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Eustatic and tectonic controls on Quaternary Ras Leona marine terraces (Strait of Gibraltar, northern Morocco)

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ABSTRACT

Well-preserved Quaternary staircased marine terraces appear on Ras Leona limestone relief. This is a peculiar sector of the Betic-Rif Cordillera, lying in the four-way junction between the Atlantic and the Mediterranean, and Europe and Africa. The age and altitude correlation of the Ras Leona terraces with travertine-covered lateral equivalent terraces fashioned in the neighbouring Beni Younech area, and comparison with those along the Moroccan Atlantic coasts, would suggest that the Ras Leona terraces were mainly formed by eustatic factors. The importance of the eustasy is supported by further comparisons with Spanish and Moroccan Mediterranean terraces and with different marine terraces developed on passive-margin coasts around the world. A tectonic event occurred mainly during the period between the formation of the Maarifian and the Ouljian terraces (i.e., between 370 and 150 ka). The moderate Quaternary tectonic uplift deduced from the marine terraces and its comparison with uplifted marine terraces developed in active subduction setting disagrees with the model of an active eastwards subduction below the Gibraltar tectonic arc.

Introduction

Marine terraces constitute key geomorphic features whose development is linked to Quaternary sea-level fluctuations associated with global climatic changes and/or to active tectonic processes. Therefore, Quaternary scientists have generally tried to determine their ages using absolute and relative dating and correlation methods (Oosterom, 1988; Sirkin et al., 1990; Cucci and Cinti, 1998; De Martini et al., 2004; Marquardt et al., 2004; Pirazzoli et al., 2004; Zazo et al., 2007; Saillard et al., 2009). The age of marine terraces developed along passive coasts can be determined by the correlation of their elevation to reconstructed global sea-level fluctuations. While these correlations present some difficulties associated with coastal erosive conditions, which partially destroy the marine deposits, and chronological limitations inherent to the different dating methods, they are largely used and accepted to quantify the role of coastal eustasy and tectonics worldwide.

We analyze the development of five marine terraces along the Moroccan side of the Gibraltar Strait, in the Ras Leona-Beni Younech sector, especially sensitive to sea-level fluctuation as a consequence of global climatic changes and tectonic movements. From the climatic standpoint, the Gibraltar Strait is located in a transitional area, constituting the gateway between the Atlantic Ocean and the semienclosed Mediterranean Sea. From a tectonic point of view, the Gibraltar tectonic arc was linked to an eastward subduction during the early and middle Miocene, and their present-day activity/inactivity is under a vigorous debate (Gutscher et al., 2002; Stich, et al., 2005, Gutscher et al., 2009).

Whereas the marine terraces along the Spanish coast of the Gibraltar area have been broadly studied (Goy et al., 1995; Zazo et al., 1999; Rodríguez-Vidal et al., 2004), the Quaternary marine terraces along the Moroccan side still lack detailed investigation, especially concerning the close age control, which percludes lateral correlations. The aim of this study was to estimate the role of eustasy and tectonics on the southern side of the Gibraltar Strait, based on study of the well-preserved marine terraces on the Ras Leona–Beni Younech sector, partially covered by travertines (Fig. 1). The U–Th ages obtained on the travertine deposits overlie the marine terraces in Beni Younech allow us to correlate these terraces with well-documented Moroccan Atlantic terraces and western Mediterranean ones. Moreover, these data are contrasted with those of diverse marine terraces of tectonically active and passive coasts of

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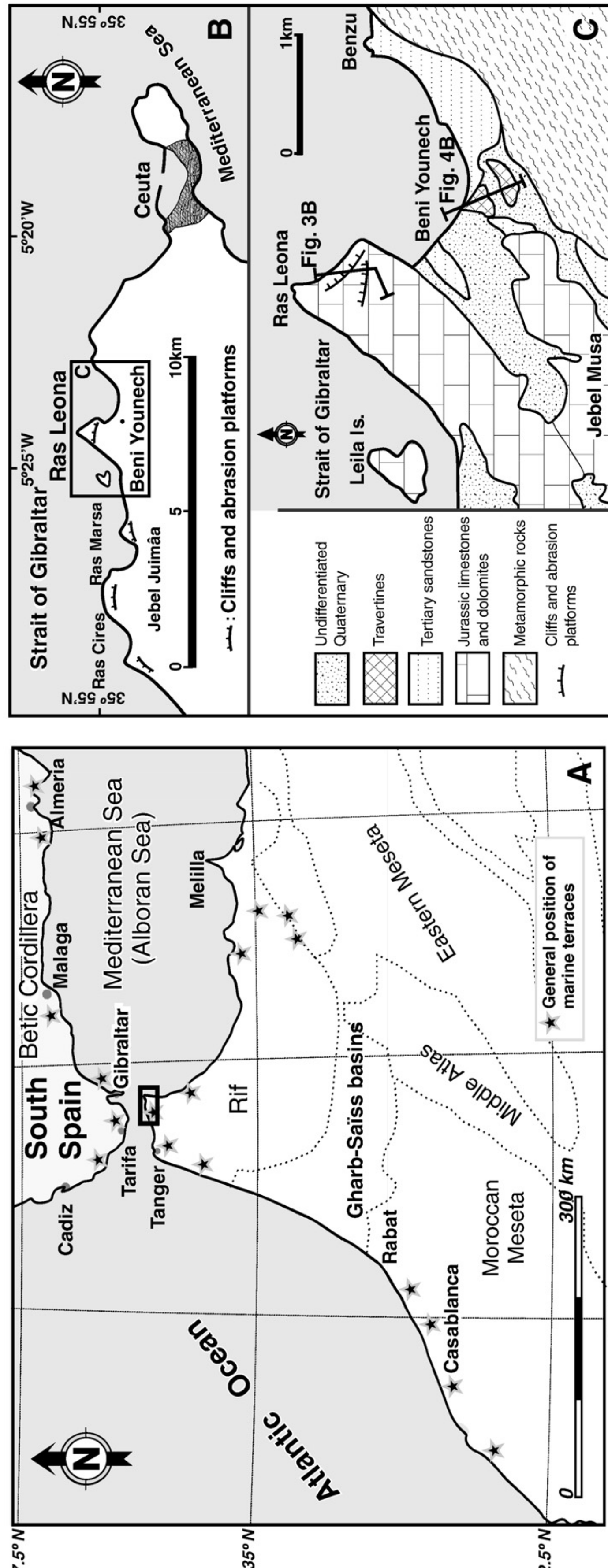

Figure 1. (A) General setting of the study sector for the northern Morocco and southern Spanish coasts. (B) Location of the Ras Leona and Beni Younech marine terraces on the southern border of the Strait of Gibraltar (general situation is marked as a rectangle in A). (C) Geological sketch of the study sector (marked as a rectangle in B). The cross sections of Figures 3B and 4B are situated on the northern side of Ras Leona block and in the village of Beni Younech, respectively.

several continents, using altitude/age graphs to assess the relative influence of the interplay of sea-level fluctuations associated with climatic changes and active tectonic processes.

Geological setting of the Gibraltar Strait

The studied Quaternary terraces are present on the southern coast of the Gibraltar Strait at the westernmost part of the Mediterranean Sea (the so-called Alboran Sea; Fig. 1A). Together with its Spanish counterpart, the relief of this coast determines the connection between the Atlantic Ocean and the Mediterranean Sea.

The Gibraltar tectonic arc is represented by the Spanish Betic and the Moroccan Rif Cordilleras, which present a common Internal Zone. During the early–middle Miocene, the Internal Zone moved westwards (Wildi, 1983; Sanz de Galdeano, 1990) and strongly deformed the external zones of both cordilleras. Simultaneously, their back portions underwent extensional processes, resulting in the formation of the Alboran Sea in the centre of the arc (Boillot et al., 1984). This geodynamic setting could be linked to an eastward subduction during the early and middle Miocene (Royden, 1993; Lonergan and White, 1997). The present-day activity of this subduction system is under debate (Gutscher et al., 2002, 2009; Stich, et al., 2005). In addition, the Betics and Rif were affected from the late Miocene by a NNW–SSE to NW–SE compression linked to the 5 mm/yr shortening between the African and the Iberia plates, which coexisted with ENE–WSW extension.

