

Environmental conditions and geomorphologic changes during the Middle–Upper Paleolithic in the southern Iberian Peninsula

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ABSTRACT

This study utilizes geomorphology, marine sediment data, environmental reconstructions and the Gorham's Cave occupational record during the Middle to Upper Paleolithic transition to illustrate the impacts of climate changes on human population dynamics in the Western Mediterranean. Geomorphologic evolution has been dated and appears to be driven primarily by coastal dune systems, sea-level changes and seismo-tectonic evolution. Continental and marine records are well correlated and used to interpret the Gorham's Cave sequence. Specific focus is given to the three hiatus sections found in Gorham's Cave during Heinrich periods 4, 3 and 2. These time intervals are compared with a wide range of regional geomorphologic, climatic, paleoseismic, faunal and archeological records. Our data compilations indicate that climatic and local geomorphologic changes explain the *Homo sapiens* spp. occupational hiatuses during Heinrich periods 4 and 3. The last hiatus corresponds to the replacement of *Homo neanderthalensis* by *H. sapiens*. Records of dated cave openings, slope breccias and stalactite falls suggest that marked geomorphologic changes, seismic activity and ecological perturbations occurred during the period when *Homo* replacement took place.

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1. Introduction

The timing and geography of *Homo neanderthalensis*' extinction is well known, but the causes for the extinction remain in dispute (Finlayson et al., 2006). Specifically, the role environmental factors play in this extinction is much debated (e.g., Wolpoff, 1989; Lahr and Foley, 1998; Stringer, 2003; Horan et al., 2005; Roebroeks, 2006; Jiménez-Espejo et al., 2007; Tzedakis, et al., 2007; Banks et al., 2008; Finlayson et al., 2008a,b; Zilhão et al., 2010b). The use of combined archeological and paleoclimate data, together with continued improvements in radiocarbon chronology, can shed light on the relationship between past climate conditions and changes in *Homo* spp. populations (e.g., Bard et al., 2004; Mellars, 2006; Tzedakis et al.,

2007; Vaks et al., 2007; González Sampéris et al., 2009; Blaauw, 2010; Müller et al., 2011; Pinhasi et al., 2011).

Archeological sites with well-dated *Homo* spp. presence over extended time intervals are most adequate for investigating the climate/environmental influence on population dynamics. Gorham's Cave (Gibraltar) is recognized as the last site occupied by Neanderthals (Finlayson et al., 2006; Jennings et al., 2011) with the youngest date for Mousterian Middle Paleolithic occupation, between 28,700 and 27,600 cal. yr BP, at the 1 σ range Calpal calibration (Weninger et al., 2011) (Tables 1 and 2), and has been occupied for extended time intervals. It can thus be used to determine the relation between occupation and regional climate/environmental changes.

Gorham's Cave is located in the southern Iberian Peninsula, an area that functions as a major faunal refuge during the Pleistocene due to its topographic, climatic and latitudinal setting (Jennings et al., 2011). Despite the refuge character of this region several *Homo*

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Table 1
Results of AMS ^{14}C dates and errors from Gorham's Cave sequence from Finlayson et al. (2006), translated to Cariaco record depths following Tzedakis et al. (2007) Supplementary information. AMS ^{14}C date numbers correspond to those give in Finlayson et al. (2006).

Sample no.	Laboratory reference	AMS radiocarbon age (yr)	Err. \pm	^{14}C added uncertainty (S+)	^{14}C subst. uncertainty (S-)	Shallowest depth C+>S- (cm)	Deepest depth S+>C- (cm)
8	Beta-184042	18,440	160	18,600	18,280	9.66	9.96
23	Beta-196782	23,360	320	23,680	23,040	12.36	12.66
15	Beta-185345	23,780	540	24,320	23,240	12.66	13.21
16	Beta-196775	24,010	320	24,330	23,690	12.65	13.21
9	Beta-196785	26,070	360	26,430	25,710	13.51	14.10
17	Beta-196773	26,400	440	26,840	25,960	13.77	14.18
11	Beta-185344	27,020	480	27,500	26,540	14.07	14.20
10	Beta-196784	28,360	480	28,840	27,880	14.23	14.69
18	Beta-196791	28,570	480	29,050	28,090	14.28	14.83
19	Beta-196779	29,400	540	29,940	28,860	14.69	15.30
12	Beta-196786	29,910	600	30,510	29,310	14.78	15.59
14	Beta-196792	30,310	620	30,930	29,690	16.07	17.16
20	Beta-196776	30,560	720	31,280	29,690	15.07	16.16
13	Beta-196787	31,480	740	32,220	30,740	15.45	16.73
25	Beta-196772	31,780	720	32,500	31,060	15.92	16.87
26	Beta-196789	32,100	800	32,900	31,300	15.69	17.16
30	Beta-196771	32,560	780	33,340	31,780	16.26	17.49

spp. hiatuses occurred at Gorham's Cave; the last one represents the extinction of the Neanderthals. The role that local, regional or global factors played in these hiatuses is poorly known, yet understanding linkages between climate and environmental change and the Neanderthals' extinction may shed light on the causes and timing of the final extinction (e.g., Higham et al., 2006, 2009; Pinhasi et al., 2011).

Recent studies indicate that the cognitive capacities of the *H. neanderthalensis* and *Homo sapiens* were very similar (Zilhão et al., 2010a; Cortés-Sánchez et al., 2011), and there are doubts about the exclusivity of Neanderthals' Mousterian tools in Europe (Balter, 2011); genetic mixture was also possible (Green et al., 2010), thus we will use the term *Homo* spp. (*H. spp.*) to refer to both throughout the present study.

