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Quaternary Science Reviews 23 (2004) 2017–2029

QSR

Neotectonics and shoreline history of the Rock of Gibraltar, southern Iberia

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Received 21 March 2002; accepted 14 February 2004

Abstract

Several sets of staircased Quaternary marine deposits can be observed along the Gibraltar coast ranging from 1 to 210 m above the present mean sea level. Geomorphological mapping establishes, from the relationship between shore, scree and dune sedimentary formations, five main morphotectonic steps on the Rock: marine terraces between 1 and 25 m, 30–60 m, 80–130 m, 180–210 m, and above. Each terrace level and its slope-aeolian linked sediments is backed by a steep relict sea cliff margin, so forming a composite cliff. The most recent coastal landforms and sediments are associated with the last 250 ka linked to Oxygen Isotope Stages (OIS) 1, 3, 5 and 7. These landforms determine a morphosedimentary highstand-lowstand sequence, with several staircased and offlapped episodes, comprising a major morphotectonic step. A well-developed palaeocliff usually separates the highstand marine terraces of OIS 9 from those of OIS 7. The Gibraltar mean tectonic uplift value of 0.05 ± 0.01 mm/yr is maintained from 200 ka to the present. Before this, at least to 250 ka, the mean uplift rate was higher (0.33 ± 0.05 mm/yr), possibly compatible with major tectonic events in response to a NNW–SSE compressive stress field between Africa and Iberia.

1. Introduction

The Rock of Gibraltar is a north–south peninsula with the eastern side being very steep and a gentler western slope (Figs. 1 and 2). It has a small area being 5.2 km in length, 1.6 km in maximum natural width and about 6 km^2 in total land area.

Topographically and geologically it is divisible into three main regions (Rose and Rosenbaum, 1990): (a) the Isthmus, a low-lying sandy plain less than 3 m above sea level, which represents Holocene sediments that join northern Gibraltar to the mainland, (b) the Main Ridge, which forms a sharp crest with peaks over 400 m above sea level, and it is formed by Early Jurassic limestones and dolomites, (c) the Southern Plateau, which is a staircased slope between 130 m and present sea level. Steep cliffs fringe this plateau at its margin with the Mediterranean Sea. Surface topography is primarily the result of Quaternary wave-cut erosion and the fringing cliffs are the product of shoreline processes.

Overall the Rock is a klippe: the remnant of a nappe now isolated by erosion. It was thrust into place as a consequence of the African–European collision that promoted a westwards displacement of the internal zones of the Betic Range, mainly during the Early Miocene, with the generation of the so called Gibraltar Arc (Sanz de Galdeano, 1990; Rose and Rosenbaum, 1994).

The Gibraltar landforms are formed by two main groups of processes (Rodríguez-Vidal and Gracia, 1994, 2000): (i) the tectonic structural movements that determine the general shape and (ii) surface erosional and depositional processes that have acted on the uplifted rocks. Coastal processes are important and these have been especially active in the eastern face of the Rock, where there is greater fetch. The combination of tectonic and eustatic fluctuations have caused change in the location of the coastal landforms, which has

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0277-3791/$ - see front matter © 2004 Elsevier Ltd. All rights reserved.
doi:10.1016/j.quascirev.2004.02.008

Fig. 1. The present-day Rock of Gibraltar with its eastern face (left) sheer and morphodynamically very active, and the western face (right) structurally controlled and of lesser relief and activity.

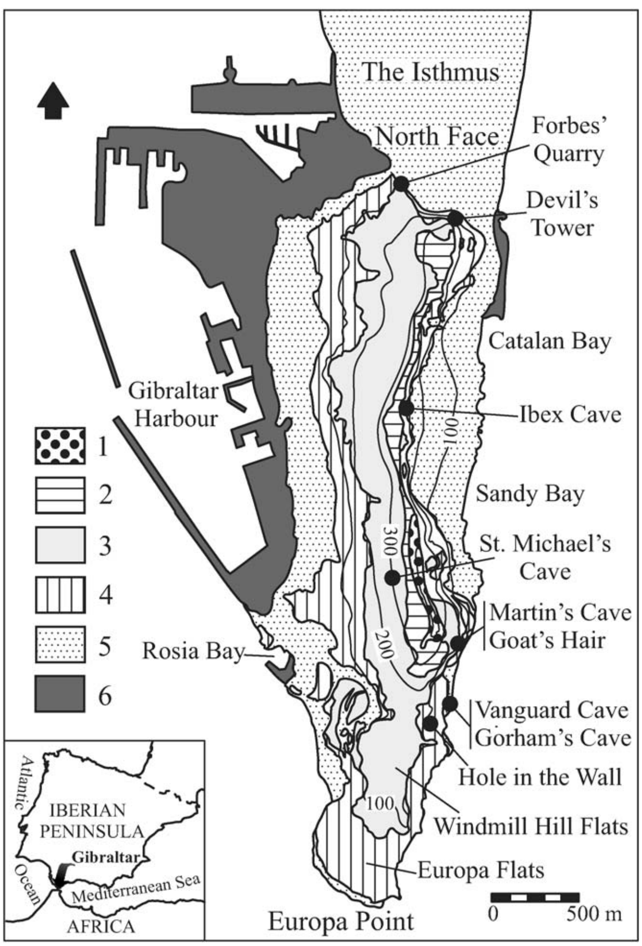

Fig. 2. Simplified morphotectonic map of the Gibraltar Peninsula. Contours at 100 m intervals. Legend: 1–5, staircased morphotectonic units ($MTU_{1–5}$), older to recent, separated by an escarpment or palaeocliff and 6, reclaimed land.

controlled the evolution of slopes. The lithification of the Quaternary deposits has led to the preservation of a varied group of sediments which represent processes that indicate a rapid and complex geomorphological development and neotectonic uplift history.