The connection between the Atlantic and the Mediterranean through the Strait of Gibraltar stems from the end of the Miocene. Before that, the Mediterranean and Atlantic seas were connected to the north by means of the Spanish Guadalquivir foredeep Basin and to the south through by the Moroccan Gharb and Saïss foredeep basins. Both connections were closed during the Messinian, when the Mediterranean behaved as a giant evaporitic basin, which caused the well-known “Salinity Crisis” (Lonergan and White, 1997; El Bakkali et al., 1998; Duggen et al., 2003).

From this general scenario, it can be deduced that the tectonic activity of the region was, from the late Miocene, relatively less than during the Palaeogene and the early–middle Miocene, although many deformations affected the Betic Cordillera (Sanz de Galdeano and Alfaro, 2004) and the Rif Mountains from the Tortonian (late Miocene) onwards. Consequently, the studied coast is expected to record tectonic deformation during the Quaternary.

Marine terraces along the Gibraltar Strait and the Moroccan coasts

Well-developed Pleistocene and Quaternary marine terraces are formed all along the Spanish coast of the Gibraltar Strait. Most of the elevated terraces include a wave-cut erosive surface located at the base and a thin fossiliferous sedimentary layer located immediately above (Zazo et al., 1999). In coasts developed over limestones, as around the Rock of Gibraltar, the coastal sedimentary deposits are scarcer, and the terraces are dominated by wave-cut platforms and coastal cave fillings (Rodríguez-Vidal et al., 2004). On the Spanish coasts, eustatic and tectonic interactions were studied by deciphering maximum average uplift rates smaller than 0.2 mm/yr and displaying a gentle deceleration from 0.15 to 0.10 mm/yr for the last 128 ka (Goy et al., 1995; Zazo et al., 1999). The Atlantic Spanish coasts were also correlated with the Rock of Gibraltar's coast (Rodríguez-Vidal et al., 2004) and with other Mediterranean coasts (Zazo et al., 2003) for the isotopic stages MIS 5 to MIS 11.

Compared to their European Mediterranean and Atlantic counterparts, the Moroccan Quaternary marine terraces of the Gibraltar Strait area are less studied, and generally only considered as part of a regional synthesis (e.g., André and El Gharbaoui, 1978; El Fahssi, 1999). Southwestwards, the Quaternary littoral deposits are very well preserved along the Atlantic coast of Morocco, in a band of up to 10 km in width, and have been studied considerably. Table 1 summarizes the classic stratigraphy of the Atlantic Moroccan marine Quaternary succession, including the stratotypes and the present-day height of the paleo-shorelines defined in the Casablanca region (Gigout, 1951; Biberson, 1959; Choubert, 1965; Stearns, 1978). The litho-chronostratigraphy of this succession has been recently revised (Lefèvre and Raynal, 2002; Texier et al., 2002), including biostratigraphiy (Geraads, 1998) and chronometric dating (Rhodes et al., 1994; Occhietti et al., 2002; Rhodes et al., 2006).

They resulted from Quaternary transgressive pulses, which formed the corresponding staircased marine terraces, situated on the paleo-shorelines that could be partially correlated with glacio-eustatic maxima, Marine Isotopic Stages MIS 1 to MIS 22 (Texier et al., 2002; Table 1). The sediments filling these terraces correspond to shallowing-upward progradant sequences, formed during a whole regressive regime following the Pliocene marine flooding. Each sequence consists of a lumachellic conglomerate comprising lumachellic clasts and upgrading to beach calcarenites, which in turn progressively graded into eolian calcarenites, with local intercalations of rubified soil deposits. These eolianites were frequently altered into pulverulent limestones, secondarily crowned by calcretes, and then covered by some levels of silt- or clay-intercalated red sands. Southwards in the Meseta coast of Morocco, the Quaternary formations built a system of dune strings and interdune furrows, more or less parallel to the present-day coast (Beaudet, 1969). These dunes, covered by silty-clayed red sands, are marked by the asymmetry of their aeolian slopes; the length of each dune string can exceed a kilometre. This system is separated from the present coastal string by a longitudinal depression (oulja in Arab), limited on the coast by the Ouljian cliff (Akil, 1990), representing a characteristic coastal landform.

Table 1
Correlation between the classic chronostratigraphy of the Atlantic Moroccan marine terraces and MIS, including the most recent lithostratigraphic units (Lefèvre and Raynal, 2002; Texier et al., 2002) and chronological data from Rhodes et al., 2006 (1), Occhietti et al., 2002 (2), Geraads, 1998 (3), and Rhodes et al., 1994 (4).

Classic chronostratigraphy—altitude above sea level (Biberson 1961)	Lithostratigraphic units from Casablanca sector (Lefèvre and Raynal, 2002; Texier et al., 2002)	Chronological data	O^{18} isotopic stages (MIS) interpretation of Texier et al (2002)	
Mellahian (2 m a.s.l.)	Reddad Ben Ali Formation	0.14 ± 0.07 ka to 4.42 ± 0.30 ka (1)	1	Holocene
	Dar Bou Azza Formation	Aterian industry	2 to 4	Late Pleistocene
Ouljian (5-8 m a.s.l.)		Amino group O (3)	5	
	Kef El Harour Formation	163 ± 0.33 ka (1)	7 ?	Middle Pleistocene
Anfatian (30 m a.s.l.)	(18-20 m a.s.l.)	303 ± 0.30 ka (1)	9 or 11	
	Anfa Formation	376 ± 0.34 ka (1)		
		492 ± 0.57 ka (1)	10 ? to 18 ?	
Maarifian (50-60 m a.s.l.)	Oulad Hamida Formation	370 ± 0.58 ka to 989 ± 208 ka (1) ~1 Ma (3)	18 to ≥ 22 ?	Early Pleistocene
	Gandour Ben Habib Unit	1380 ± 390 ka (4) 989 ± 208 ka (4)		
		804 ± 227 ka (4) 747 ± 390 ka (4)		
	Dar Bou Chaïd Ben Caïla Unit			
Messaudian (90-100 m a.s.l.)	Sidi Messaoud Unit			Pliocene

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Ras Leona Quaternary marine terraces and Beni Younech travertines

Most of the terraces of the southern shore of the Strait of Gibraltar were eroded because they took shape in the soft flysch sediments (deep-water interbedded marine muds, silts, and sandstones). Nevertheless, those of the studied Ras Leona area were sculpted in hard, massive limestones (early Jurassic in age).

Quaternary marine terraces at Ras Leona

The staircased Ras Leona terraces are shown in Fig. 2A and B in a view towards the southeast and in a NE–SW cross section, respectively. These terraces were correlated based on their altitudes with those situated along the Moroccan Atlantic coasts (El Fahssi, 1999). Therefore, the classic Moroccan Atlantic chronostratigraphy was attributed to the Ras Leona terraces, determining from youngest to oldest: (a) the Ouljian terrace, divided into two terraces situated at 6 m and 8 m, (b) the Anfatian terrace at 30 m, (c) the Maarifian terrace at 55 m, and (d) the Mesaudian terrace at 90 m.

The altitude values were measured using a barometric altimeter with 0.5-m precision. These barometric altitudes were referenced to the mean sea level of Casablanca after correlate the barometric height data with well-defined base points of the topographic map of "Détroit de Gibraltar- Sebta, sheet 4-3" scale 1:25,000 performed by the SNED (Societé Nationale des études du Détroit). The data acquisition was done in cycles of less than 1 hour and during sunny weather with the aim to minimize and correct the barometric changes. In narrow terraces, the altitude was measured in the central planar flats, near the position of the cliff closing the terrace. In the wider terraces, the mean altitude is more difficult to measure and the altitude values can be considered only as approximate (Fig. 2). The altitude values of the terraces located around the Perejil/Leila Island (Fig. 2C) are deduced from the topographic map.