In order to recognize all the factors that controlled the occupational pattern of Gorham's Cave and other places located in the South Iberian refugia, we utilize information from extensive fieldwork, new dates, and a marine sediment record from South Iberia, to understand the environmental conditions affecting the last *H. spp.* transition. This multidisciplinary paleo-ecological study integrates geomorphological, climatic, paleoseismic, faunal, and archeological records. Calibrated radiometric ages provide a chronology for *H. spp.* cave occupation, allowing us to relate it to climatic and geomorphological reconstructions

Table 2
Results of calibrated AMS ^{14}C dates and errors from Gorham's Cave sequence from Finlayson et al. (2006) using Calpal2007_Hulu (Weninger et al., 2011). AMS ^{14}C date numbers correspond to those given in Finlayson et al. (2006).

Sample no.	Laboratory reference	AMS radiocarbon age (yr)	Err. \pm	Calibrated radiocarbon age (BP)	Err. \pm	68% range (cal. BP)
8	Beta-184042	18,440	160	22,120	290	21,714–22,396
23	Beta-196782	23,360	320	28,190	300	27,666–28,698
15	Beta-185345	23,780	540	28,740	600	28,072–29,321
16	Beta-196775	24,010	320	28,920	450	28,406–29,326
9	Beta-196785	26,070	360	30,950	410	30,585–31,410
17	Beta-196773	26,400	440	31,160	440	30,714–31,612
11	Beta-185344	27,020	480	31,700	380	31,178–32,097
10	Beta-196784	28,360	480	32,870	510	32,320–33,413
18	Beta-196791	28,570	480	33,050	540	32,461–33,624
19	Beta-196779	29,400	540	33,700	490	33,182–34,182
12	Beta-196786	29,910	600	34,100	520	33,535–34,606
14	Beta-196792	30,310	620	34,540	530	33,997–35,206
20	Beta-196776	30,560	720	34,770	600	34,185–35,501
13	Beta-196787	31,480	740	35,760	910	34,865–36,750
25	Beta-196772	31,780	720	36,220	1130	35,084–37,293
26	Beta-196789	32,100	800	36,570	1190	35,398–37,796
30	Beta-196771	32,560	780	37,000	1110	35,952–38,178

of representative marine and continental records. We also examine how local geomorphological characteristics correspond to climatic variations and how these events coincide with *H. spp.* population hiatuses in Gorham's Cave.

2. Topographic, climatic and Quaternary historical context of the study region

Gorham's Cave is located in the Gibraltar promontory (southernmost tip of Iberia; Fig. 1). It was repeatedly occupied by *H. spp.* populations and was not covered by glaciers during Pleistocene glaciations (Finlayson et al., 2006; Carrión et al., 2008). The limestone substrate in this region contributed to the development of caves and shelters with a unique potential for preserving human and environmental records (Finlayson et al., 2008a). In addition, this area underwent uplifting, which prevented the significant loss of deposit during periods of sea-level rise (Rodríguez-Vidal et al., 2004). Therefore, this unique setting resulted in an excellent archeological record close to the adjacent narrow Alborán marine basin, which is characterized by exceptionally high sedimentation rates, with continuous sedimentary records that allow precise climatic reconstructions (Cacho et al., 2002; Moreno et al., 2005; Martrat et al., 2007; Jiménez-Espejo et al., 2008; Rodrigo-Gámiz et al., 2011).

This region is also characterized by active seismicity linked to tectonic boundaries between the African and Iberian plates. Two major seismogenic zones are identified, one in the west, from Cape St. Vincent to the Gulf of Cádiz area (Baraza et al., 1999; Thiebot and Gutscher, 2006) and the other in the East Alboran Sea basin (Gracia et al., 2006). Evidence from the former indicates that high magnitude earthquakes took place within the Gibraltar area over time (Baptista et al., 1998; Ruiz et al., 2005; Gracia et al., 2006; Gutscher et al., 2006; Vizcaino et al., 2006). Such seismic activity may have also impacted the coastal environments (Benavente et al., 2006; Rodríguez-Vidal et al., 2011).

3. Climate records and age models

The climate record for the studied period was gathered from marine and continental archives. A marine sediment core (TTR-300G, Fig. 1a) from the westernmost Mediterranean Sea, in the Alborán Sea basin, was analyzed at very high resolution. The age model for this core is based on five ^{14}C -AMS dates obtained from monospecific planktonic foraminifera (*Globigerina bulloides*) at the Leibniz-Labor for Radiometric Dating and Isotope Research and Poznan Radiocarbon Laboratory. The ages were calibrated to calendar years (cal. yr BP) using Calpal software (Weninger et al., 2011) (Table 1). Stable oxygen

