 5a substage, creating favorable conditions for the development of smoothed notches under lower rate of rising sea-level (Sl-2 to Sl-3, Fig. 7B). The sea-level rise could be originated by hydro-isostasic subsidence, forcing the increase of the notch amplitude and its smoothed geometry (see point 5.3). Finally, stillstand conditions prevailed again at the ending of MIS 5a and that is recorded in prograding conglomerate beaches and red algal bioherms in shoreface and shallow marine zones (Sl-3, Fig. 7B). The activity of bioeroding organisms continued under this brief sea-level stillstand at higher elevation onto the cliff wall and boulders. However, borings of endobenthic bivalves (*Gastrochaenolites torpedo*) are concentrated in horizons at heights very close to the sea level.

5.3. Recent tectonics and uplift rate

Assuming the two highstands that have been described and dated in the study area correspond to the Last Interglacial (MIS 5e and MIS 5a), the older one (131.2 ± 7.4 ka) probably records the first highstand of the interglacial (MIS 5e-2) at 13–15.5 m asl. Nevertheless, no erosional markers were observed and sedimentary facies were interpreted as backshore/foreshore environments exposed to storm events. These facies are not considered to be more reliable nor more accurate sea-level indicators. Thus, it is very difficult to infer a certain sea-level height for the MIS 5e-2 substage. On the other hand, the lower altitude of these deposits (+13 m asl) could be used as a good approximation to infer the maximum uplift tectonic rate of this zone during the last 130 ka. This hypothesis is partly endorsed by the isolated occurrence of upper foreshore facies in Section A.

In the western Mediterranean, the tectonically stable coasts of the island of Mallorca (Vesica et al., 2000) present caves that provide an extraordinary setting for capturing past sea-level changes (Tuccimei et al., 2006; Dorale et al., 2010). The altitudinal comparison of MIS 5e-2 in the Mallorca record with the Gebel Mousa record (see Table 1 and Fig. 8) allows inference of a maximum tectonic uplift rate to just below ~0.08 mm/yr for the last 130 kyr in the study area. On the other hand, a much more certain height of sea-level can be estimated for the MIS 5a highstand on the basis of the occurrence of marine notch bioeroded by *Gastrochaenolites* at +10 m asl, resulting in a similar tectonic uplift rate of 0.11 mm/yr for the last 83 kyr.

The uplift rates deduced in this work are higher than those proposed by El Kadiri et al. (2010) for the last 200 kyr (0.05 mm/yr) in the same study area. These authors do not present the results of direct dating of the deposits linked to erosive markers of sea-level highstands and appear to deduce this value from an uncertain correlation between travertine accumulations and staircased marine terraces that pre-date the last interglacial terraces. In addition, these data are supported by a tentative regional correlation of altitudes between the Cape Leona terraces and the remote marine terraces situated along the Moroccan Atlantic coast (El Fahssi, 1999).

A precise estimation of the uplift rate can be made assuming a maximum difference in altitude of 1.1 m between MIS 5e-2 and MIS 5a highstands observed in the quasi-stable coast of Mallorca (Tuccimei et al., 2006). This fact allows us to suppose that only 1.9 m of the 3 m of elevation difference measured in Cape Leona between both highstands has tectonic origin, although a non-quantifiable error is possible due to hydrostatic movements. Thus, a tectonic uplift rate of 0.05 mm/yr, lower than the expected, can be assumed for the time interval between 135 and 83 ka.

In this sense, it is important to highlight that in contrast to local tides amplitudes (Jaaidi et al., 1992), the amplitude of the MIS 5a marine notch is above 50 cm and it presents a smoother and more elongated shape than that otherwise expected in notches sculpted in sea-level in relative stillstand episodes and microtidal regime. Previous authors have interpreted that a fossil smoothed notch records the enlargement of a former tidal notch carved during a highstand stage that migrates upwards due to the action of a slow hydro-isostatic subsidence, but others factors cannot be excluded (e.g., exposition to waves and water turbulence, biodegradation of substrate) (e.g. Antonioli et al., 2006b). Although these morphologies have been described for the MIS 5e highstand, the fact that they are found in different Marine Isotope Stages suggests that isostatic adjustment movements were active also in younger and older stages. In any case, we assume that the coastal subsidence rate in the study area must have been higher than the estimated tectonic uplift rate of ~0.1 mm/yr during the MIS 5a substage. If we assume for our study area a lower hydro-isostatic subsidence rate than that established by Antonioli et al. (2006b) for Sardinia and the Western Italian coast during MIS 5e, it should be sufficient to justify the enlarged morphology of the MIS 5a notch in Section B (Fig. 7B). In the same way, this circumstance would also explain the decrease of 0.03 mm/yr in the uplift tectonic rate deduced for the period between MIS 5e-2 and MIS 5a substages with regard to the mean of 0.08 mm/yr assumed in the Gebel Musa Coast for the last 130 kyr.

