Morphosedimentary evidence of the Last Interglacial Maximum on the coast of Governor's Beach, Gibraltar

Evidencias morfosedimentarias del Último Máximo Interglacial en la costa de Governor's Beach, Gibraltar

J. Rodríguez-Vidal [(1)], L.M. Cáceres [(1)], M. Abad [(1)], F. Ruíz [(1)] y A. Martínez-Aguirre [(2)]

[(1)] Universidad de Huelva, Departamento de Geodinámica y Paleontología, Campus del Carmen, Avda. de las Fuerzas Armadas s/n, 21071 Huelva, Spain. jrvidal@uhu.es; mcaceres@uhu.es; manuel.abad@dgyp.uhu.es; ruizmu@uhu.es.
[(2)] Universidad de Seville, Departamento de Física Aplicada I, EUITA, ctra. de Utrera km. 1, 41013 Sevilla, Spain. arancha@us.es

RESUMEN

Los registros marinos, erosivo-sedimentarios, en la costa de Gibraltar son el resultado de episodios de elevaciones eustáticas, sobre los que se depositan secuencias continentales eólicas y gravitacionales de descenso eustático, en las que se intercalan paleosuelos. En la costa oriental de Governor's Beach, se han reconocido dos altas paradas marinas durante OISs-5e. La primera transgresiva, a +5,0 m, con un amplio y marcado socave, cuevas, abrigos, cantiles y un cortejo bioerosivo de ascenso eustático; la segunda regresiva, a +1,5 m, con pequeñas rasas mareales y una secuencia sedimentaria de playa-duna-suelo rojo. Registros semejantes han sido reconocidos en otros lugares del Mediterráneo occidental a ~130 ka y ~120-110 ka. Todas estas evidencias fueron parcialmente cubiertas por episodios continentales posteriores de carácter eólico-kárstico-gravitacional.

***Palabras clave**: costa rocosa, eustasia, Neotectónica, Último Interglacial, Gibraltar.*

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Morphodynamic framework

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

The Rock is an outcrop of Mesozoic carbonates and shales designated the Gebel Tariq Group (Rose and Rosenbaum, 1990) and divided into three formations: Little Bay Shale, Gibraltar Limestone, and Catalan Bay Shale. 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, which promoted a westward 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).

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 has caused change in the location of the coastal landforms, and has controlled the evolution of slopes.

Quaternary sediments on Gibraltar's flanks have a widespread distribution and are both marine and continental deposits (Fig. 1). They include sand and cobble shore sediments, aeolian dust and sands, scree breccias, and karstic products, such as clays, fallen rocks, and speleothems.

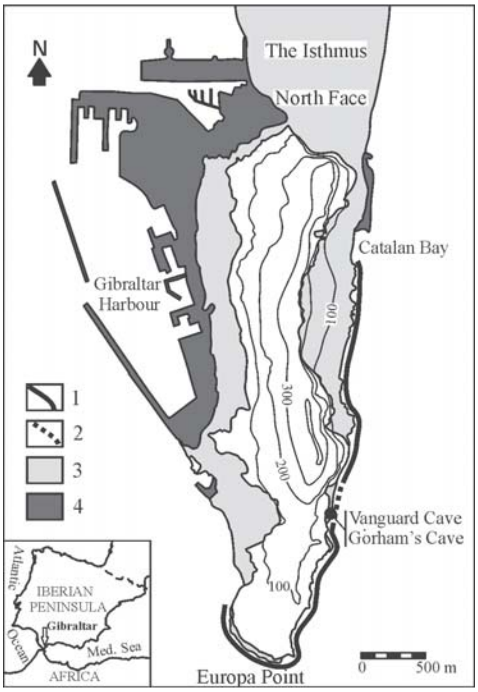

Fig. 1.- Simplified topographic map of the Gibraltar Peninsula. Contours at 100 m intervals. Legend: 1, OISs 5e littoral outcrop. 2, Governor's Beach sector. 3, Late Pleistocene morphosedimentary record. 4. reclaimed land.

Fig. 1.- Mapa topográfico esquemático del Peñón de Gibraltar. La equidistancia entre curvas de nivel es de 100 m. Leyenda: 1. Afloramientos costeros del subestadio isotópico 5e. 2, sector de Governor's Beach. 3, Registro morfosedimentario del Pleistoceno superior. 4, Terreno ganado al mar.

Tectonic uplift of marine high-stand landforms shows raised shorelines staircased across the Gibraltar slopes (Rodríguez-Vidal *et al.*, 2004). Geomorphological techniques are required to establish a suitable chronological situation given the different location and height of these sediments and their spatial interrelation.