New absolute age data from travertines that cover the marine terraces in the nearby Beni Younech (Chalouan et al., 2008) and the synthesis by Texier et al. (1985, 2002), Lefèvre and Raynal (2002), and Rhodes et al. (2006) are here considered to complete and partially reinterpret the Quaternary marine terraces at Ras Leona (Table 1; Figs. 2A and B) as follows (from youngest to oldest, using the classic chronostratigraphy of Biberson, 1961): (a) the Ouljian terrace, corresponding with MIS 5 (Occhietti et al., 2002; Texier et al., 2002), which, according to our estimations, sits at 4–5 m above mean sea level (MSL); (b) a terrace intercalated between the Ouljian and the Anfatian, at approximately 18 m above MSL, that is correlated with the lower part of

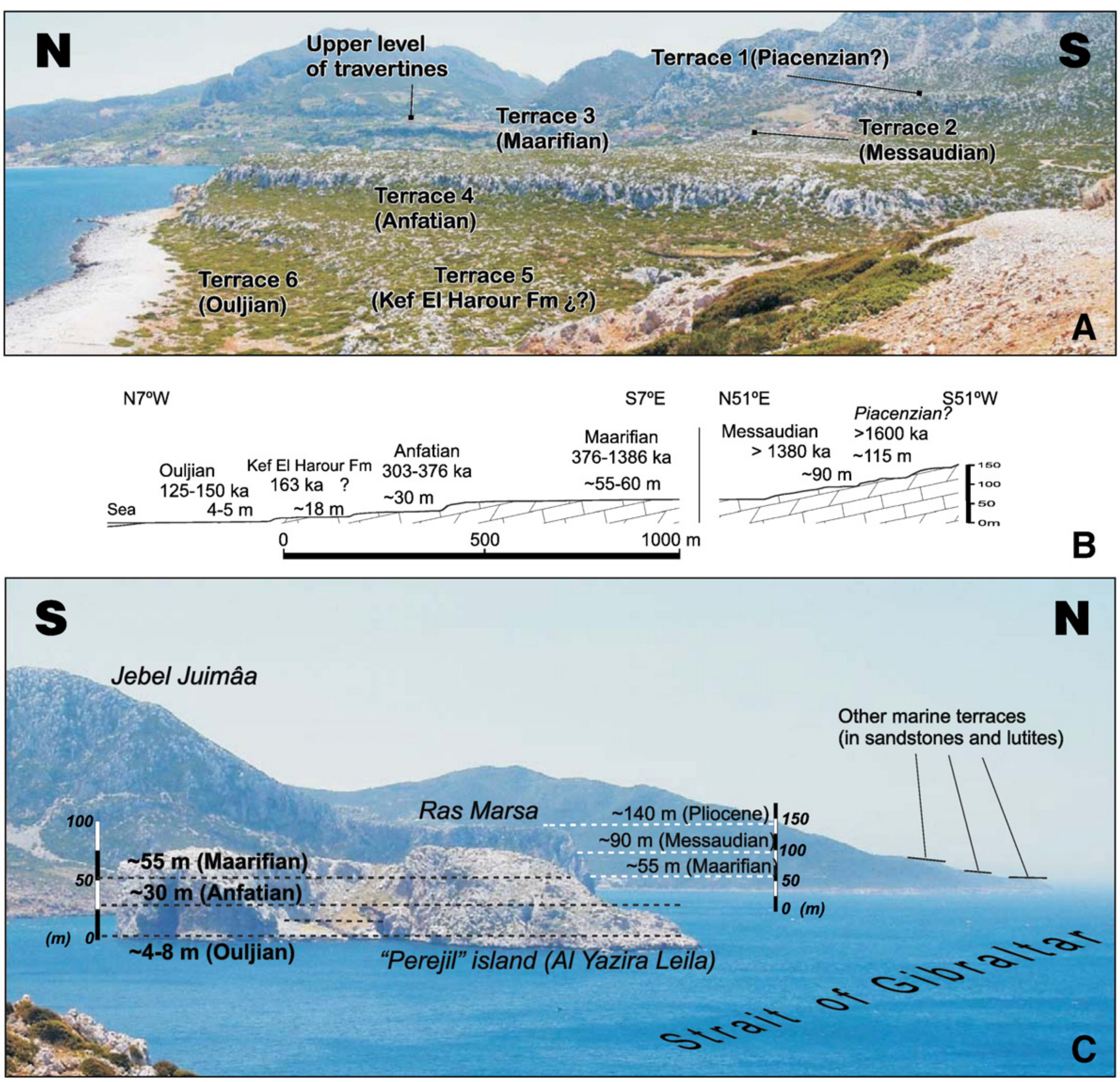

Figure 2. (A) Marine terraces of Ras Leona (view towards the SE). The upper travertine level of Beni Younech appears in the background. (B) Schematic cross section of the staircased marine terraces of Ras Leona, with an indication of their altitude and attributed ages. Note that this cross section is formed by two parts in different directions, to show all the marine terraces. The position of the cross section is indicated in Figure 1C. (C) Marine terraces of the Leila island (Isla Perejil in Spanish) and Ras Marsa, west of Ras Leona cape.

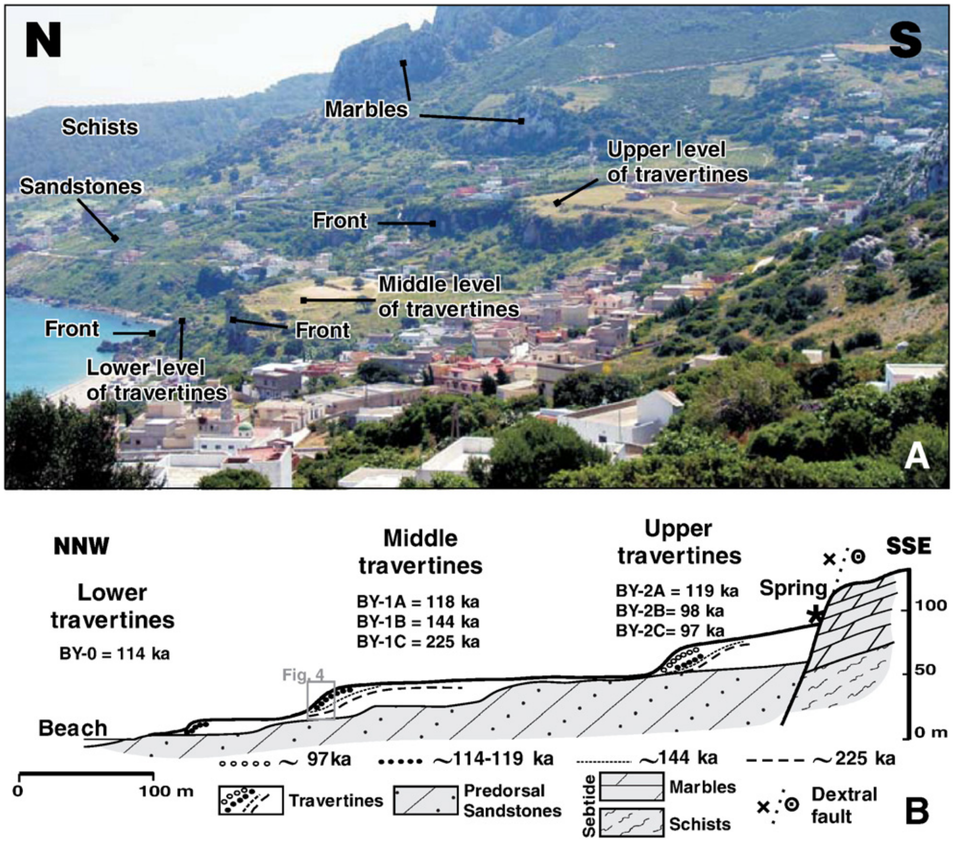

Figure 3. (A) Travertine levels of Beni Younech. (B) Schematic cross-section of the three levels of travertines of Beni Younech and the position of the samples, together with the ages assigned. The position is indicated in Figure 1C.

the Formation Kef El Haroun of 303 ± 0.3 ka (Rhodes et al., 2006), which is assigned to MIS 9 or 11 (Texier et al., 2002); (c) the Anfatian terrace located at 30 m above MSL and probably developed between 376 ± 0.34 and 492 ± 0.57 ka (Rhodes et al., 2006); (d) the Maarifian terrace developed between 370 ± 0.58 and 1380 ± 390 ka (Rhodes et al., 2006); and (e) a new highest terrace, situated at 115 m above MSL, developed before 1380 ± 390 ka (Rhodes et al., 2006) probably during the Pliocene.