In general, the relationship between sea-level fluctuations and the uplift or subsidence of the coastline and the resulting landforms is very close (Keller and Pinter, 1996; Trenhaile, 2001). When tectonic uplift exceeds the rate of eustatic sea level rise, or when the sea level falls, then the coastal cliffs can be isolated from wave attack and preserved as relict features. At this stage subaerial processes may act, degrading the slope. Conversely, when the relative sea-level rise is positive, the cliffs can be reached more frequently by waves and therefore subject to greater erosion rates.

Along the coast of Gibraltar the relative land has been missing at rates of 0.04 to 0.06 mm/yr in the last 100 ka (Goy et al., 1995). Coastal cliffs and shore sediments are thus being uplifted and preserved.

This paper constitutes a review and updating of work on the Middle and Late Pleistocene marine and continental landforms of the Rock of Gibraltar, including the results of former and new age determinations. The aim of this study focuses on the evaluation of vertical movement rates in the last 250 ka and proposes a recent evolutionary morphotectonic model (Rodríguez-Vidal and Gracia, 2000).

2. Sedimentary record

Features of Quaternary geology of Gibraltar have excited interest since the mid-18th century. Vertebrate faunas from bone breccias in caves and fissures were prolific and stimulated early work. The finds included the discovery of a Neanderthal cranium in Forbes' Quarry in 1848 (Busk, 1865) and the fragmented cranium of Neanderthal child in Devil's Tower Rock Shelter in 1926 (Garrod et al., 1928). Cave deposits have been the subject of a series of excavations during the past 130 years (Stringer et al., 1999). Recent work commenced in 1991 and focused on Gorham's, Vanguard and Ibex Caves (Barton et al., 1999) at the east side of the Rock. The results of these investigations so far have been recently reported in the monograph, "Neanderthals on the Edge" (Stringer et al., 2000). The sequences at Gorham's and Vanguard have been intensively studied and extensively dated by ESR, AMS, OSL and U/Th. They confirm that the sediments cover a timescale commencing in the Last Interglacial and concluding with the presence of a Phoenician/Carthaginian shrine that ceased functioning in the third century BC (Gutiérrez López et al., 2001). Within the sequences at Gorham's and Vanguard Caves there is a detailed record of vegetation and fauna that has provided evidence for the quantitative reconstruction of environments that were exploited by Neanderthals (Finlayson and Giles, 2000), the abrupt environmental changes at the end of OIS 3, that can be correlated with the last presence of Neanderthals on the site at 31 ka, and the subsequent occupation of the site by Modern Human after 29 ka. Thus, these sites provide a unique record of human occupation and environmental change in the south of the Iberian Peninsula.

Smith (1846) and Ramsay and Geikie (1878) initiated the documentation of the Quaternary deposits on the flanks of the Rock. Rose and Rosenbaum (1990, 1991) redefined and mapped (Rosenbaum and Rose, 1991) Quaternary sedimentary units and later studies were made by Rose and Hardman (1994, 2000).

Quaternary sediments on Gibraltar flanks have a widespread distribution and are both marine and continental deposits (Fig. 3). They include sand and cobble shore sediments, aeolian sands, scree breccias, and karstic products, like clays, fallen rocks and speleothems. Tectonic uplift of marine highstand landforms shows raised shorelines staircased across the Gibraltar slopes. Geomorphological techniques are required to establish a suitable chronological situation given the different location and height of these sediments and their spatial interrelation.

Detailed geomorphological research indicates that the relationships between beach, scree and dune sedimentary formations form five main morphotectonic steps on the Rock (Figs. 2 and 9): marine terraces between 1 and 25 m (e.g. Gorham's Cave), 30–60 m (e.g. Europa Flats), 80–130 m (e.g. Windmill Hill Flats), 180–210 m (e.g. Martin's Cave), and features above this level. Each terrace succession and associated slope-aeolian sediments is backed by a steep relict sea cliff along its landward margin, so forming a composite cliff (Rodríguez-Vidal and Gracia, 2000). The cliffs appear much better developed on the eastern side of the Rock, since the littoral erosive processes here are much greater. The higher morphotectonic steps are older than lower ones, and probably formed in the Early Pleistocene.

2.1. Uplifted marine terraces

The reconstruction of global sea-level changes during the Quaternary involves great difficulty. The position of the sea level at a particular moment is influenced not only by global factors, but by regional factors which operate on different time, space and amplitude scales.

Elevated marine terraces are common along tectonic collision coasts where uplift is taking place (Griggs and Trenhaile, 1994). Each terrace consists of a nearly horizontal or gently seaward dipping erosional or depositional platform backed by a steep or degraded relict sea cliff along its landward margin (Fig. 4).

Raised shorelines in Gibraltar are represented by marine sediments and landforms and are best developed to the south and east of the Rock. Current evidence suggests that there are traces of at least 12 former levels that are now raised above present mean sea level (MSL) at heights of 1–3, 7–9, 15–17, 20–25, 30–40, 50–60, 80–86, 90–130, 180–190, about 210, and possibly 240–250 m or even 300 m (Rose and Rosenbaum, 1990, 1991). The