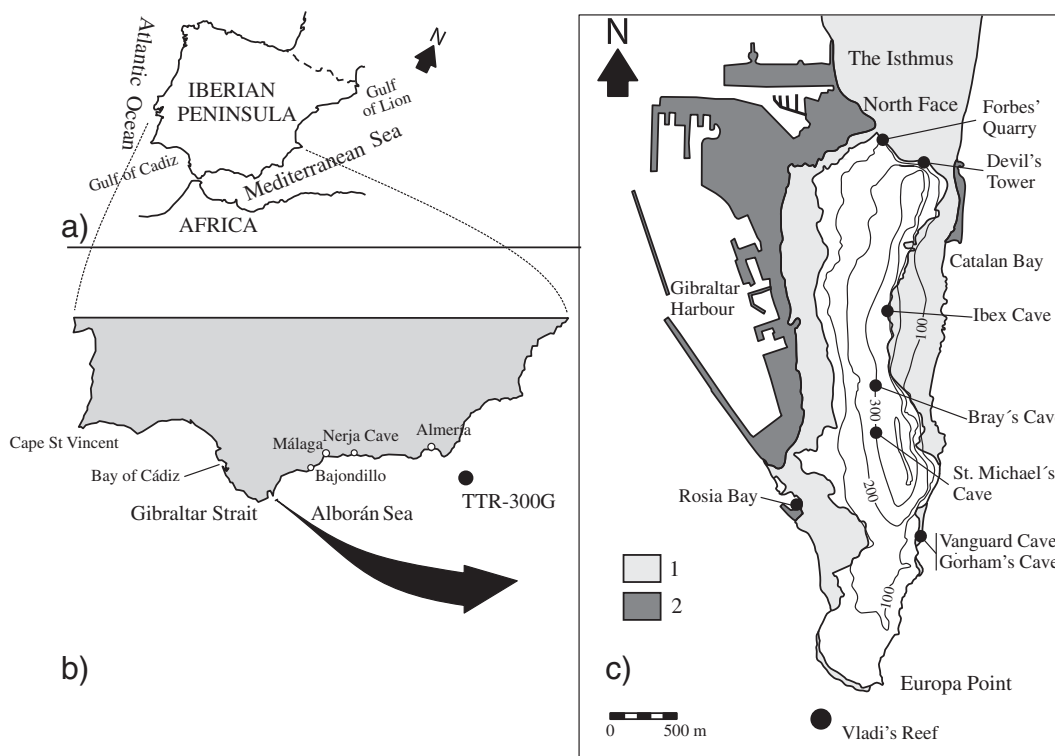


Fig. 1. a) Location of the Iberian Peninsula. b) Locations of the studied South Iberia continental outcrops and marine core TTR-300G. c) Detailed map of the Gibraltar promontory caves and archeological deposits studied. 1: Light gray indicates Late Pleistocene deposits; 2: dark gray indicates land reclaimed from the sea.

isotope stratigraphy and paleo-sea surface temperatures (SST) of the core were compared with the Greenland Ice Sheet Project 2 (GISP 2) ice-core (Grootes et al., 1993) and the comparison was used to refine the age model. Specifically, the strong relationship between SST oscillations and the Dansgaard–Oeschger (D–O) stadials (e.g., Cacho et al., 1999; Moreno et al., 2005) was used to constrain the ages. The average sedimentation rate in the core was 9.4 cm/ka for the represented period, and oscillated between ~6 cm/ka and ~17 cm/ka during the Heinrich periods (H), giving a time resolution from ~170 to ~50 years for each sample.

Dates for continental records were determined on pure calcite samples from speleothems and other cave deposits (e.g., calcite flowstone seals). Ages were based on U-series (Laboratory of Física Aplicada I, University of Sevilla, Spain) and ^{14}C -AMS methods (Radiocarbon Laboratory, CNR Roma, Italy). We used an α -spectrometry analytical method to determine the activities of the U-series isotope (Alcaraz-Pelegrina et al., 2012). All given uncertainties were based on propagated errors from counting statistics and presented at the $\pm 1\sigma$ (standard deviation) level. In the case of non-pristine calcite samples, several coeval samples, diluted with different HNO_3 concentrations, were analyzed and the ISOPLOT program (Ludwig, 1991) was used to obtain activity ratios and ages (University of Seville Laboratory, Spain).

3.1. Material and methods

The location and relief of the studied area is shown in Fig. 1. Key sites for understanding *H. spp.* environments spanning the period between 20 and 40 ka are Forbes' Quarry, Devil's Tower, Rosia Bay, Vanguard Cave North, and Gorham's, Bray's, and St. Michael's Caves (Fig. 1c). At a regional scale, the geological outcrops are located in the Bay of Cádiz and Málaga coast.

The records from these sites are compared to a high resolution (1.5 cm sampling) climate reconstruction of the past 40 ka obtained

from the marine record, TTR-300G (black point Fig. 1b). This core was collected during the TTR-Cruise 14-Leg 2 in the eastern Alborán basin. Previous core analyses in this region also confirm the uniqueness of the Alborán Sea record for paleoclimatic reconstruction (e.g., Cacho et al., 2002; Combourieu-Nebout et al., 2002; Martrat et al., 2004). Sediments in the core are grayish olive nannofossil clay and nannofossil-rich silty clay with highly homogeneous coloration (Comas and Ivanov, 2006). Mineralogical and geochemical analyses were performed for paleoclimatic reconstruction.

Major element (Si, Al, and Mg) measurements (Figs. 2 and 3) were obtained by X-ray fluorescence (XRF; Bruker AXS S4 Pioneer) with an analytical error of 2%. Analyses of trace elements (Ba and Zr) were conducted using inductively coupled plasma-mass spectrometry (ICP-MS; Perkin-Elmer Sciex Elan 5000) following $\text{HNO}_3 + \text{HF}$ digestion. Measurements were made on triplicates with Re and Rh as internal standards. Variation coefficients determined by the dissolution of 10 replicates of powdered samples were 3% and 8% for concentrations of 50 ppm and 5 ppm, respectively (Bea, 1996).

Stable oxygen isotope ratios of calcareous foraminifers from core 300G were also measured. Approximately 25 specimens of *G. bulloides* were picked from the $> 125 \mu\text{m}$ fraction and senescent forms were avoided. Foraminifers were cleaned in an ultrasonic bath to remove fine-fraction contamination, rinsed with distilled water, and thoroughly washed in alcohol. Stable isotopes were measured using a Finnigan MAT 251 mass spectrometer (Isotope Laboratory, Marum, University of Bremen, Germany). All $\delta^{18}\text{O}$ data are reported relative to the PDB standard. Analytical reproducibility of the method is approximately $\pm 0.07\%$ for $\delta^{18}\text{O}$.