This age/altitude classification of Ras Leona terraces remains to be tested by direct dating as done in other places of the western Mediterranean (Bardají et al., 2009; Stokes and Garcia, 2009). Although subaerial processes degraded the Ras Leona terraces and they do not preserve marine sediments, making direct paleontological dating impossible, the travertine deposits of the Beni Younech allow us to test the assigned correlation providing a minimum age for some of these marine terraces.

Perched spring travertines at Beni Younech

Absolute U–Th ages were obtained from three levels of travertine cropping out 2 km southeastward of the Ras Leona area, by the village of Beni Younech (Figs. 1C, 2, and 3; note that in this study, the term "travertine" is used in its broadest sense to refer to all nonmarine carbonate precipitates formed in or near terrestrial springs [Sanders and Friedman, 1967] and in this case probably involves freshwater tufa).

Three perched spring travertines are formed over terraces at the same altitudes as those of three marine terraces of Ras Leona. The upper travertines form a platform situated at an altitude of 95–100 m above MSL, extending up to 60 m above MSL in the lower part where it shows a nearly vertical front. The middle travertines form a platform situated at 45–50 m above MSL, with their bottom at 20–25 m above MSL, and also develop in a nearly vertical front. The lower travertines form a platform at 18–20 m above MSL, and although they likewise develop in a vertical front, it has fallen to the beach at many points. These Beni Younech terraces are fashioned in Tertiary sandstones and lutites, while the higher level is limited by Triassic marbles, separated from the sandstones by a dextral strike-slip fault.

The internal architecture of the travertines is characterized by unconformities that bound prograding irregular beds (Fig. 3). Three facies associations were distinguished, deposited in three subenvironments:

Table 2
Ages assigned to different samples of travertines from Beni Younech, using several radioisotopes of the disintegration series of the U-238 and Th-232 by alpha spectrometry.

	Sample	U^{238} (ppm)	Th^{232} (ppm)	U^{234}/U^{238}	Th^{230}/U^{234}	Th^{230}/Th^{232}	Nominal date (yr BP)
Upper platform	BY - 2C	1.46 ± 0.02	0.16 ± 0.00	1.30 ± 0.01	0.61 ± 0.01	23.1	97,300 + 3090/ −3010
	BY - 2B	2.01 ± 0.04	0.20 ± 0.01	1.29 ± 0.01	0.61 ± 0.02	25.3	98,430 + 3920/ −3790
	BY - 2A	1.09 ± 0.02	0.14 ± 0.00	1.28 ± 0.01	0.69 ± 0.01	21.7	119,480 + 4480/ −4310
Middle platform	BY - 1C	0.77 ± 0.01	0.21 ± 0.01	1.21 ± 0.01	0.91 ± 0.02	13	225,200 + 13,870/ −12,400
	BY - 1B	1.20 ± 0.02	0.05 ± 0.00	1.26 ± 0.01	0.76 ± 0.02	67.7	144,200 + 6270/ −5950
	BY - 1A	1.90 ± 0.03	0.13 ± 0.00	1.16 ± 0.01	0.68 ± 0.01	35.8	118,540 + 4640/ −4460
Lower platform	BY - 0	1.22 ± 0.02	0.14 ± 0.00	1.31 ± 0.01	0.68 ± 0.01	23,684	114,720 + 4120/ −3980

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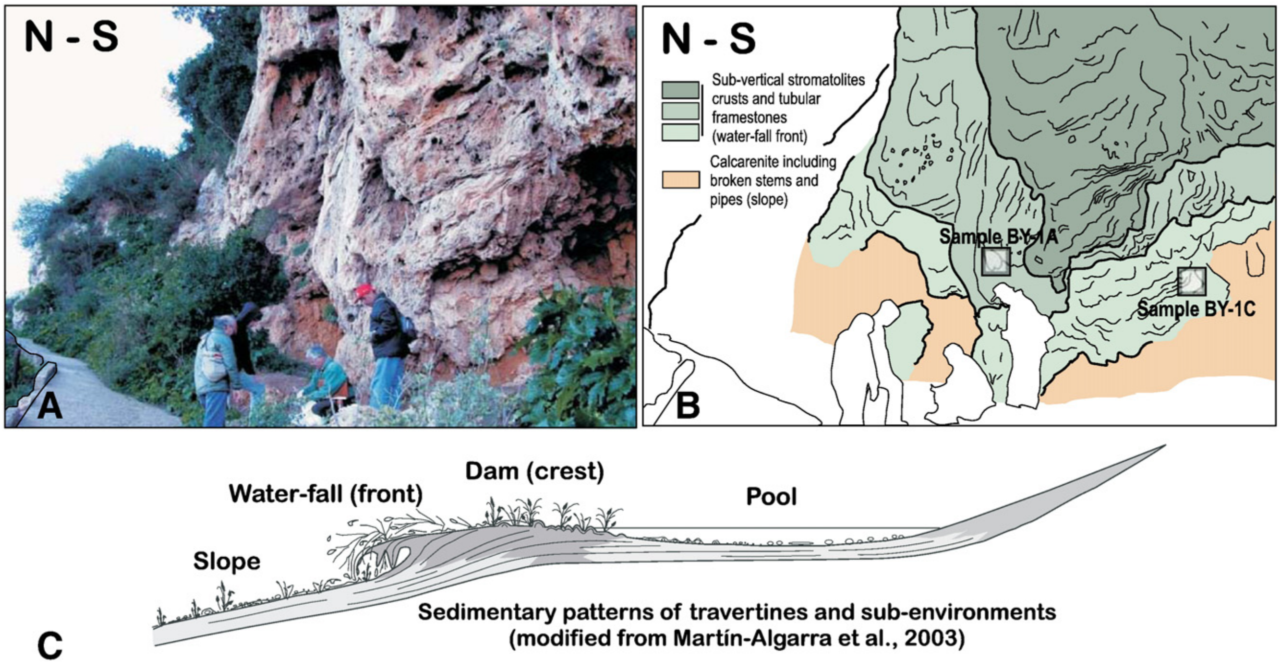

Figure 4. Field view of the travertine front of the intermediate level (A) and facies architecture interpretation with the location of the samples (B). Interpretation of the Beni Younech travertines sedimentary patterns and subenvironments (modified from Martín-Algarra et al., 2003).

pools, dams, and waterfalls (Martín–Algarra et al., 2003). Facies indicative of a pool environment are characterized by subhorizontal beds formed by fine-grained carbonates, oncolites, and stromatolites. The second facies association is linked to the dam (crest) and the waterfall (front) environment and is characterized by subvertical stromatolite crusts and tubular framestones allowing for the development of the pool. Downstream of the waterfall, the third facies association (slope) is characterized by calcarenites including broken stems and pipes.

After establishing the architecture of the travertine, seven samples were collected, mainly from layers where laminar growth bands are dominant. These samples were analysed at the University of Barcelona (Spain) to determine quantities of the radioisotopes in the disintegration series of U-238 and Th-232 by alpha spectrometry. The samples were taken at depth, up to 3 m from the front of each level. The deepest travertine levels were not accessible, and their age remains invariably younger than the hosting terraces. The cross section of Figure 3B shows sample distribution and the obtained results.