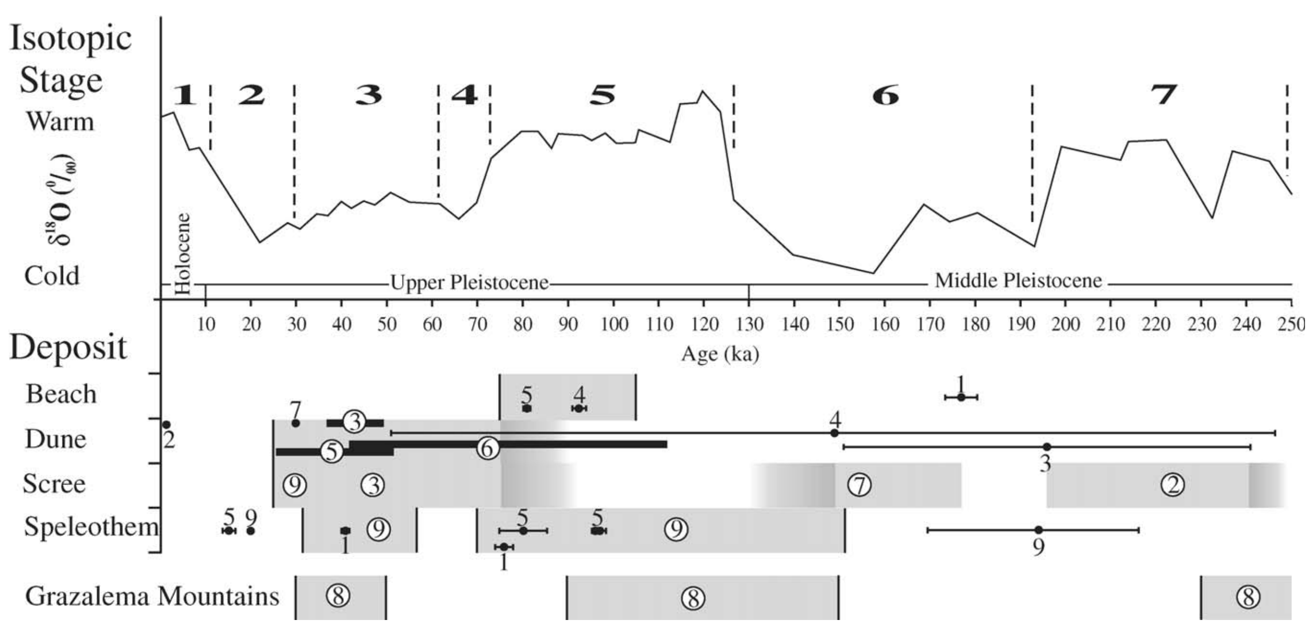

Fig. 3. Dates of the sedimentary units displayed in Tables 1 and 2, with individual dates (black point), sets of dates at a single site (thick black bar with number in white circle), and sequence of dates (number in white circle on grey shadowed band). Comparison with the Oxygen Isotope sequence (after Shackleton and Opdyke, 1973 and Williams et al., 1988). References: (1) Lario (1996) and Zazo et al. (1999), (2) Rhodes, in Rose and Hardman (2000), (3) Rhodes et al. (2000), (4) Pettitt and Bailey (2000), (5) Díaz del Olmo (1994), (6) Rink et al. (2000) (7) Hoyos et al. (1994) (8) Rodríguez-Vidal et al. (1999) and (9) Present paper in Table 2.

Fig. 4. Fossilized marine beach of OIS 5 highstand at the foot of a cliff to the SE of Gibraltar. Gorham's Cave, Governor's Beach.

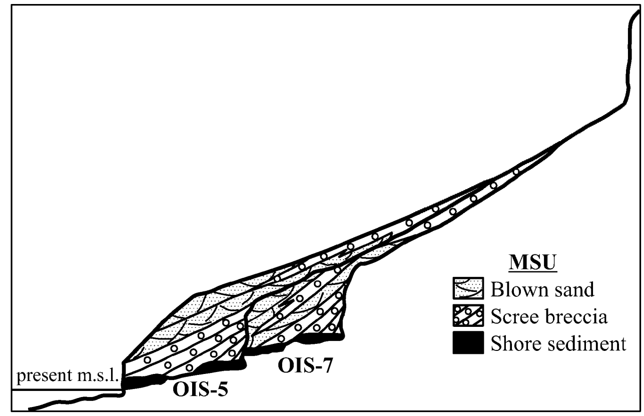

Fig. 5. Idealized model of staircased, offlap geometric sequence of the morphosedimentary units (MSU), with marine-aeolian-gravitational record, for the most recent morphotectonic unit (MTU-5) on the sides of the Rock of Gibraltar. This situation is produced with low rates of tectonic uplift.

cartographic and morphostratigraphic disposition of the terraces, their faunal content and their U-Th age (Lario, 1996; Zazo et al., 1999) provide tools for reasonable chronostratigraphic interpretation of the marine sequence, especially of the most recent terraces.

The last morphotectonic step in the Gibraltar emerged coast (Fig. 5) is related with Oxygen Isotope Stages 7, 5 and 1. Dated marine terraces linked with them (Table 1) are located at 25–20 m, 17–15 m and 10 m (OIS 7), 5 m (OIS 5c), 2–1.5 m (OIS 5a), and 1.5 m above present MSL (OIS 1). All represent emerged highstand positions of interglacial sea levels (Hoyos et al., 1994, Zazo et al., 1994a).

In general, the first two episodes (OIS 7 and 5) are characterized by warm faunas, typical of Equatorial Africa, that reached the Mediterranean Sea through the Strait of Gibraltar. This marine fauna is not found in OIS 1 level, suggesting that the other two Isotope Stages were warmer than the present one.

During OIS 7, the Penultimate Interglacial (250–195 ka), elevated marine terraces of selected areas around the world show two main highstands (Zazo, 1999). In stable areas the sea level during Substage 7a was higher than the present MSL. In the SE Iberian coast substage 7a (Tyrrhenian I), dated at around 180 ka, is very well represented with scarce specimens of *Strombus bubonius* (Goy et al., 1986). In Gibraltar, in spite of the absence of warm fauna, U-Th isotope measures confirm the presence of marine terraces corresponding to the Isotope Stage 7 (Zazo and Goy, 1989) and probably of the substage 7a (Zazo et al., 1999).

The 20–25 m and 15–17 m raised beach levels, recognised by Smith (1846) at Europa Point and other scattered locations, were attributed by Zazo and Goy (1989) to the Isotope Stage 7e, by regional stratigraphic correlation.

Evidence of a shoreline about 7–10 m above present MSL is best preserved at the North Face, in the cliffs below Europa Point, and to a lesser extent in Gorham's Cave. Garrod et al. (1928), in their description of excavations within Devil's Tower rock shelter, described cave deposits resting upon a marine beach. Hoyos et al. (1994) interpreted this deposit to be simultaneous with the Europa Point marine sediments aged at OIS 7a.

The Last Interglacial or OIS 5 (130–74 ka) is usually represented by several highstands along the southern Iberian littoral (Zazo, 1999). There is always evidence of lowstands between the different highstands, which are recorded by interbedded terrestrial deposits and erosive processes.