Using planktonic foraminifera assemblages, paleo-sea surface temperatures (SST) estimates for winter and summer were calculated as the mean temperature of three colder and warmer months, respectively. Transfer functions were based on González-Donoso and Linares (1998) who examined more than 300 modalities and used modern analog techniques (MAT) to estimate SST values. We selected

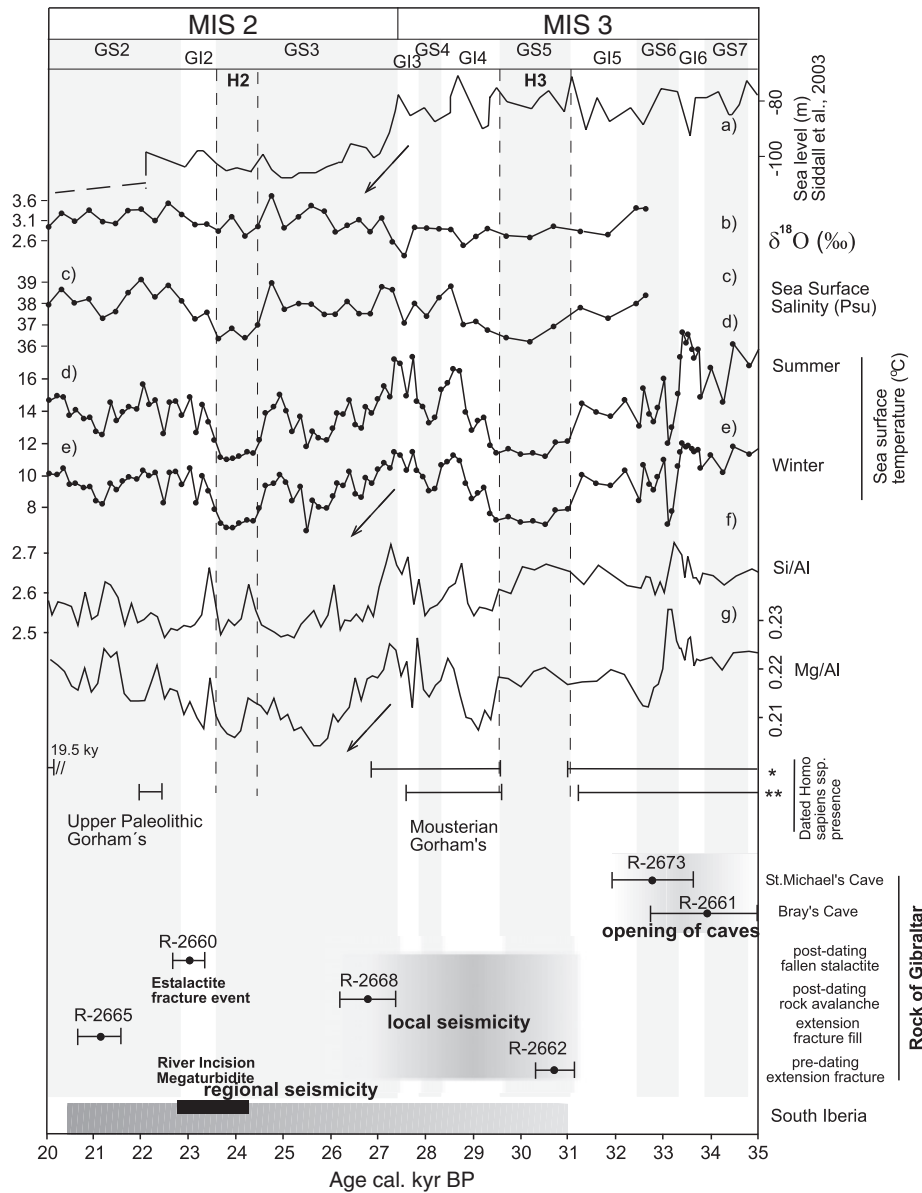


Fig. 2. Integration of marine and terrestrial data. (a) Sea level (Siddall et al., 2003). Core TTR-300G age profiles of: (b) $\delta^{18}\text{O}$ *Globigerina bulloides* (‰). (c) Paleo-sea surface salinity (Psu). (d) Sea surface temperature during summer ($^{\circ}\text{C}$). (e) Sea surface temperature during winter ($^{\circ}\text{C}$). *Homo* spp. presence in Gorham's Cave plotted versus calibrated age – * following Calpal calibration software (Weninger et al., 2011) and ** following the calibration method proposed in Tzedakis et al. (2007). The black bar indicates estimated ages for river-incision events (Schulte et al., 2008) and megaturbidite deposit (Owen et al., 2007). The degraded gray bar indicates reconstructed local (Gracia et al., 2008) and regional seismicity events. The event chronology proposed by the Integration of Ice-core, Marine and Terrestrial records (INTIMATE) group (Lowe et al., 2008) is indicated. Gray bars indicate Greenland Stadials (GS). The dashed line indicates Heinrich event time intervals (H).

the ten closest core top samples of the calibration database (i.e., those that show lowest dissimilarity) for each core sample analyzed and calculated the mean SST value, weighting inversely the modern analogs selected as a function of their dissimilarity to the core sample. The SST associated with each sample was obtained from the archives of the National Oceanographic Data Center (NODC) (Conkright et al., 2002). For more information about paleo-SST calibration data set, see Serrano et al. (2007).