5.4. Regional uplift

Numerous authors have described the Last Interglacial marine terraces in southern Spanish coasts, and northern Mediterranean and Atlantic littoral areas of Morocco. Their spatial distributions display a concentric pattern with maximum coast uplift in the

	Zone	MIS 5 sea-level range	MIS 5a Uplift rate (mm/year)*	MIS 5e Uplift rate (mm/year)**	Marker	Reference
WESTERN EUROPE	Trafalgar	4-13** m	No data	0,08	no data esp.	Zazo et al. (1999)
	Tarifa	11-20** m	No data	0,13	no data esp.	Zazo et al. (1999)
	Gibraltar	1,5*-5** m	-	0,02	beach /notch	Rodriguez-Vidal et al. (2004)
	Marbella	< 0-2* m	0	-	no data esp.	Zazo et al. (1999)
	Almería	3,5*-8** m	0,02	0,04	beach / wcp	Zazo et al. (2003)
	Murcia	10** m	?	0,05	coastal facies	Zazo et al. (2003)
	Alicante	3*-5,5** m	0,01	0,02	beach	Dabrio et al. (2011)
NW AFRICA	Casablanca	5-8 m	No data	0,04 (?)	coastal facies	Texier et al. (2002)
	Tanger	15-20 m	No data	0,13 (?)	coastal facies	GRN (1977)
	Tetuan	3-6 m	No data	0,02 (?)	coastal facies	GRN (1977)
	Alhoceima	5-10 m	No data	0,05 (?)	coastal facies	Gigout et al. (1974)
	Melilla	4-5 m	No data	0,02 (?)	coastal facies	Gigout et al. (1974)
	Cap Leona	**10*-13** m**	**0,11**	**> 0,08**	**beach /notch**	**This work**

Fig. 8. Above, location of the main outcrops of marine terraces (and other markers) belonging to MIS 5 in southern Spain and northern Morocco. Circles with vertical (0.1 mm/yr) and oblique lines (0.05 mm/yr) define areas of moderate and low tectonic uplifting in the Strait of Gibraltar, respectively (after Goy et al., 1995; Zazo et al., 1999 and present work). Below, occurrence range of MIS 5 marine terraces altitude and tectonic uplift rates deduced for MIS 5a and MIS 5e-2 considering the data of sea-level altitude and age from Tuccimei et al. (2006) as references. White zone, tectonically stable area; light grey zone, low tectonic uplift rate; dark grey zones, moderate tectonic uplift rate. Marker: wcp, shore platform; "no data esp" in Zazo et al. (1999) indicates beach or notch evidence without specifying a marker. (*) Altitude of MIS 5a highstand with dated sea-level marker. (**) Altitude of MIS 5e highstand with dated sea-level marker. (−) Subsiding area; (0), Stable area. GRN, Groupe de recherche néotectonique de l'Arc de Gibraltar (1977). (?) Where we are not certain of the marine terrace age, we have inferred that the higher altitude of MIS 5 marine terrace in Africa are linked to MIS-5e. The data are not always consistent. Tectonic uplift rates deduced for MIS 5e-2 in this work is a maximum estimation.