Within the area of the Strait of Gibraltar, between the Atlantic and Mediterranean seas, this episode is well represented (Goy et al., 1995; Lario, 1996) and there is abundant evidence that each substage has a complex history with several positive events. Associated with substage 5e are two episodes, at ca 132 ka and ca 117–125 ka. The first probably corresponds to the transition

Table 1
A synthesis of dating (AMS radiocarbon, U/Th, OSL and ESR) from the Rock of Gibraltar (based on data by authors cited in text)

Location Sample code (*reference)	Dating method (Laboratory)	Sample material	Height (m.a.s.l.)	Age (ka)	Error (ka)
Europa Point					
PG-25 (*1)	U/Th (1)	Shell	5.2	92.5	±1.3
PG-26a (*1)	U/Th (1)	Speleothem	5.7	76.4	±1.8
PG-26e (*1)	U/Th (1)	Speleothem	5.7	41.2	±0.6
PG-28 (*1)	U/Th (1)	Shell	8.5	176.5	±3.6
PG-29 (*1)	U/Th (1)	Marine crust	9.2	470.0	+166/−62
EP1 (*2)	OSL (2)	Sand		149.0	±98.0
Gorham's Cave					
PG-39 (*1)	U/Th (1)	Shell	1.5	81.0 ?	±0.9
PG-40 (*1)	U/Th (1)	Shell	1.5	53.8 ?	±0.5
GO-ST-2 (*5)	U/Th (4)	Speleothem	16.0	80.2	±5.4
GO-ST-3 (*5)	U/Th (4)	Speleothem	~18.0	15.3	±1.4
17 samples (*4)	AMS (5)	Charcoal	>9.0	25.7 to 51.7	±2.8/±3.3
2 samples (*6)	U/Th (6)	Speleothem	8.4	96.1/97.1	±0.9/±1.3
Vanguard Cave					
7 samples (*4)	AMS (5)	Charcoal		41.8 to 54.0	±1.4/±3.3
VAN-1 (*4)	OSL (5)	Sand		46.3	±3.3
VAN-7 (*4)	OSL (5)	Sand		93.4	±7.0
VAN-2 (*4)	OSL (5)	Sand		111.8	±10.0
Ibex Cave					
IB11 (*2)	OSL (2)	Sand	~260	196.0	±45.0
554/555 (*3)	ESR (2)	Teeth mammals	260	49.4	±3.2
Sandy Bay					
AL1 (*2)	OSL (2)	Sand		1.34	±0.15
Devil's Tower Shelter					
1 sample (*7)	14C	Charcoal	~12	30.0	

References: (*1), Lario (1996), Zazo et al. (1999); (*2), E.J. Rhodes, in Rose and Hardman (2000); (*3), Rhodes et al. (2000); (*4), Pettitt and Bailey (2000); (*5), Díaz del Olmo (1994); (*6), Rink et al. (2000); (*7), Hoyos et al. (1994); ?, Open geochemical system. Laboratories: (1), GEOTOP, Université du Québèc, Montreal, Canada; (2), Department of Geography, Royal Holloway, University of London, Surrey, UK.; (3), Research Laboratory for Archeology, Oxford University, UK.; (4) CERAK, Université du Montpellier, France; (5), Radiocarbon Accelerator Unit, Oxford University, UK.; (6), McMaster University, Ontario, Canada.

between OIS 6 and 5. In substage 5c, which is represented by the most continuous unit observed throughout the peninsular coast, three events are recorded, centred at 107, 100 and 90 ka, respectively. The episode associated with substage 5a corresponds to the Tyrrhenian-IV Mediterranean episode. It appears discontinuously throughout the coast and has been dated in this area at 80 ka.

At Europa Point, Hoyos et al. (1994) recorded a marine conglomerate at 5.25 m above present MSL, dated at 92.5 ka. These authors also recognized three marine levels on the exterior of Gorham's Cave, one at 1.0 m (dated at 81 ka, substage 5a) covered with an aeolian sand, another one at 2.5 m containing marine conglomerates preserved in hollows, and a third one at 5 m (substage 5c), only represented by an erosion level. Most of these examples are related with karstic depressions, protected against later erosion.

OIS 3, between 59 and 24 ka, is not recorded by emerged marine terraces along the Iberian coastline. On Gibraltar scree breccias and aeolian sands formed, as shown by the dated sediments in Gorham's, Vanguard and Ibex Caves, Devil's Tower rock shelter (Fig. 3), and the speleothems from Gorham's Cave and Deadman's Beach (Europa Point).

Along the Spanish coasts, the postglacial sea level reached the current position, or slightly higher, at about 6450 yr BP (Zazo et al, 1994b), and this is the case on Gibraltar. The stabilization or slight eustatic fall of the last few thousand years has caused a modest coastal progradation in some places, with the formation of sandy and shingle beaches (Rosia Bay, Catalan Bay, Sandy Bay, etc.), including the Isthmus Sands formation (Rose and Rosenbaum, 1991) and La Atunara spit (Lario et al., 1995).

2.2. Windblown sands

There are two prevailing winds in the Gibraltar area: the easterly (Levante) and the westerly (Poniente). The former is by far the stronger, particularly in the region of Gibraltar, and is responsible for the creation of great lone dunes along the Cádiz coastline. Dunes formed by easterly winds were also formed on the Rock during the Quaternary, although obviously limited to zones which have a sufficient sand supply. In these sectors large, rampant type dune were built against the steep slopes of the Rock (Fig. 6).

Rose and Hardman (2000) have recognised three types of windblown sands. They are sufficiently distinctive, thick and widespread to be mapped as separate units: Catalan Sands on the east side of the Rock, the Alameda Sands on the west side, and the Monkey's Cave Sandstone on the south-east coast. The latter unit is the oldest one (>250 ka), deduced from its geomorphological situation. Probably, its generation took place at the end of the fourth morphotectonic step (OIS 8) linked with 30–60 m marine terraces.