The upper travertine level is developed over an erosive surface interpreted as Maarifian. After sampling the front of the upper travertines, samples BY-2 A, B, and C (Fig. 3 and Table 2) gave ages of

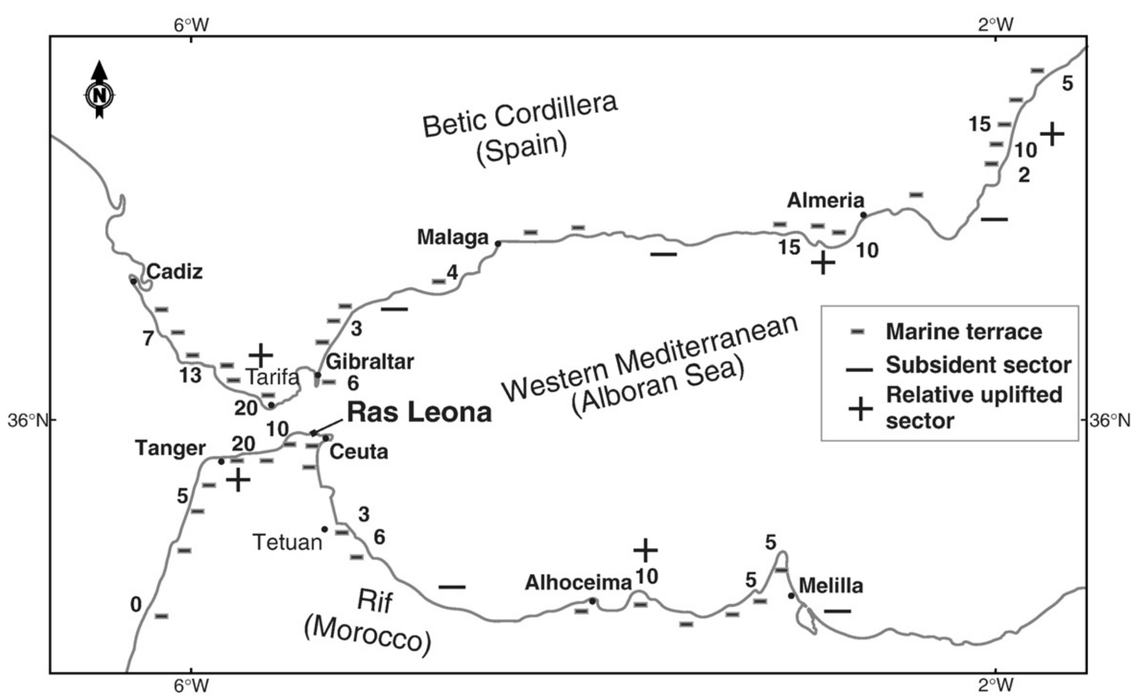

Figure 5. Sketch showing the approximate position of the marine terraces in southern Spain and northern Morocco. The data, not always consistent, were taken from Groupe de Recherche Néotectonique (1977), Lario et al. (1993), and Zazo et al. (1999). The numbers correspond to the altitude in meters of the terraces formed during MIS 5.

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119.48 ± 4.4 ka, 98.43 ± 3.9 ka, and 97.3 ± 3 ka, respectively, the first one being closer to the interior of the front. The middle travertines, developed over the assigned Anfatian terrace, correspond to samples BY-1 A, B, and C taken at three different points along the front, and gave ages of 118.54 ± 4.6 ka, 144.2 ± 6.2 ka, and 225.2 ± 13.8 ka, respectively (Fig. 4). Sample BY-B was taken towards the interior of the front and BY-C more to the east, in the middle part of the scarp. In the lower travertines, near the beach and approximately 10 m in altitude above the Ouljian terrace, sample BY-0 yielded an age of 114 ± 4.1 ka. All these results are indicated in Table 2.

The intermediate level gave the oldest age (225.2 ± 13.8 ka), even greater than that of the higher level. Most likely, the travertines formed during this time, in both the intermediate and higher levels, from a spring situated in the boundary zone between the marbles and the sandstone/lutite alternation (the formation of the upper travertines would have begun previously, immediately after the formation of the Anfatian terrace, 303 ± 0.3 to 376 ± 0.34 ka).

This spring continued to hold flowing water over time, and during 120–110 ka, a triple waterfall existed, passing the water of the spring progressively from the higher level to the intermediate and finally to the lower one (Chalouan et al., 2008). In the lower level, where the travertines are directly upon the beach, they probably formed in the glacial stage after the Ouljian. The spring may have disappeared around 97–98 ka ago, when erosion laterally opened a new via of water flow.

Comparison of travertine ages with those attributed to the marine terraces of Ras Leona shows that each travertine platform is younger than the age attributed to the hosting marine terrace. The younger age of the travertines is to be expected as they grew successively over previously created marine terraces, equivalent in height to those of Ras Leona. Therefore, as occurs with the development of marine terraces, travertine deposition usually coincides with warm and wet interglacial periods when limestone dissolution prevails, in conjunction with great outflow from springs and the precipitation of calcium

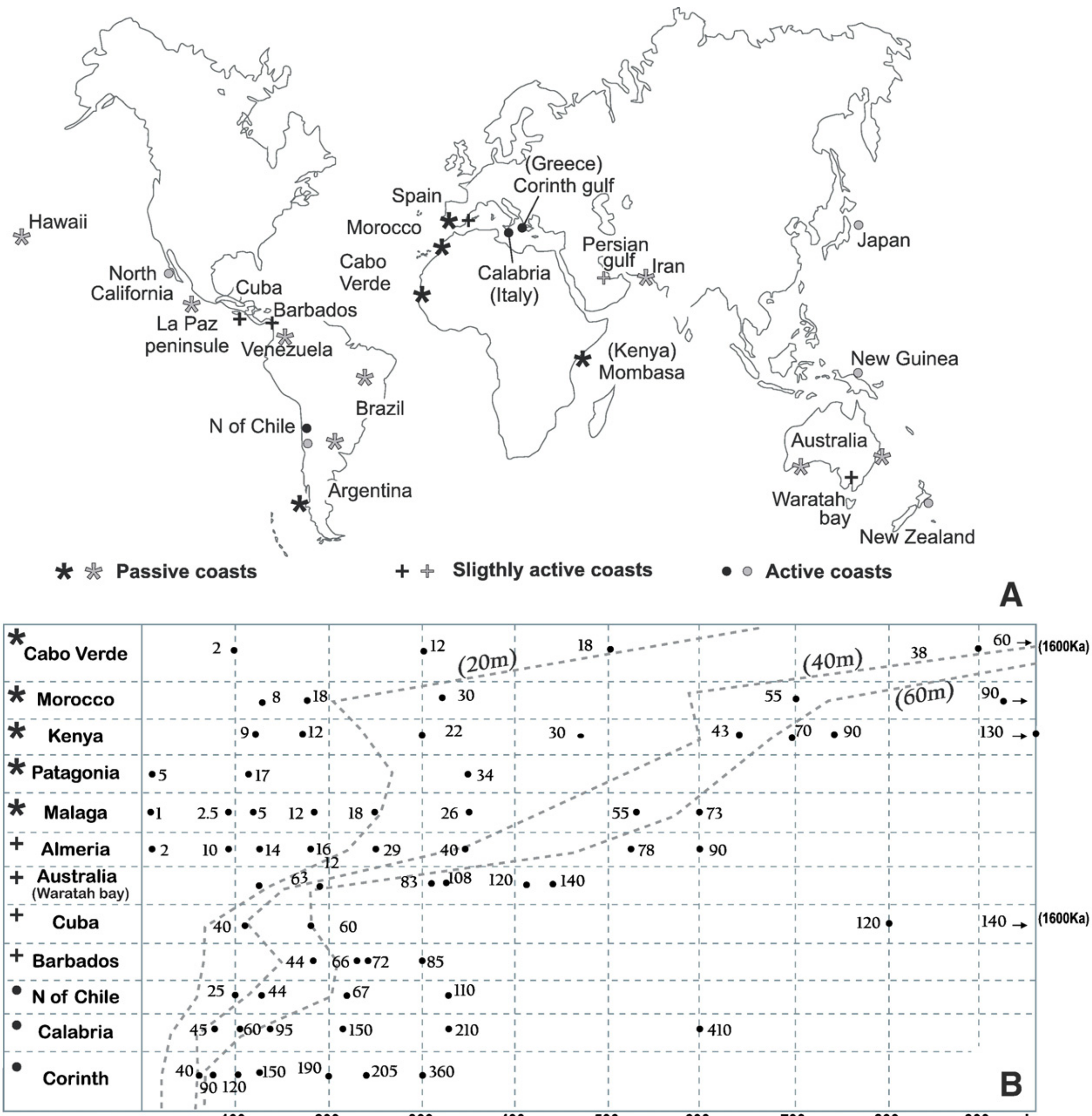

Figure 6. (A) Approximate position of the marine terraces indicated in the text and in Figures 6B and 7 around the world. (B) Black dots indicate the altitude of passive and active marine terraces developed worldwide (above the present sea level), broken lines correspond to heights of 20, 40, and 60 m above MSL and permit comparisons of the different times needed on each coast to reach its height.