Marine and continental records were correlated using ^{14}C ages. This requires an acceptable calibration curve for ^{14}C . Prior to 26,000 cal. yr BP, however, there is no consensus between different calibration curves, and differences among models strongly affect the calculated ages (Bard et al., 2004). Accordingly for the Gorham's Cave sequence two independent calibration curves were used (Fig. 4a, b); those

proposed by Tzedakis et al. (2007) and Calpal software (Danzeglocke et al., 2011; Weninger et al., 2011).

3.2. Inorganic geochemical marine proxies

Excess Ba is used as a paleo-productivity proxy. This is a well established proxy that capitalizes on the relation between biologically mediated barite formation in the water column and its accumulation in marine sediments (Paytan et al., 1996; Eagle et al., 2003). Ba content also depends on sediment provenance, sedimentation rates, barite preservation, Ba cycling within sediments and lateral transport (Mercone et al., 2001; Sanchez-Vidal et al., 2005). These factors can compromise the Ba excess signal, and Ba-based proxies must be used with caution. Nevertheless, Ba based proxies have been used

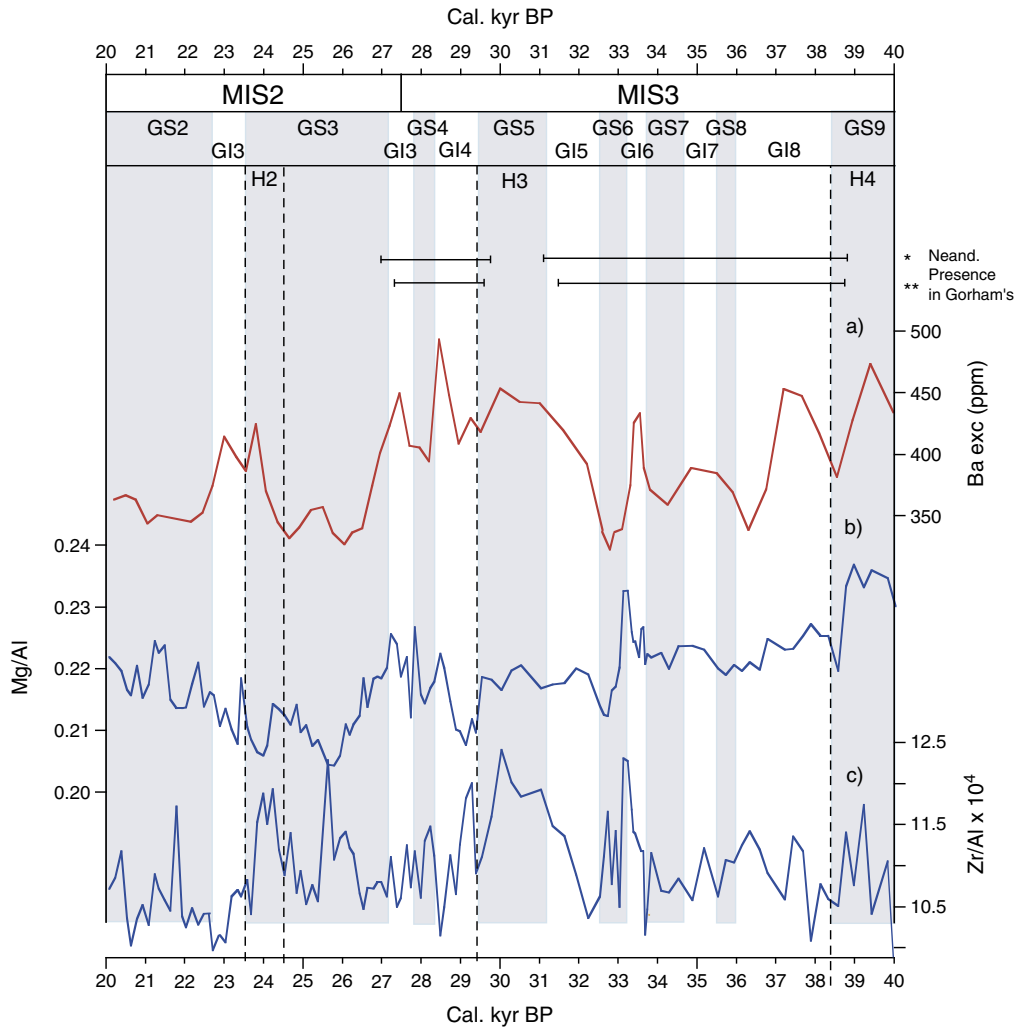


Fig. 3. Core TTR-300G age profiles of: (a) Ba excess (ppm); (b) Mg/Al ratio; and (c) Zr/Al ($\times 10^4$) ratio. The event chronology proposed by the Integration of Ice-core, Marine and Terrestrial records (INTIMATE) group (Lowe et al., 2008) is indicated. Gray bars indicate Greenland Stadials (GS), white bars indicate Greenland Interstadials (GI). The dashed line indicates Heinrich event time intervals (H). * Age calibrated following Calpal software. ** Age calibration following the method proposed by Tzedakis et al. (2007). R-number corresponds to laboratory ^{14}C date code and 1σ uncertainty (Table 3).

extensively for paleoproductivity reconstructions in the Mediterranean basins, and seem to be reliable (e.g., Dehaire et al., 1987; Emeis et al., 2000; Martínez-Ruiz et al., 2000, 2003; Weldeab et al., 2003; Paytan et al., 2004; Nieto-Moreno et al., 2011). We note that no indications for barite dissolution have been observed at this site.