Catalan and Alameda Sands were generated during OIS 4 and 3, between 75 and 40 ka. This is inferred from their geomorphological position and the dating of similar sandy cave sediments (Barton et al., 1999; Macphail and Goldberg, 2000; Pettitt and Bailey, 2000; Rhodes et al., 2000). Both formations have originated on a marine beach before being blown inland to accumulate as rampant dunes.

During the period represented by the Gorham's, Vanguard (Fig. 7), Ibex and Devil's Tower cave sediments, and the Catalan Sands climbing dunes, it was likely that Gibraltar was part of the mainland, with a broad coastal plain covered with wind-blown dunes. The Catalan Sands developed between 40 and 50 ka, at the same time as the latest sandy sediments of Ibex Cave (Rhodes et al., 2000), and the infilling of Vanguard Cave (Barton et al, 1999; Goldberg and Macphail, 2000; Pettitt and Bailey, 2000).

Fig. 6. Outcrop of Catalan Sand dune sediments on the eastern face of Gibraltar, between Catalan Bay and Sandy Bay. These reach up to 300 m in height.

Fig. 7. Marine cave at Vanguard (Governor's Beach), filled with aeolian sediments and palaeosols. Recent archaeological excavations have uncovered abundant remains of fauna and clear evidence of human occupation over the past 100 ka.

2.3. Scree breccias

Massive slopes of scree breccia occur widely on the flanks of the Rock of Gibraltar. They are the most widespread and volumetrically the most important Quaternary deposits. They are best developed at the base of the North Face and along much of the east coast, dipping gently outwards from the Main Ridge source (Rose and Rosenbaum, 1991) with a staircased disposition. The western hillslope of the Rock shows scree breccia interbedded with reddish brown palaeosols.

The scree breccias are largely composed of very poorly sorted angular fragments of Gibraltar Limestone which may be up to several metres in diameter. The angularity, size and shape indicate that they formed under terrestrial conditions, facilitated by slope instability and gravitational processes. The intervening matrix is usually a well-cemented brown and red coloured sand and clay. Aeolian sand lenses are interbedded in the scree breccias, mainly in the upper stratigraphic levels. Flemming (1972) observed that along some parts of the south-western coast breccias continued down to 20 m depth below sea level.

At the North Face, associated with a morphotectonic step older than 250 ka (MTU-4, Fig. 2), there is a well-cemented breccia overlying a wave-cut platform level at 55 m above present MSL (Rose and Hardman, 2000). Younger scree deposits lie upon it and upon lower levels of marine erosion outcropping at the northern and eastern sides of the Rock (Fig. 3). The preliminary ESR dating of mammal teeth on Ibex Cave (Table 1, Rhodes et al., 2000), contained in a sandy aeolian deposit, postdates the age of an underlying scree breccia (i.e. 50 ka).

There are also fissure breccias, sometimes sufficiently rich in vertebrate skeletal remains to have been described as bone breccias (e.g. Rosia Bay), where clasts and a clayey matrix are likely to have been introduced by flowing water. At the entrance to St. Michael's Cave we have studied a wide outcrop of exposed, layered, speleothems that show a chemical precipitation sequence from ca 151 to 30 ka (Table 2, Fig. 3). The top is covered by a synchronous scree breccia that entered the cave. Dated samples were taken from the upper part of the sequence, indicating the end of massive gravitational sedimentation (i.e. 25–30 ka) (Fig. 3) on the western side of the Rock.

The major scree breccias on Gibraltar appear to be rockfall screes. Scree breccia is not only a climatic deposit but also a product of marine highstand. The flank of the Rock was eroded by marine action and the scree breccias formed subsequently once the cliffs were not reached by the sea. The breccia deposits therefore overlay former marine landforms such as beach terraces, cliff and wave-cut platforms, or fill karstic holes and former screes (Fig. 5).

2.4. Karstic sediments

The products of karstic solution are a pervasive feature of the Rock. The sedimentary record of cave infill include levels of both external and internal provenance, and accumulations of clastic, chemical and organic debris.

Allochthonous sediments are aeolian sands, marine boulders and sands, scree and fissure breccias and rillwash silts and sands. The autochthonous sediments are fallen rocks, waterlain silts and sands, bat guano and bones, human artefacts, combustion zone ash layers, organic and phosphatic sediments, and speleothems.

It is not unusual to find terrestrial deposits and speleothem sealing the marine deposits in coastal caves (e.g. Gorham's and Vanguard Caves). These caves

Table 2
Activity ratios and age (U-series) of speleothem samples collected at Gibraltar

Locality/Sample code	$^{234}U/^{238}U$	$^{230}Th/^{234}U$	$^{234}U/^{238}U_0$	U/Th age (±error) ka
St. Michael's Cave Entrance				
GB0001	0.974 (0.014)	0.747 (0.032)	0.960 (0.021)	151.0 (±14.0)
GB0002[a]	1.060 (0.035)	0.246 (0.025)	1.066 (0.038)	30.5 (±3.5)
GB0003	1.067 (0.020)	0.551 (0.021)	1.085 (0.025)	86.1 (±4.9)
GB0004	0.997 (0.012)	0.723 (0.025)	0.995 (0.017)	139.5 (±9.9)
GB0005	1.045 (0.018)	0.725 (0.025)	1.066 (0.027)	138.0 (±9.0)
GB0006[a]	1.029 (0.035)	0.476 (0.051)	1.035 (0.043)	70.0 (±11.0)
GB0007	1.023 (0.022)	0.394 (0.015)	1.027 (0.026)	54.3 (±2.7)
GB0008	1.052 (0.017)	0.319 (0.012)	1.058 (0.019)	41.5 (±1.8)
GB0009	1.021 (0.023)	0.767 (0.028)	1.032 (0.036)	157.0 (±13.0)
Forbes' Quarry				
GB0010[a]	1.258 (0.043)	0.532 (0.035)	1.323 (0.054)	79.8 (±8.4)
GB0011	1.159 (0.024)	0.168 (0.008)	1.168 (0.025)	19.9 (±1.1)
Rosia Bay				
GB0207	1.005 (0.022)	0.833 (0.037)	1.009 (0.038)	193.5 (±24.0)

We used α-spectrometry analytical method. All uncertainties given are based on propagated errors from counting statistics and are quoted at the $\pm 1\sigma$ (standard deviation) level. Results for pure calcite samples were obtained from the analysis of one or two coeval samples. For each dirty calcite several coeval samples, diluted with different HNO_3 concentrations, were analysed and the ISOPLOT program (Ludwig, 1991) were used to obtain activity ratios and ages (University of Seville Laboratory, Spain).