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carbonate. There is a clearly positive correlation between the terrace intercalated between the Ouljian and the Anfatian at approximately 18 m above MSL, probably developed 303 ± 0.3 ka, and the middle level of travertines (after 225.2 ± 13.8 ka) situated at an equivalent height. In addition, the lower level at 114 ± 4.1 ka practically coincides in age with the Ouljian terrace assigned to MIS 5.

Correlation with the marine terraces in the Mediterranean Moroccan and southern Spanish coasts

After correlating the marine terraces of Ras Leona with their equivalents in the Atlantic Moroccan coast, it is interesting to further examine the main features of the terraces of northern Morocco and southern Spain and compare them (Fig. 5). These terraces were described by Cadet et al. (1977) and by Gigout et al. (1977), both members of the Groupe de Recherche Néotectonique (1977). The paleo-shore line associated with the last interglacial period (MIS 5) is well defined in the western Mediterranean (e.g., Zazo et al., 2003; Bardají et al., 2009). We should underline the following features of northern Morocco and southern Spain: (a) most of the present-day altitudes of the Ouljian marine terraces in this region, with development assigned during MIS 5, are moderate, ranging from 2 to 10 m above MSL; (b) in the central part of the Strait of Gibraltar uplift is more pronounced, the Ouljian marine terraces rising up to 20 m above MSL in altitude on both sides, yet decreasing progressively to the east and west (Ras Leona occupies an eastern position in the Strait of Gibraltar like some of the marine terraces shown in Fig. 2C, situated immediately to west of Ras Leona); and (c) the juxtaposition of subsiding areas and relatively uplifted ones, both in the Moroccan and Spanish coasts, are distributed along NNE–SSW-oriented bands (Fig. 5).

On the southern coast of Spain, between Cadiz and Malaga—i.e., to the west and the east of Gibraltar—Zazo et al. (1999) showed that the marine terraces of 128 ka lie at an altitude of 20 m in Tarifa (southern tip of the Iberian Peninsula), as previously indicated by Cadet et al. (1977). This value decreases to the east and west, down to just 6 m in Gibraltar.

In Gibraltar, Rodríguez-Vidal and Cáceres Puro (2005) describe terraces situated higher than 160 m, although only the age of the lower ones has been determined. They indicate a middle–late Pleistocene age for a terrace situated at approximately 60 m above MSL. The terrace that would have formed during MIS 5c occurs at 5.25 m, and another corresponding to MIS 5a is at 1 m above MSL. They indicate uplift rates of 0.33 ± 0.05 mm/yr between 200 and 250 ka; and lower values, 0.05 ± 0.01 mm/yr, from 200 ka to the present.

In the Betic Mediterranean coasts, Lario et al. (1998) described the marine terraces of the Malaga coasts and also alluded to the Almerian coasts, situated more to the east. Data from both sectors are included in Figures 5, 6, and 7. Despite the imprecision of some ages, age/height graphic relationships indicate that (a) the graph of the Malaga coasts is nearly identical to those of the passive ones (see Discussion section below) although with more pronounced uplift and (b) the Almeria coasts present moderately high elevations, indicating greater tectonic activity.

Discussion

Quaternary marine terraces and travertine deposition usually correspond to moments of interglacial periods linked to warm, wet climatic conditions, and maximal marine encroachment (Keller and Pinter, 1996). Travertine formation in the Ras Leona–Beni Younech sector was pulsating throughout the Quaternary, and during MIS 7 and 5e, just after the development of marine terraces, providing the first absolute ages for marine terraces of the northern Morocco.

Marine terrace correlation along the Gibraltar Strait

The marine terraces of the Gibraltar Strait are especially sensitive to sea-level fluctuations as a result of global climatic changes and tectonic processes. A positive correlation between the U–Th ages was obtained from the Beni Younech travertines and the Ras Leona terraces. According to their altitudes and the altitude/age data of the Moroccan Atlantic terraces, the travertines of Beni Younech are younger than the equivalent marine terraces of Ras Leona. Moreover, the travertine cover is not much younger than the terraces, probably because travertine formation began with the onset of marine regression, just after the formation of each marine terrace, during a

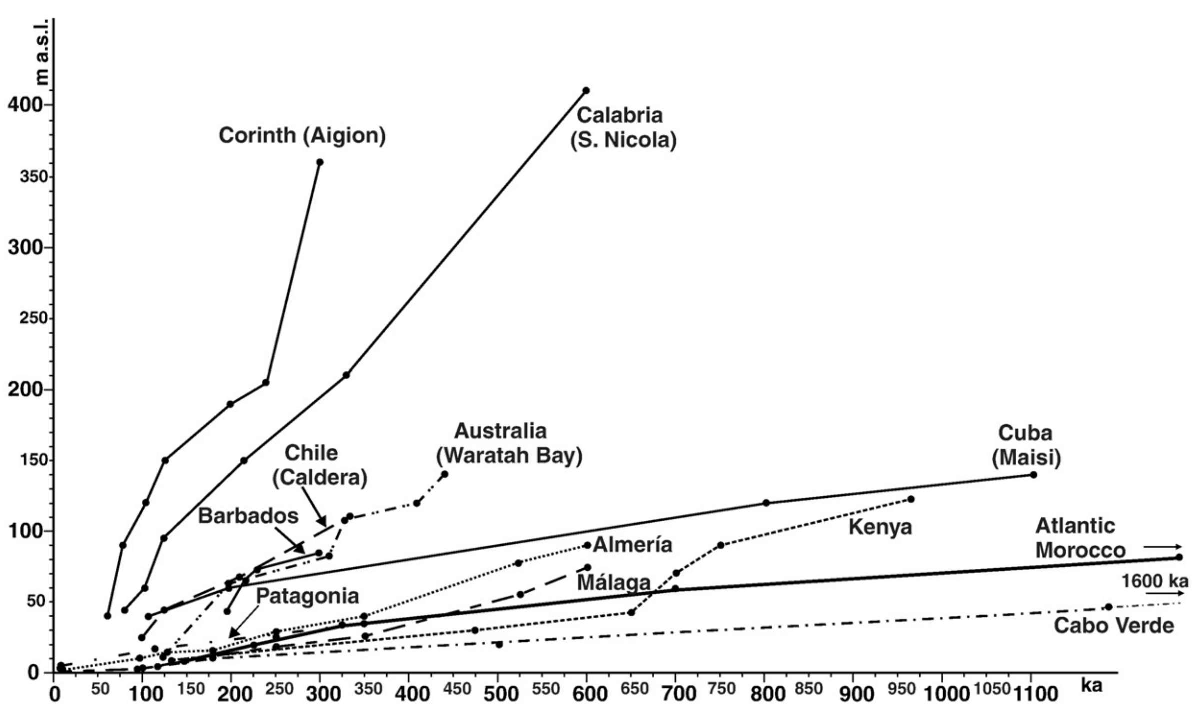

Figure 7. Altitude/age graphs of the marine terraces on selected coasts of the world as mentioned in the text.

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transgressive pulse that coincided with warm and wet interglacial periods MIS 7 and 5e. This correlation between ages and heights provides evidence that the ages and altitudes of the Ras Leona marine terraces are consistent with those of the Moroccan Atlantic coasts firstly estimated by El Fahssi (1999).

The existence of some 114 ka-dated travertines over the Ouljian terrace, close to the present-day sea level, further indicates that the tectonic uplift ceased to have a significant effect after MIS 5 in Beni Younech. This conclusion is supported by the height of the neighbouring Ras Leona-associated terrace (2–5 m above MSL). Indeed, Bardají et al. (2009) indicate that in the Western Mediterranean (for instance, on the island of Mallorca), the eustatic uplift deduced from MIS 5e reaches roughly 2–3 m above MSL, practically of the same order as in Beni Younech and Ras Leona.