Patterns of vertical deformation can be inferred from the study of emerged marine terraces. 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 kyr) 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). The calculated mean rate for the Rock of Gibraltar is about 0.05 ± 0.01 mm/year during the last 100 kyr (Lario, 1996). The maximum uplift rate inferred by Rodríguez-Vidal *et al.* (2004) is about 0.33 ± 0.05 mm/year and represents a logical consequence of the uplift rate curve on Gibraltar's coast, 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/year is calculated from 200 kyr to the present (Rodríguez-Vidal *et al.*, 2004).

Last Interglacial evidence

The cartographic and morphostratigraphic disposition of the terraces, their faunal content, and their U-Th age (Lario, 1996; Zazo *et al.*, 1999; Rodríguez-Vidal *et al.*, 2004 and this work) provide tools for reasonable chronostratigraphic interpretation of the marine sequence. All represent emerged high-stand positions of interglacial sea levels (Hoyos *et al.*, 1994, Zazo *et al.*, 1994).

In the coastal caves (e.g. Gorham's and Vanguard Caves), it is not strange to find terrestrial deposits and speleothems sealing the marine deposits (Fig. 2). These caves operate like sediment traps, and a detailed Quaternary record of Gibraltar can be obtained from them, although other correlative events are registered outside.

Allochthonous cave sediments are represented by aeolian sand and dust, marine pebbles and sands, scree and fissure breccias, and rillwash silts, sands and gravels. The autochthonous sediments are fallen rocks, waterlain silts and sands, bat guano and bones, human artefacts, combustion zone ash layers (Finlayson *et al.*, 2006), organic and phosphatic sediments, and speleothems.

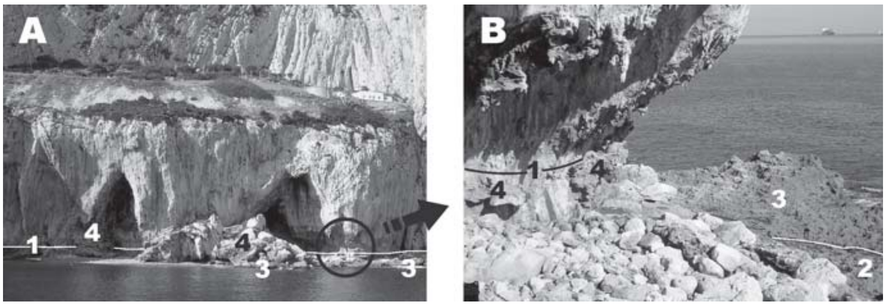

Fig. 2.- Morphosedimentary features from OISs 5e Governor's coastline. (A) Bennett and Gorham's Caves shore, (B) Gorham's Cave Entrance. Key: 1, +5 m notch. 2, +1.5 wave-cut-platform. 3, beach deposit. 4, post-OISs 5e continental deposits attached to the wall cave and cliff face.

Fig. 2.- Rasgos morfosedimentarios costeros del subestadio 5e en Governor's Beach. (A) costa de Bennett Cave y Gorham's Cave, (B) entrada de Gorham's Cave. Leyenda: 1, Socave de +5 m. 2, Rasa de +1,5 m. 3, Depósito de playa. 4, Depósitos continentales posteriores al OISs 5e, adosados a las paredes de las cuevas y a los acantilados.

The Mediterranean basin can be considered a tideless sea, with an atmospheric tidal range that hardly surpasses 0.5 m, so the topographic elevation measured in the raised morphostratigraphic units is close to the real value (Datum). The heights of the marine units have been measured at the inner edge of the marine terraces or in the middle part of the notches in the case of cave fillings, always referring to the considered present MSL.

The marine deposits on the coast of Gibraltar are the result of high-stand episodes, on which are deposited low-stand aeolian continental and gravitational sequences, into which are inserted palaeosoils. When this record is located inside caves (e.g. Governor's Beach), it shows intercalated levels of speleothems, and remains of fauna and human occupation (Finlayson *et al.*, 2006).

The Last Interglacial (OIS 5), between 130 and 74 kyr, is represented at Gibraltar by substage 5e (132 kyr and 125-117 kyr). At Europa Point, Hoyos *et al.* (1994) dated terrace remains at 5.25 m (92.5 kyr at substage 5c), and in Gorham's Cave at 1.0 m (81 kyr, at substage 5a), though with some doubts, as the latter sample of shell is in an open system. In Catalan Bay, in an outcrop at the foot of Caleta Hotel, Rodríguez-Vidal *et al.* (2007) have recognised two marine high-stands of OIS-5e, possibly coincident with those of Goy *et al.* (1995). The first is transgressive, at +5.0 m, with a wide, conspicuous notch, caves, shelters, ledges, and a bioerosive procession of eustatic rise; the second is regressive, at +1.5 m, with small tidal benches and a generalised sequence of beach/dune/red soil.