[a] Dirty calcite samples.

operate like sediment traps (Fig. 7), and that provide a detailed Quaternary record of Gibraltar.

Behind the road at Rosia Bay there is a prominent limestone cliff. The sediments exposed at first sight appear to be entirely limestones. However, a closer examination shows that some of the exposures are cave breccias. These deposits and bones were first described in detail by Boddington (1771) and studied later by Smith (1846) on account of the fauna that they contained. Their age, deduced from the position in our morphotectonic model, may well be Middle Pleistocene. The U/Th dating exercise that we are currently carrying out on speleothems interposed within breccias, with a preliminary date of 193.5 ± 24.0 ka (Table 2), appear to confirm this hypothesis.

Chemical deposition in caves is very important for Quaternary history reconstruction. Slow calcite and aragonite accummulations are useful for dating and palaeoenvironmental reconstruction purposes in situations where the age can be determined with reasonable accuracy. Many kinds of speleothems have been found in Gibraltar's caves and rock shelters, but we do not yet have sufficient dates for them. Isolated speleothems from Europa Point, Gorham's Cave and St. Michael's Cave have previously been dated but a full karstic chronology needs to be developed (Fig. 3).

We have studied a wide outcrop of exposed speleothems at the entrance to St. Michael's Cave that reveal a chemical precipitation sequence from ca 151 to 30 ka (Table 2). Many petrographic facies are exposed, including flowstones, stalagmites, fallen stalactites, pool pearls, pool rim encrustations, microgours, etc., recording a long palaeoclimatic history.

Isotopic U/Th dating of Gibraltar speleothems and those from neighbouring regions (e.g. Grazalema Mountains, Fig. 3) are useful in establishing a regional Pleistocene climatic sequence. Both series show a close correlation with warm-wet OIS 3 and 5, similar to the North African climatic trend (Lézine and Casanova, 1991; Rognon, 1996), that also shows two main Upper Pleistocene pluvial periods between 125–70 ka and 40–25 ka.

3. Erosional landforms

The most recent coastal erosion landforms are associated with the last eustatic pulses of the Holocene. The present-day vertical cliffs, wave-cut platforms, coastal rock-shelters and the oldest open caves were formed during the Holocene Transgression. The subsequent stabilization, or slight eustatic fall, has caused a modest coastal progradation in coves and retrogradation in headlands through cliff retreat.

The relative sea level position determines the vertical portion of the rocky coast that is affected by marine processes (Trenhaile, 2001). It also affects slope development and the karstic system. Phreatic and marine levels therefore define a morphogenic plane on isolated rock coasts. It incorporates littoral erosional and continental features, including coastal platforms, cliffs, slopes and karstic caves.

3.1. Cliffs and wave-cut platforms

Steep or undercut cliffs are typical of wave-dominated environments (Griggs and Trenhaile, 1994). The steep cliffs which fringe Gibraltar (Figs 1 and 4) were formed by coastal erosion during periods of relative marine sea level highstand and stillstand.

Composite cliffs have more than one major slope. They include bevelled cliffs with convex or straight seaward-facing slopes above steep, wave-cut faces, and multi-storied cliffs with two or more steep surfaces separated by gentler slopes. At Gibraltar, composite cliffs reflect the combined effects of subaerial and marine processes and progressive tectonic uplift during the Quaternary.

The eastern side of the Rock is exposed to easterly storms from the western Mediterranean. It has a fetch of more than 1500 km (Flemming, 1972). As a result, the eastern side is subject to a much stronger littoral erosion, leading to a continuous coastal retreat, while the western side is hardly affected by such a process. Thus the relief of the eastern side has changed more quickly, giving rise to a great variety of erosional landforms. The erosional relief of the western side is the result of a slower morphological evolution, with a lower variety of forms that are more mature.

The wave-cut highstand cliffs, isolated during the later glacial stages, were gradually replaced by the upward growth of convex slopes that developed beneath the accumulating talus. The early age of these cliffs is established from their attached marine terraces (Figs. 4 and 9) and that of the later ones to overlying scree breccia and sand dune formations (Fig. 5).

The lower morphotectonic step (i.e. the last 250 ka) is backed by a steep relict sea cliff. Many places on the eastern flank of the Rock have marine terraces at the base of the slope, from example the +9 m platform (Forbes' Quarry, Devil's Tower, Gorham's Cave), dated at ca 180 ka.

Wave-cut platforms extend from approximately the mean high water mark, at the base of the receding cliff, to an elevation below the mean low water mark. The zone of greatest wave erosion is therefore probably above the neap high water level, particularly in microtidal environments and where hard rocks resist all but the most vigorous storm waves that operate at elevated, supratidal, levels (Griggs and Trenhaile, 1994; Pirazzoli, 1996).

Fig. 8. Staircased marine erosion platforms at Windmill Hill Flats (upper level) and Europa Flats (lower level), separated by a palaeocliff and scree slope.

Two raised shorelines are represented by extensive wave-cut platforms that are backed by steep cliff lines which form the southern Gibraltar plateau (Figs. 2 and 8). Windmill Hill Flats sloping south from 130 to 90 m, is replaced further south by Europa Flats sloping from 40 down to 30 m. Other fossil shorelines and the easterly continuation of the southern plateau are marked by narrow platforms and associated cliffs (Rose and Rosenbaum, 1994).