central part of the Strait of Gibraltar (0.2 mm/yr) that decrease toward the East and West (Goy et al., 1995; Zazo et al., 1999) (Fig. 8). This model fits well with the altitude and uplift rate deduced from the marine terraces described in Cape Leona. On both sides of the central sector of the Strait of Gibraltar, the uplift is much more pronounced than in Cape Leona, increasing up to 20 m asl toward the west of the altitude of MIS 5 marine terrace in Tarifa and Tangier-Ksar el Shir sectors. In the Casablanca Atlantic coast, the MIS 5 emerged highstand deposits of Ouljian stratotype are distributed between +5 and +8 m asl (Texier et al., 2002), revealing lower Quaternary tectonic uplift compared to the results obtained in the study area. Likewise, in eastern positions of the opposite Iberian shore (Rock of Gibraltar) an uplift value of 0.05 ± 0.01 mm/yr is calculated for the last 200 kyr (Rodríguez-Vidal et al., 2004, 2007b) on the basis of uplifted marine terraces located at +1.5 to +2 and +5 m asl (MIS 5a and MIS 5e, respectively). Finally, near Tetuan and Malaga, in the Moroccan and Spanish Mediterranean coasts, MIS 5 terrace heights range from +3 to +6 m asl (Zazo et al., 1999, 2003; Bardají et al., 2009a and references therein; El Kadiri et al., 2010 and references therein) indicating a very similar uplift rate in both regions.

Consequently, the moderate to low tectonic uplift deduced indicates a prevailing role of eustasy over the tectonic in the development of marine terraces in the North of Morocco, with the exception of the central part of the Strait of Gibraltar. On the other hand, it is obvious that the importance of tectonic movements must not be discarded (El Kadiri et al., 2010). A comparison between the uplift rates deduced from the terraces of Cape Leona and the altitude distribution of MIS 5 marine terraces of western Mediterranean and Atlantic coasts of Africa with different degrees of tectonic activity allows us to classify the study area as a moderately active coast (0.08–0.11 mm/yr, Fig. 8). In order to make this calculation and formulate a comparison, the different tectonic uplift rates estimated by several authors in the Strait of Gibraltar have been recalculated taking as new references the highest sea-level data and the age for MIS 5e-2 and MIS 5a substages (135 and 83 ka, respectively) provided by Tuccimei et al. (2006) for the Island of Mallorca. This value of tectonic uplift is close to that obtained in Murcia and Trafalgar southern of Spain, Zazo et al., 1999, 2003) or Alhoceima regions (northeastern coast of Morocco, Gigout et al., 1974) (Fig. 8). Zazo et al. (1999) propose that differential uplifting in NNE/SSW bands described in the Strait of Gibraltar area for the last 128 kyr is accommodated along NE-SW sinistral and NW-SE dextral strike-slip fault system generated in a transpressive setting in response to roughly N-S convergence between the African and Eurasian plates.

6. Conclusions

In this work we described, for the first time in the North of Africa, complete sequence of onshore erosional and depositional features linked to sea-level rise. This sequence comprises palaeo-seacliff, marine notch, and shore platform. These largely erosional morphologies are fossilized by sedimentary littoral sediments deposited during the Last Interglacial period (MIS 5) as indicated by U-series analyses.

Shore sedimentary facies described into travertine accumulations (Section A) were deposited in foreshore and mainly backshore environments by storms during MIS 5e-2 substage. These facies were probably formed in a few meters above sea level. In the same way, microtidal, high-energy beaches and shallow-marine environments can be inferred from erosive markers (Section B_1 and B_2) and palaeontological and sedimentological evidence (Section C) dated to MIS 5a.

We establish a tectonic uplift rate of ~0.1 mm/yr, which has been estimated for the last 130 kyr on the basis of the occurrence of upper foreshore MIS 5e-2 deposits and the *Gastrochaenolites* horizon in the notch formed during MIS 5a highstand. Nevertheless, a subsidence of hydro-isostatic origin could have taken place during the culmination of MIS 5a, forcing a relative sea-level rise after the initial stillstand conditions. This rising level caused enlargement of the marine notch and a significant decrease of the relative uplift rate.

During Late Pleistocene, eustasy played a predominant role over the tectonic uplift in the development of marine terraces in the North of Morocco, although the importance of the last must not be disregarded. A comparison between the uplift rates from the terraces of Cape Leona and MIS 5 marine terraces of Western Mediterranean and Atlantic coasts of Africa permit to define the study area as a moderately active coast from a tectonic point of view. This classification is consistent with previous models of differential coast uplifting calculated for the Strait of Gibraltar during the Last Interglacial.

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