The Ouljian marine terraces of northern Morocco assigned to MIS 5 (Texier et al., 2002) and those of southern Spain show some differences from place to place. On certain coasts of Almeria (southern Spain) and in Ras Tarf, to the East of Alhoceima (Morocco; Fig. 5), the Ouljian terraces occur at 10 m above MSL (Gigout et al., 1977; Zazo et al., 2003), an altitude interval that slightly exceeds the long-term eustatic fall. This indicates a moderate tectonic uplift since the late Ouljian (0 to 4 m in most places, although there are some exceptions; see Fig. 5), a result that may be extended to the Mediterranean terraces of the Malaga coast and to the Spanish Atlantic coast between Cadiz and Gibraltar overall, as well as to the Moroccan Mediterranean counterpart coasts in the Tetouan area. Contrariwise, some areas underwent subsidence. The exception is found in the central part of the Gibraltar Strait, where both margins (east of Tangier and in Tarifa) underwent significant uplift (20–22 m). Except for certain points, data reveal low Quaternary tectonic uplift (2–5 m) on the southern Spanish coasts.

Estimating the role of eustasy and tectonics from global correlation

Correlation of worldwide marine terraces as an indicator of paleo-sea levels produces valuable information related to global climatic changes and to regional active tectonic processes. Altitude/age data from the coasts of diverse continents are presented (as done by Bull, 1985) for marine terraces, linked to tectonically active and passive margin coasts, in Figures 6 and 7. These data are compared with those pertaining to the Moroccan Atlantic coasts to assess the respective role of eustasy and tectonics. Figures 6B and 7 present altitude/age diagrams of terraces from several parts of the world, including those of the Moroccan Atlantic coastline and southern Spain. Many of these coasts correspond to areas *a priori* considered to be tectonically passive, as most Argentine coasts or those of Kenya, while others correspond to areas clearly affected by active subduction and tectonic uplift, as is the case of some Chilean, Calabrian, and Corinthian gulf coasts.

The shoreline limit of the marine terraces is often difficult to identify. Indeed, the altitude and dating of many marine terraces worldwide suffer from inaccuracies. Yet most values for altitude and age are correct, or at least lie within a margin of acceptable error. These values are given in Figures 6B and 7, some corresponding to average values (when there is a significant variation in the age and/or altitude).

Data presented in Figures 6B and 7 show the coastal Quaternary marine terraces to be staircased downwards, from older to younger ones. Samples of passive coasts are the following: (a) Kenya (Mombassa coasts), where Oosterom (1988) described many marine terraces with moderate altitudes, similar to their lateral equivalent known along the Kenyan coasts; (b) Argentinean coasts (from the Bahia Blanca to Rio Grande, in the Tierra de Fuego), where Rostami et al. (2000) described terraces of the Camarones area, situated in the central part of the Patagonian coasts; and (c) Sal Island, in the Cabo Verde archipelago, where Zazo et al. (2007) depict many marine terraces with moderate altitudes. Many other data could be added as in the Baja California Peninsula (Sirkin et al., 1990) or in the Persian Gulf isles (Pirazzoli et al., 2004). Some of these points are indicated in Figure 6.

The examples selected above (including those of the Moroccan Atlantic coasts and, by analogy, those of Ras Leona) correspond to old passive margins where the isostasic readjustment was damped or occurs at a very low rate. This explains why their coasts have similar altitude/age curves (Figs. 6 and 7). These values clearly differ from those of tectonically active coasts, experiencing variable uplift rates.

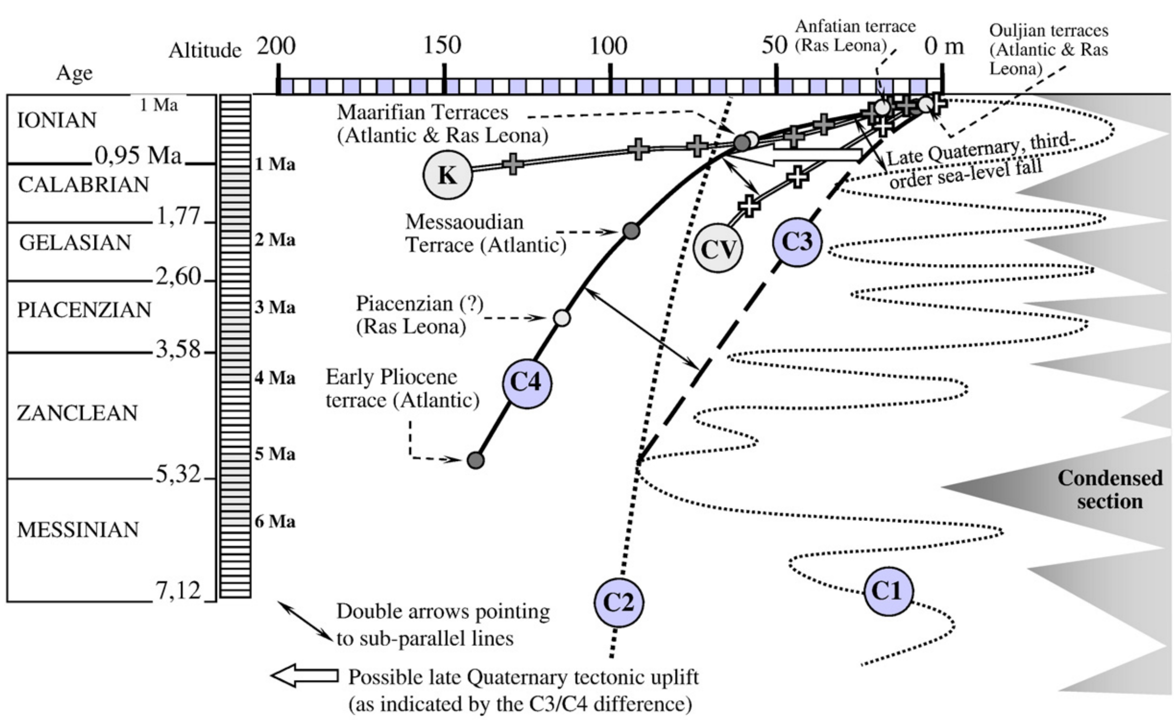

Figure 8. Third- (C1) and second- (C2) order eustatic curves (after Haq et al., 1987) for the Plio-Quaternary showing a long-term sea-level fall (90 m) that occurred during the last 5 Ma. Curve C3 is added and corresponds to a more precise adaptation of the second-order sea-level curve joining the Plio-Quaternary interglacial-related transgressive peaks of the C1 curve (third-order Exxon curve). Curve C4 corresponds to the projection of the Moroccan Atlantic and Ras Leona terraces, curve CV to those of Cabo Verde, and curve K is for Kenya.

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Well-documented examples occur in Cuba (in the Maisi area, on the eastern edge of the island) and Barbados (Peñalver Hernández et al., 2003), (Figs. 6 and 7), and in the Waratah Bay–Liptrap Cape, in the SE of Australia (Amborn, 2003).

Instances of much stronger uplift are cited on the northern coasts of Chile (Ortlieb et al., 1996; Marquardt et al., 2004; Quezada et al., 2007), indicating major coastal uplifting (Figs. 6 and 7). In Calabria, southern Italy, there are very high Quaternary marine terraces, as indicated by Cucci and Cinti (1998). Still higher altitudes are described in the Gulf of Corinth (De Martini et al., 2004). Their extreme altitude/age values range between 30 m/60 ka and 360 m/300 ka.

Interestingly, Figures 6 and 7 show that all the Atlantic Moroccan terraces (except for some subsident areas, such as the coast of the Gharb basin, north of Rabat) and the terraces of Ras Leona have an altitude/age behaviour that can be positively correlated with that of the passive-margin coasts, with eustasy being the main factor of their formation. This general concordance with the passive coast confirms at the same time that the age attributions for the Atlantic Moroccan terraces are correct, consistently within a narrow margin of error in each case. This concordance refers to the general values because we cannot discard the possibility that some sectors experienced the effect of active faults (e.g., the area where Atlas faults reach the Moroccan coast in Agadir; Fig. 1) which could have caused significant deviations. This is also the case of the central part of the Strait of Gibraltar, where tectonics most likely compounded the effects of eustasy.