Si/Al, Mg/Al and Zr/Al ratios in the Mediterranean region have been extensively used as proxies for terrigenous input or sediment supply that can be linked to environmental conditions in the source areas (e.g., Wehausen and Brumsack, 1999; Martínez-Ruiz et al., 2000; Moreno et al., 2002; Weldeab et al., 2003; Frigola et al., 2008). Recent studies demonstrate that variations in Zr/Al ratio is mainly relate to Sahara input, because Sahara dust is the main source for heavy minerals into marine basins (Rodrigo-Gámiz et al., 2011). Variations in Mg and Si content show a more complicate pattern in this basin because they can be relate with different detrital or carbonate phases such as chlorite and dolomite in the case of Mg or Quartz and other silicates in the case of Si. However, increase in Mg/Al and Si/Al are mainly inversely correlated with Zr and used in conjunction with Zr/Al ratios.

4. Results: correlations of continental and marine records

The two independent ^{14}C age models of the Gorham's Cave sequence show almost identical results (Fig. 4). Thus, we accept these

data as valid for correlation of marine and continental records. Cave openings, slope breccias, and stalactite falls were dated using radiocarbon and U-series methods in calcite flowstone seals (Tables 3 and 4). Obtained dates and extensive fieldwork were used to determine the timing of local seismic activity that resulted in the geomorphological changes summarized in Table 3 and Fig. 2 (Mattey et al., 2008; Rodríguez-Vidal et al., 2008). The regional paleoseismic evolution is based on data from the Bay of Cádiz and Upper Pleistocene beach deposits published in Gracia et al. (2008). Regional comparisons between coeval structures suggest a vertical tectonic uplift of about 25 m ($\sim 0.6 \text{ mm yr}^{-1}$ for the last 30 ka). An extensive review of relevant data indicates massive tectonic activity in the region from 22 to 25 cal. kyr BP, specifically, in the vicinity of the last Neanderthals' cave occupation in Gibraltar, between 28 and 30 cal. kyr BP (Fig. 2).

The new results from high resolution analysis of the marine sediment record are plotted in Figs. 2b, c, d, e, f, g and 3a, b, c. Proxy interpretation can be found in Rodrigo-Gámiz et al. (2011) and references therein. These records show oscillations in SST and salinity (Fig. 2c, d, e), ocean productivity ($\text{Ba}_{\text{excess}}$) (Fig. 3a), and fluvial–detrital/aeolian input (e.g. Si/Al, Mg/Al and Zr/Al) (Figs. 2 and 3). Based on the marine record, the lowest temperatures (7°C during winter), higher productivity ($\text{Ba}_{\text{excess}}$), and highest aeolian/detrital input were during Heinrich