The morphostratigraphic sequence of Governor's Beach (Zazo *et al.*, 1999; in Gorham's Cave), and particularly in Vanguard Cave (Rodríguez-Vidal *et al.*, in press) is similar to the Caleta Hotel outcrop. All the marine caves of this coast show a marked notch at +5.0 m (Fig. 2), widening and deepening their earlier morphologies, reaching the interior of all the caves. Excavated in the wave-cut-platform of this marine level are the tidal benches of a later palaeolevel of +1.5 m and, covering them is a littoral deposit of sandy gravels and abundant remains of shells, with a thickness of up to 4 m, representing facies of foreshore and backshore (Fig. 3a).

The cartographic geometry of this beachrock terrace on Governor's Beach indicates that the widening of the caves at their base was due to this marine high-stand episode, and that the large fallen blocks protected the deposits from being later eroded by wave action.

The base of the entrance of Vanguard Cave has two tidal erosive benches and notches (Fig. 3b), built on Jurassic limestones, 0.6 m apart, indicating the present situation of high and low tide. Immediately above are another two erosive platforms, also 0.6 m apart, marking a marine palaeolevel at +1.5 m a.s.l. and covered to +4.0 m a.s.l. by a contemporary foreshore-backshore deposit of marine pebbles, blown sand, and blocks fallen from the cliff, bioeroded and rounded by the waves. This deposit is fossilising and filling the palaeorelief of a wave-cut platform with potholes of < 1m in diameter, now in a phase of exhumation.

The abundant fauna of mollusc shells in this marine deposit and their good state

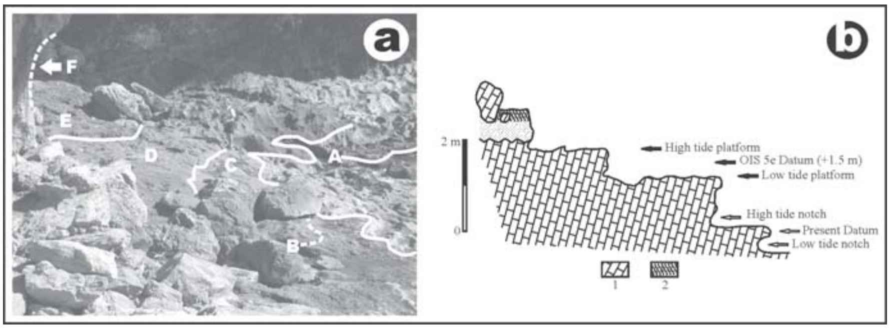

Fig. 3.- Morphostratigraphic record of both present and OISs 5e rock-sandy shore in Vanguard Cave. (a) A, present Datum. B, beachrock berm. C, beachrock deposit and dated samples. D, blown sand deposit. E, carbonated red paleosoil. F, +5 m wide notch. (b) Tidal erosive benches and notches. Key: 1, limestone bedrock. 2, blown sand and red palaeosoil.

Fi. 3.- Registro morfoestratigráfico de la costa de Vanguard Cave con los niveles actuales y del subestadio 5e. (a) A, Datum actual. B, berma de playa cementada. C, depósito de playa cementada y muestras datadas. D, eolianita. E, paleosuelo rojo carbonatado. F, socave marino a +5 m. (b) Plataformas y socaves intermareales. Leyenda: 1, sustrato de caliza. 2, eolianita con paleosuelo.

Sample	$^{234}U/^{238}U$	$^{230}Th/^{234}U$	T (kyr)	$(^{234}U/^{238}U)_o$
GB0310a	1.318±0.034	0.6746±0.0226	114.4±6.5	1.437±0.047
GB0310b	1.271±0.037	0.6558±0.0263	109.9±7.3	1.368±0.050

Table I.- Applied Physics Laboratory, EUITA, University of Seville, Spain.

Tabla I.- Laboratorio de Física Aplicada, EUITA, Universidad de Sevilla, España.

of conservation has enabled the collection of specimens of *Acanthocardia tuberculata*, which have been dated by U/Th (alpha count), giving the following ages (Table I):

On this deposit are found a continuum of very cemented backshore aeolian sands, with large metric blocks of limestone and broken stalactites. These sands are coarse, with shell fragments, gradually decreasing in diameter towards the roof, and have a maximum thickness of 2 m. The surface is eroded and flattened, later becoming a red soil with horizon Bk of calcrete and abundant fragments of fallen stalactites. In this karstic medium, still more continentalised, are deposited flowstones and new stalactites and stalagmites (Fig. 2).