3.2. Staircased slopes

The successive sea-level fluctuations throughout the Quaternary undoubtedly constitute the most important factor determining the morphosedimentary evolution of the Rock. The most recent slope profiles show a design with two well-differentiated elements: a semi-vertical cliff, and a rectilinear to concave basal slope. The cliff is the product of gravitational processes: collapses and falls associated with intense fracturing of the calcareous mass possibly affected by other secondary processes and factors such as the network of surface-breaking endokarst conduits, root activity and mechanical weathering.

With a stable sea level, these slopes retreat by replacement (Finlayson and Statham, 1980): the accumulation of debris at the foot is not completely balanced by the removal of sediments by wave action and the height of the cliff diminishes progressively. The head of the slope grows at the same time. The end of the process is reached with a convex–concave profile when the forms, in dynamic balance, evolve very slowly.

Thus, a relative sea level rise will have two basic consequences. First, the hillside will tend to acquire a gentler profile. This will be achieved by a progressive accummulation of debris along the base sections of the old slope. Talus deposits can be found fossilized by dunes and beaches, a mechanism recognizable at various points on the northern and eastern coast of Gibraltar. Second, a relative sea level rise will also produce a submerged morphology very similar to that observed by Flemming (1972), with echo sonar, to the east of Gibraltar.

In contrast, a relative sea level fall will sharpen the profile, tending towards the former design but starting at a lower height above sea level. Littoral erosive processes will create a cliff edge at the base of the profile that will retreat. The earlier profile will be formed, once more, through gravitational processes. If this new situation is maintained long enough, the original profile could be entirely eliminated and substituted by the new profile. If time is insufficient, the profile will again be preserved at the head of the slope. We therefore observe "hanging slopes" in which the two elements, cliff edge and slope, can be recognized, associated with a sea level that is higher than the present one.

This type of morphology is associated with the so-called "composite cliffs", whose polycyclic evolution is usually related to tectonoeustatic fluctuations and to the different rates of erosional retreat of the escarpments due to wave action (Trenhaile, 1987). In the case of Gibraltar (Fig. 5), it seems clear that the surface weathering and debris falls have been responsible for the retreat of the escarpment. Hanging slopes appear much better developed on the eastern side of the Rock where the coastal erosional processes are much more important.

All the dates that have been obtained so far from the Quaternary marine deposits of Gibraltar (Table 1, Fig. 3), are situated in the morphotectonic step of lowest altitude (MTU-5, Figs. 2 and 9B). This morphological episode is delimited above by an old marine slope. There were positive and negative sea-level changes during the time required for its development.

It is possible to recognize up to five levels of stepped hillsides in Gibraltar between Catalan Bay and Europa Point. Each one has two elements: cliff-edge and talus slope (Fig. 9). We do not know the total area reached by the each of the basal slopes and, at present, we can only delimit their lower height above sea level. It will be necessary to conduct, in the future, detailed studies of the deposits that are situated in the oldest morphotectonic units (MTU_{1-4}) in order to test this evolutionary model.

3.3. Endokarstic system

Gibraltar is honeycombed with natural caves and man-made tunnels. At least 143 caves, situated above present day sea level, have been located (Rose and

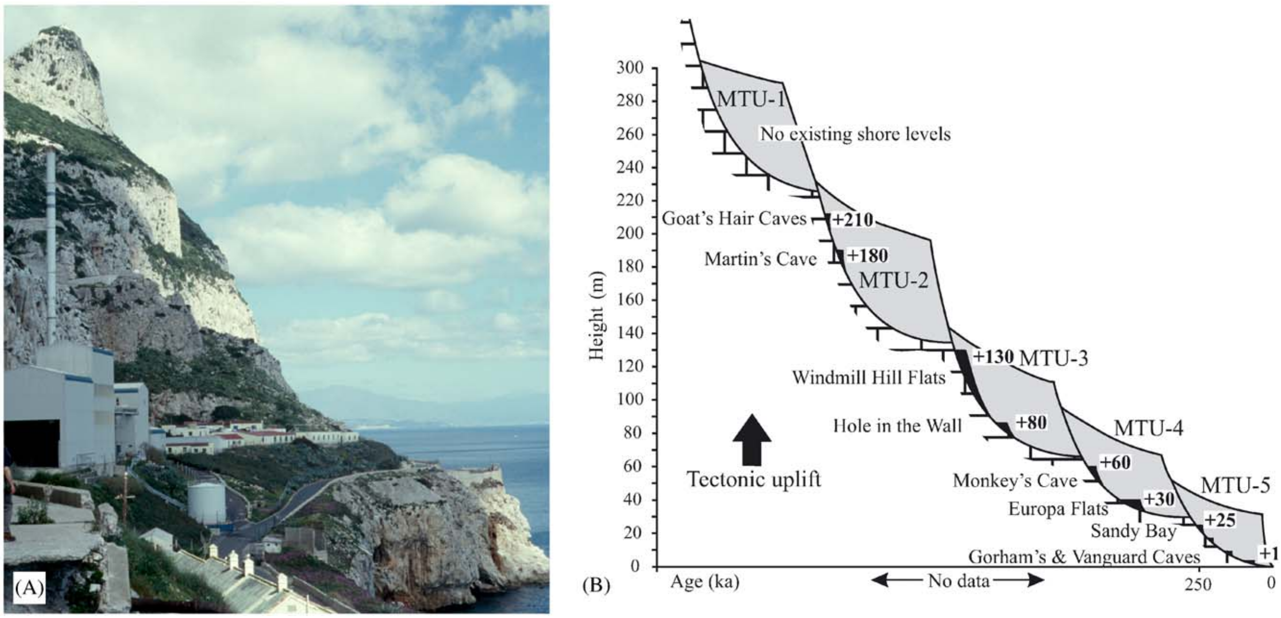

Fig. 9. (A) Composite cliffs on the SE coast of Gibraltar. Each shelf separates a morphotectonic unit (MTU) with a complete morphosedimentary (MSU) record. (B) Idealized morphotectonic diagram of a transect across this side of the Rock of Gibraltar, based on Fig. 2. Five morphotectonic units (MTU) are distinguished. In each unit there examples of marine terraces that act as a reference.