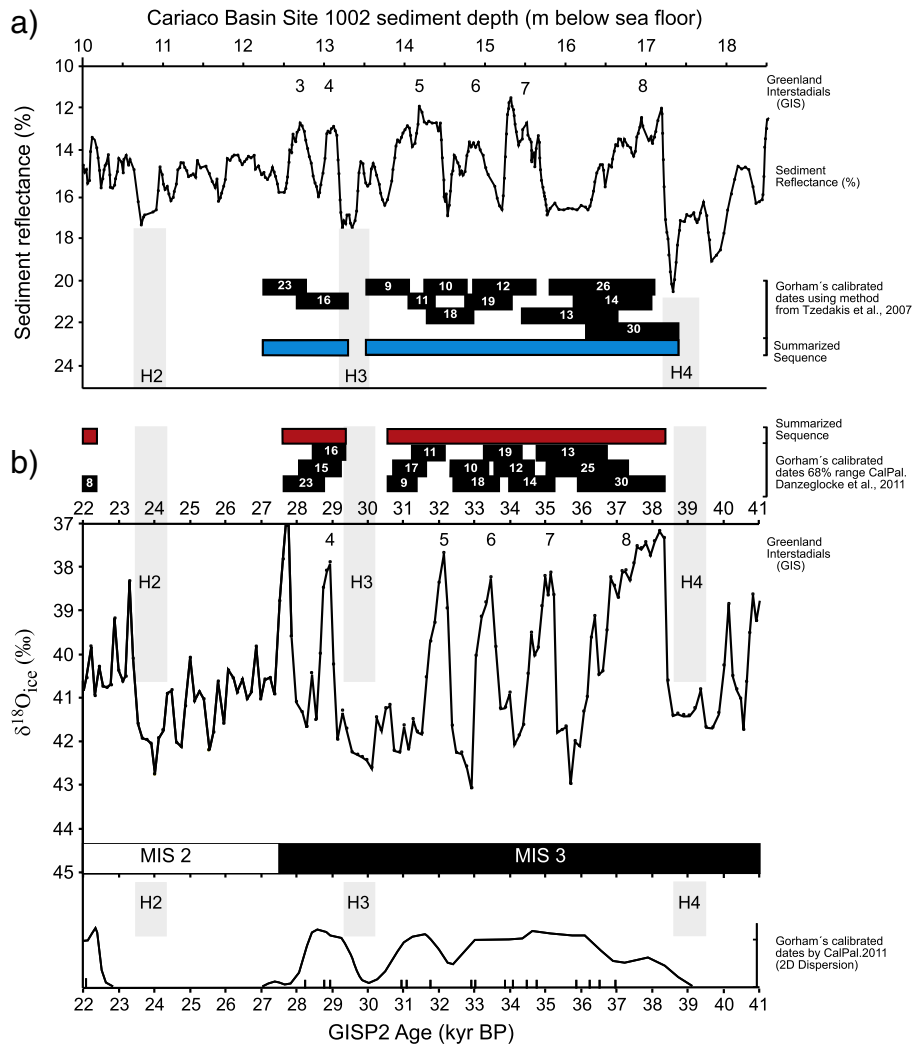


Fig. 4. a) Mapping GORHAM'S CAVE ^{14}C dates onto the paleoclimate record of the Cariaco Basin as proposed in Tzedakis et al. (2007). Sediment reflectance at 550 nm wavelength (green) is a proxy for organic carbon content and corresponds to upwelling, trade-wind intensity and nutrient runoff. Millennial-scale climate oscillations are numbered according to the corresponding Greenland Interstadials (GIS), and Heinrich events (H2, H3 and H4). Numbers in black bars correspond to those given by Finlayson et al. (2006) for specific radiocarbon measurements in GORHAM'S CAVE. The width of the black bar reflects depth uncertainty in ^{14}C dates. Blue bars summarize the *H. spp.* presence in GORHAM'S CAVE. Gray vertical bars indicate Heinrich events (H2, H3 and H4). b) Calibrated GORHAM'S CAVE ^{14}C dates follow the calibration software (Danzeglocke et al., 2011; Weninger et al., 2011) mapped in the GISP2 curve. The width of the black bar reflects 1σ uncertainty, following radiocarbon convention. Red bars summarize the *H. spp.* presence in GORHAM'S CAVE.

periods H4, H3 (Marine Isotope Stage 3; MIS 3), and H2 (MIS 2), corresponding to ~40, ~30, and ~24 cal. kyr BP respectively (Fig. 3b, c). In general, D–O interstadial conditions are characterized by relatively high temperatures, high productivity levels, low aeolian input, and relatively low detrital input. D–O stadial conditions in contrast were distinguished by low temperatures, low marine productivity, high aeolian input and highly variable detrital input, although aeolian inputs were not as extreme as during H4, H3, and H2 (gray bars Figs. 2 and 3). These data are consistent with previous studies throughout the Alboran Sea basin (e.g. Cacho et al., 2002; Moreno et al., 2005; Fletcher and Sánchez Goñi, 2008), with the exception of the high productivity seen during the Heinrich events.

5. Discussion

Slope-erosion events from 35 to 32 cal. kyr BP appear to be related to transitions associated with Dansgaard–Oeschger (D–O) cycles: Greenland Stadial 7 (GS-7), Greenland Interstadial 6 (GI-6), and GS-6, according with the nomenclature proposed in Lowe et al. (2008). These events are identified in the marine record as sharp

increases in detrital input, as indicated by high Mg/Al and Si/Al ratios (Fig. 2f, g). Obtained and reviewed data do not identify any significant tectonic activity, pointing to climatic changes, specifically dry intervals, as triggering factors for slope-erosion events. Climate impacts on geomorphology in this region have been previously described (e.g., Goldberg and Macphail, 2006; Schulte et al., 2008), and changes in sedimentation rates associated with increased terrigenous input in marine records have also been described for this period (from GS-7 to GS-6) (e.g. Moreno et al., 2004; Sánchez Goñi et al., 2008). The observed correspondence indicates the utility of Mg/Al and Si/Al ratios not only as proxies of fluvial input, but also as recorders of high detrital input events, such as those caused by high erosion during rapid climate changes (Rodrigo-Gámiz et al., 2011).

Rock avalanches in Gibraltar between ~29 and 27 cal. kyr BP (Fig. 2, Table 3) correspond with the D–O GI-3 and GS-3 transition, despite dating uncertainties. Between 28 and 27 cal. kyr BP also, a major drop in sea level occurred, mirrored by SST and detrital proxies Mg/Al and Si/Al (see black arrow in Fig. 2). These simultaneous changes point to strong marine–land connections, as proposed by Goldberg and Macphail (2006), and indicate that some slope instabilities seen at the Gibraltar

Table 3

Results of AMS ^{14}C carbon dating of calcite flowstone taken from different Gibraltar outcrops and event interpretation. The calibration was performed using Calpal2007_Hulu (Weninger et al., 2011) software.

Location/ Dated event	Lab. code	Field no.	^{14}C age (yr)	Calibrated age (1σ)
Vanguard North/ Paleoseismic stalactite-fall event sealed by carbonate flowstones	R-2660	GB 0312	19,300 ± 200	23,060 ± 320 cal. BP
Forbes' Quarry/ Seal surface post-dating huge rock avalanche event	R-2668	GB 0011	22,300 ± 500	26,850 ± 670 cal. BP
Forbes' Quarry/ In situ shell associate to ephemeral lake associate to Aeolian Dune deposit	Beta 228878	GB 0701	39,210 ± 480	
Forbes' Quarry/ In situ shell contain in minor lake associate to Aeolian Dune deposit	Beta 228879	GB 0702	40,650 ± 450	
Rosia Bay/ Horizontal in situ speleothems	R-2662	GB 0314	26,200 ± 500	30,820 ± 320 cal. BP
Rosia Bay/ Carbonate deposits infilling extensional cracks associated to huge submarine landslide	R-2665	GB 0301	17,700 ± 250	21,110 ± 410 cal. BP
St. Michael's Cave/ Carbonate deposit with first external detrital input associate to cave opening	R-2673	GB 0002	29,200 ± 800	32,800 ± 910 cal. BP
Bray's Cave/ Carbonate deposit with first external detrital input associate to cave opening	R-2661	GB 0208	28,130 ± 550	33,920 ± 1170 cal. BP

promontory were most likely a regional phenomenon throughout the surrounding Alboran Sea high relief region.