In a clearly regressive phase of sea level, with successive fluctuations, is deposited in unconformity the whole sequence of aeolian sands that fill the large caves of Governor's Beach (Barton *et al*., 1999; Macphail and Goldberg, 2000; Pettitt and Bailey, 2000) and ascend the sides of the east face of Gibraltar (Catalan Sands: Rhodes *et al.*, 2000; Rodríguez-Vidal *et al*., 2004). The walls of Gorham's and Vanguard caves conserve hanging shelves of sand, with their original dipping, as on the highest part of the roofs. Intercalations of gravitational episodes, rockfalls, and rock avalanches are seen stratigraphically in the roof and wall of the aeolian sands.

Chronological discussion

The U/Th datings that we have made on shells of *Acanthocardia tuberculata* situate the genesis of the marine deposit at ~114.5 – 110 kyr that is, at substage 5e.

The work carried out by Zazo *et al.* (1999) in the Iberian zone of the Strait of Gibraltar, with a profile in the mouth of Gorham's Cave, assumes that this marine level would have been produced during OISs 5c. However, the shell datings place it between 81.0±0.9 and 53.8±0.5 kyr, and reveal the existence of an open system, which would rejuvenate the real ages of the samples.

According to U-Th data of Zazo *et al*. (in press), in the Gibraltar Strait north sector (Barbate-Trafalgar coast), the marine sediment below the blown-sand sequence is of Last Interglacial age (OIS 5), but the available information is inadequate to distinguish between OIS 5e and OIS 5c. Arguments in favour of OIS5e, ~5 m on stable coasts, are the most-widely accepted. Further support is provided by the existence of more than one high-stand during OIS 5e (e.g. Bard and Hamelin, 1990), also recognised on the Spanish Mediterranean coasts between ~135 and 117 kyr (Hillaire-Marcel *et al*., 1996, Zazo *et al*., 2003), but always with similar high-stand elevations. However, on the Atlantic coasts of Spain, the deposits of OIS 5e and 5c are known (so far) to be single high-stands, with U-Th ages ~128 kyr and ~ 95 kyr respectively (Zazo *et al*., 1999).

The datings (< 124 kyr) made on the aeolian series in Vanguard Cave (Stringer *et al*., submitted) immediately above the beachrock deposit, using the OSL method, and our datings, made by U-series, seem to indicate that the age of the marine terrace would be more in accord with OISs 5e between 125 and 117 kyr than with OISs 5c.

To these chronological criteria we can add other, morphosedimentary ones, which appear similarly in the Bahamas Islands zone-type (Hearty and Neumann, 2001). During the Last Interglaciation (MIS 5e), the sea level rose rapidly at the end of the period (132 kyr), etching notches and wave-cut platforms, with later shore deposits at +1.5 m a.s.l. (125 kyr). After a brief still-stand, the sea level rose again to +5 m (118 kyr), cutting deep notches of flattened elliptical profile by bioerosion. During the MIS 5d regression, aeolianite was formed and emplaced after a prolonged high-stand (132-118 kyr). A reddish calcrete and soil, with land snails and rhizomorphs, was formed during the beginning of this low-stand stage.

Dumas *et al*. (2006), from new geomorphologic and U-series dates in Haiti, confirm the age of coral reef double terraces assigned to MIS 5.5. The sea level was at 5 m a.s.l. at 130.5 kyr for the first event, and 2.7 m a.s.l. for the second, estimated at 117.9 (U/Th dating) but more probably ca. 123-122 kyr.

Phreatic speleothems palaeolevels in Mallorca (Fornós *et al*., 2002 and Tuccimei *et al*., 2006), belonging to substage 5e, are very well documented, with ages ranging between 110 and 138 ka BP. U-series method using MC-ICPMS and TIMS recognize two different high-stands at 110-122 and 128.5-138 kyr BP.

The morphostratigraphic and chronological comparison of these examples with those found on the eastern coast of Gibraltar seems to indicate that, at the beginning of stage 5, the sea level rapidly reached the current height of +5 m a.s.l., shaping very persistent bioerosive forms over several thousand years, leaving Gibraltar with the geographical appearance of an island. A subsequent rapid decrease, analysed on the coast of Mallorca (Tuccimei *et al*., 2006) at a depth of 16.5 m b.s.l. (125 kyr BP), has not been recorded at Gibraltar, as it would be submerged; however, the subsequent rise to +1.5 m a.s.l., which was marked by a bioerosive procession of tidal benches, has been recorded. The fall in sea level from the end of OISs 5e to OISs 5d formed pocket-beaches of pebbles and coarse sands with shells, accompanied on the backshore by cave fillings, red soils, and cliff-front dunes, which completely filled the marine caves.

Thus, both +5.0 m and +1.5 m morphosedimentary features of the Gibraltar coast were probably formed during the double high-stand peak of OISs 5e. This erosional shore model is similar to the «double notches» originated on the coastline of Italy (Antonioli *et al*., 2006) by a glacial isostatic adjustment during MIS 5.5.

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