Although eustasy is the main factor explaining the staircased architecture of the Moroccan Atlantic and Ras Leona marine terraces (Haq et al., 1988 indicated a global sea-level fall of 90 m from the early Pliocene, approximately at 5 Ma), tectonics are another important factor, given that one terrace, the Piacenzian(?) Terrace (attributed age 3 Ma), is situated 115 m above MSL. To evidence the tectonic effect, we reconstructed (Fig. 8) the position of the Moroccan Atlantic terraces, Cabo Verde and Kenya terraces, together with the second-order (C2) eustatic curve by Haq et al. (1988). None of the curves derived from the cited regions coincides with the C2 curve because of their high altitude values. The Cabo Verde curve presents more moderate values and fits better with line C3, a curve intended to adapt line C2 to the present sea level. Cabo Verde is probably an area where tectonic uplift had minor repercussions, at least after the beginning of the Pleistocene.

On the contrary, the curve of the Moroccan Atlantic terraces presents higher altitudes, particularly during the period between the Ouljian and the Maarifian, a time interval when tectonic uplift appears to have been more accelerated. The Messaoudian terrace illustrates the problem of age duration. The position of the Piacenzian(?) terrace (3 Ma) seems to indicate a short period of tectonic uplift, but one must bear in mind that there may be considerable error in age attributions and, consequently, the conclusions drawn.

The curve of the marine terraces of the Mombassa region of Kenya indicates tectonic uplift, particularly before 500 ka, if the age attribution is correct. The curve of Patagonia more or less coincides with

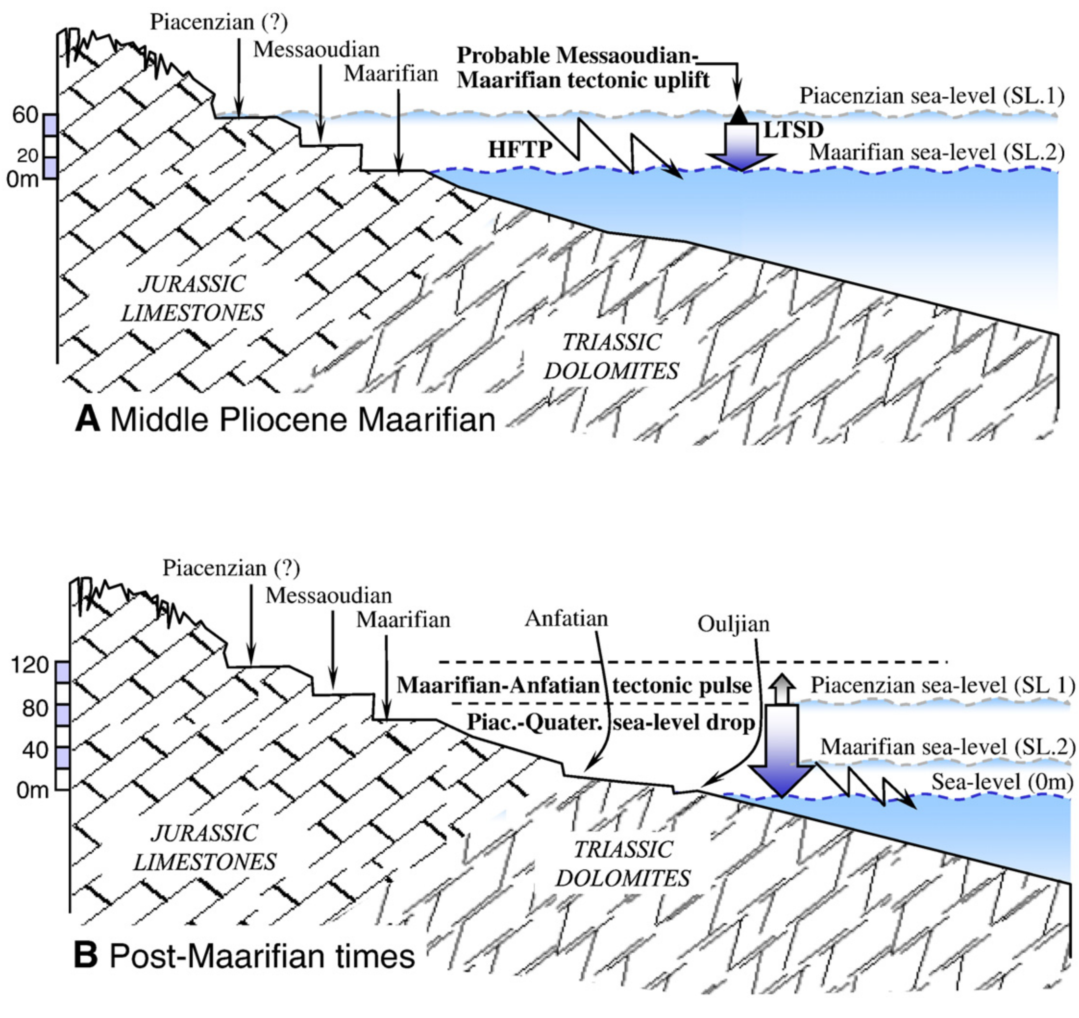

Figure 9. Proposed tectono-eustatic formation scenario of the Ras Leona terraces. (A) Middle Pliocene–Maarifian: The marine terraces are fashioned by transgressive pulses induced by high-frequency glacio-eustatic sea-level changes (HFTP), while the cumulative effect of long-term sea-level drop (LTSD) and the tectonic uplift caused the older terraces to emerge irreversibly. (B) Post-Maarifian times: tectonic pulse and fashioning of the Anfatian and Ouljian terraces during the late Quaternary sea-level drop. Total Piacenzian–Quaternary relative sea-level drop: ca. 115 m (eustatic effect = 75 m, plus tectonic effect = 40 m).

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those of the Morocco and Kenya; however, there are no data older than 350 ka.

In sum, tectonics in the Moroccan Atlantic and Ras Leona terraces prove to have caused global uplift of some 40–50 m—less significant than eustasy, considered to be of the order of 90 m, according to Haq et al. (1988). Granted, the time distribution of this tectonic uplift during the Pliocene and Quaternary should be studied in more detail; but according to our data from the southern Gibraltar Strait, the main tectonically active period occurred between the formation of the Maarifian and the Ouljian terraces, i.e., between 370 and 150 ka, situated at an equivalent height. This result leads to the synthetic scenario presented in Fig. 9.

Conclusions

The role of eustasy and tectonics on the southern side of the Gibraltar Strait has been tackled from study of the well-preserved marine terraces on the Ras Leona–Beni Younech sector, partially covered by travertines. The travertine cover proved to be just slightly younger than the marine terraces, probably because travertine formation started at the beginning of the marine regression, just after the formation of each marine terrace during a transgressive pulse, coinciding with warm and wet interglacial periods MIS 7 and 5e.

The 114 ka U–Th ages obtained from the Beni Younech travertines confirm the classic Ouljian chronostratigraphic attribution to the marine terrace developed between 4 and 8 m above sea level, assigned to MIS 5. Comparisons of the Ras Leona marine terraces with those developed in the Alboran Sea during MIS 5 (on the southern coast of Spain and the northern coast of Morocco) suggest that eustasy is a main controlling factor in the eastern part of the Gibraltar Strait. Tectonic uplift in this region is only locally important, as in the central part of the Strait of Gibraltar (on both the Moroccan and Spanish shores).

Moreover, a positive altitude/age correlation exists between the Moroccan Atlantic marine terraces and those of the tectonic passive margins known throughout the world. This confirms previous data from these Moroccan terraces signalling eustatic controls as a principal sculpting factor. The comparison of age/altitude curves for the Moroccan (eastern Atlantic), Cabo Verde (eastern central Atlantic), and Kenyan (Indian ocean) terraces with the second- and third-order of the sea-level curves (Haq et al., 1988), supports the preceding result, indicating that eustatic control is the main factor (Fig. 6). At the same time, however, for the Moroccan Atlantic and Ras Leona marine terraces, it indicates a superimposed tectonic uplift by the Calabrian/Ionian boundary, probably of the order of 40–50 m.

The moderate Quaternary tectonic uplift deduced from the marine terraces and their comparison with well-known actively subducted coasts disagrees with the model of active eastward subduction below the Gibraltar tectonic arc. Therefore, the juxtaposition of subsiding areas and moderately uplifted ones along NNE–SSW-oriented bands, on both the Moroccan and Spanish coasts, could be linked to the slow NW–SE active convergence between the European and African plates.

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