Rosenbaum, 1990) and more are known to occur below (Flemming, 1972; Fa et al, 2000). Tratman (1971) inferred at least two solution phases in the Gibraltar caves.

The karst system of the Rock shows clear morphological evidence that its underground evolution was closely related to the history of the subaerial relief. Abundant vertical conduits and horizontal galleries have been seen in the endokarst (such as in the Saint Michael's Cave system, Rose and Rosenbaum, 1991); the former represent periods of falling karstic base-level while the latter are associated to stability, or even a rise, of the base-level. Caves at high levels should therefore be older in origin than caves at low levels. Speleothem deposits interbedded with cave floor sediments may provide evidence of ancient climatic change (Fig. 3).

4. Recent tectonics

Patterns of vertical deformation can be inferred from the study of emerged marine terraces. In neotectonic studies dealing with vertical movements of the coastal zone, however, two problems must be addressed: the age determination of emerged shorelines and the original position of the sea level at the time the terrace was formed (Lajoie, 1986; Zazo et al., 1999). In order to quantify the movements we need to assume a constant rate and direction (uplift or subsidence).

The height distribution of the OIS 5e and 5c palaeoshorelines (i.e. 128 and 95 ka) of the Strait of Gibraltar show a clear differential uplift in the central sector of the Strait (Goy et al., 1995; Zazo et al., 1999). Evaluated mean uplift rates range from maximum values of 0.15 mm/yr, in Tarifa, to lower values of 0.10 mm/yr, in the west, for the last 128 ka. The calculated mean rate for the Rock of Gibraltar is about 0.05 ± 0.01 mm/yr during the last 100 ka (Lario, 1996).

Zazo et al. (1999) inferred that differential uplift and subsidence along the coast of the Strait was mainly set along individual faults. Major faults interacting with the coast have NE–SW and NW–SE orientations and they mainly work as strike-slip faults separating crustal blocks with different associated uplifting or subsiding character.

Mean uplift rates for the last 100 ka in the central sector of the Strait of Gibraltar are lower than those recorded in other areas located at convergent plate boundaries such as New Zealand (1.2–3.0 mm/yr: Lajoie, 1986). The Gibraltar data could be comparable, however, to rates recorded in convergent-transpressive settings like some sectors of the southern Peruvian coast (Ortlieb et al., 1996) where oblique subduction promotes mean uplift rates of around 0.16 mm/yr. Horizontal convergence between the African and Eurasian plates is mostly due to shear tectonics (Goy et al., 1995).

Maximum uplift rates inferred in this study is about 0.33 ± 0.05 mm/yr and represent a logical consequence of the uplift rate curve on Gibraltar coast (Fig. 10), where the OIS 1, 5 and 7 shorelines have been compared with their present heights. A mean uplift value of 0.05 ± 0.01 mm/yr is calculated from 200 ka to the present. Previously, at least to 250 ka, the medium uplift rate was higher (0.33 ± 0.05 mm/yr), possibly compatible

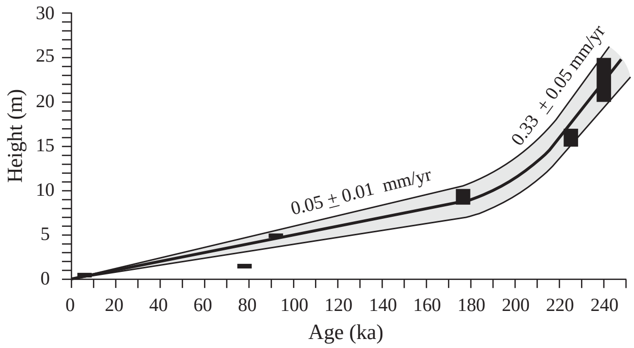

Fig. 10. Mean rates of tectonic uplift of the Rock of Gibraltar in the last 250 ka, based on the evidence presented in this paper. Height and age of terrace shore deposits (thick black bar) after Goy et al. (1995), Hoyos et al. (1994), Lario (1996), Zazo and Goy (1989) and Zazo et al. (1999).

with major tectonic events in response to a NNW–SSE compressive stress field (Ribeiro et al., 1996).

5. Conclusions

The abundant landform and deposits of Gibraltar, possibly spanning almost the entire Quaternary, make this area one of the most important and complete records for sea level changes and neotectonics in the western Mediterranean.

The Quaternary sea level changes create a landform and deposits complex of marine, aeolian, gravitational and karstic origin, that are distributed over an altitude range of 210 m. The uplift processes delimit the shoreline levels into several steps and palaeocliffs.

Uplift rates of about 0.05 ± 0.01 mm/yr generate morphosedimentary units (MSU) that are stepped and offlapped. Higher rates, inferred to be about 0.33 ± 0.05 mm/yr, isolate these units by way of main cliffs and form morphotectonic units (MTU). The most recent ones are dated between 250 ka and the present. Their linked marine terraces are located at 25–20 m, 17–15 m and 10 m (OIS 7), 5 m (OIS 5c), 2–1.5 m (OIS 5a), and 1.5 m above present MSL (OIS 1). Other higher and older shorelines are now raised at heights of 30–40, 50–60, 80–86, 90–130, 180–190 and 210 m.

The tectonoeustatic model that Gibraltar offers may be used totally or partially in other similar sites along the Mediterranean coast, due to the abundance of limestone blocks, the marked Quaternary tectonic activity and the similar latitudinal behaviour of the eustatic changes.

Acknowledgements

This work has been supported by "PalaeoMed project" Interreg IIIB of the EU MEDOC Programme: 2002-02-4.1-U-048, the Government of Gibraltar and the Plan Propio of Huelva University. We wish to thank F. Giles, D. Fa, G. Finlayson, M. Mosquera and other collaborators of the Gibraltar Museum, as well as the people of Gibraltar. We also thank the referees for useful suggestions and corrections of an earlier draft. It is a contribution to the INQUA Neotectonics and Shorelines Commissions and IGCP 437.

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