The origin of this correspondence illustrates the role of climate in controlling chemical/physical weathering and vegetation cover in this region (Turon et al., 2003; Fernández-Salas et al., 2008) and sea-level triggering slope stability (Mienert et al., 2003). Such relationships between climate, vegetation cover, weathering, detrital input to the basin and eustatic signals have been described in other areas (Marsaglia et al., 2004; Borgatti and Soldati, 2010; Bourget et al., 2010; Schneider et al., 2010). In the Mediterranean region the intensities and amounts of soil loss and runoff on sloping land are governed by rainfall patterns and vegetation cover (e.g., Durán Zuazo et al., 2006). In the South Iberia margin, close to the marine site studied, alpine mountain chains (>3000 m above sea level) with high slopes are located close to the coast. Such conditions are conducive to extreme erosion rates (Calvache et al., 1997; Pérez-Peña et al., 2010). Indeed, recent studies in the Iberian Peninsula demonstrate that rapid climate transitions towards arid conditions enhance flood erosion events (e.g., Domínguez-Villar et al., 2012). Our marine and continental records are both indicative of climatically- and eustatically-induced erosion events in the region.

Nevertheless, not all climate change transitions indicated by the marine core appear to be recorded in the continental records, and vice versa. This may be related to the pre-conditioning, feedback, and threshold characteristics of natural processes (e.g., Goldberg and Macphail, 2006). To investigate the potential impacts of environmental change and particularly climate changes on human populations we compare the physical/environmental records with cave occupation records. Archeological data indicate *H. spp.* Mousterian occupation in Gorham's Cave between ~39 and 28 cal. kyr BP with three occupational hiatuses in the following order: from ~40 to 38.5, from ~30.5 to 29.3, and from ~28 to 22.5 cal. kyr BP, when *H. spp.* Upper Paleolithic technologies appear in the record. The persistence of *H. spp.* occupation at this site is a testimony to the high level of adaptation of *H. populations* to the different climate and environmental changes that took place (e.g., Finlayson and Carrión, 2007). The recorded hiatuses warrant comparison with the timing of climatic and geomorphological changes.

Described cave openings associated to slope-erosion during the D–O GS-7, GI-6, and GS-6 do not appear to have affected the settlement of

Gorham's Cave. Only during the Heinrich periods, characterized by cold, arid, and windy conditions (Figs. 2 and 3), and associated with major oceanographic changes (Sierra et al., 2005, 2009), is abandonment of the Gibraltar area observed. The relationship between erosive unconformities and other hiatuses promoted by paleo-environmental changes have been described in other circum-Mediterranean regions during the MIS 3 (Aubry et al., 2011; Müller et al., 2011). However, *H. spp.* populations remained in other South Iberian locations during these periods (Cortés-Sánchez, 2007). The different response of the population in Gibraltar compared to other sites may suggest that the hiatuses in Gibraltar might have been caused by local factors rather than regional climate impacts. Local conditions that can limit occupation include reduction in access to caves due to blocking of cave entrances. Indeed, our study indicates that paleo-dunes were ubiquitous in Gibraltar and movement of such dune systems can block cave entrances. For example, Forbes' Quarry was sealed by dunes between 40,650 and 39,120 cal. yr BP when dunes completely filled the Ibex Cave (300 m asl) (Fig. 5). Dates from Gorham's Cave entrance indicate a reduced entrance to the cave since 47.5 cal. kyr BP, and several undated dune progradation episodes may have occurred after this time (Figs. 6 and 7). These records imply high sensitivity of the surrounding Gorham's area to dune deposits, or some other cave-blocking phenomenon (Figs. 6 and 7). The inferred dune accumulations would seem to correspond to episodes of major aeolian input seen in marine cores during H4 period (Fig. 3) and strong dune system activity has been observed during Heinrich events in other Mediterranean locations (Roskin et al., 2011). Dune development is a reliable proxy for past windiness (Telfer and Thomas, 2006), and it is possible that during these periods with intense winds, high aeolian input and dune advance, cave access/hospitality conditions deteriorated to led to cave abandonment. In addition, intense tidal level variations took place during Heinrich periods (Arbic et al., 2004), making the rocky intertidal zone more exposed. In such conditions the opportunity of coastal foraging activities increases and populations are likely to move to coastal areas. Indeed, the use of shellfish has been a resource for *H. spp.* (Colonese et al., 2010) and evidence of gathering and consumption of molluscs can be traced back at least 150 ka in this area (Cortés-Sánchez et al., 2011). Therefore, the upper Gibraltar cave system including Gorham's Cave, appears to have been less attractive to occupation during H4 and H3.

Table 4

Activity ratios and U/Th analytical results from flowstone layers in Gorham's Cave stratigraphy (see Fig. 6).

Sample	^{238}U	^{234}U	^{230}Th	^{232}Th	$^{234}\text{U}/^{238}\text{U}$	$^{230}\text{Th}/^{232}\text{Th}$	$^{230}\text{Th}/^{234}\text{U}$	T (ka BP)	$^{234}\text{U}/^{238}\text{U}$
GB0704a	4.80 ± 0.10	5.22 ± 0.11	1.85 ± 0.05	0.059 ± 0.007	1.089 ± 0.019	31.2 ± 3.9	0.3546 ± 0.0124	47.2 ± 2.1	1.101 ± 0.021
GB0704b	6.90 ± 0.10	7.31 ± 0.11	2.77 ± 0.07	0.016 ± 0.004	1.059 ± 0.010	176 ± 40	0.3789 ± 0.0116	51.4 ± 2.0	1.068 ± 0.011

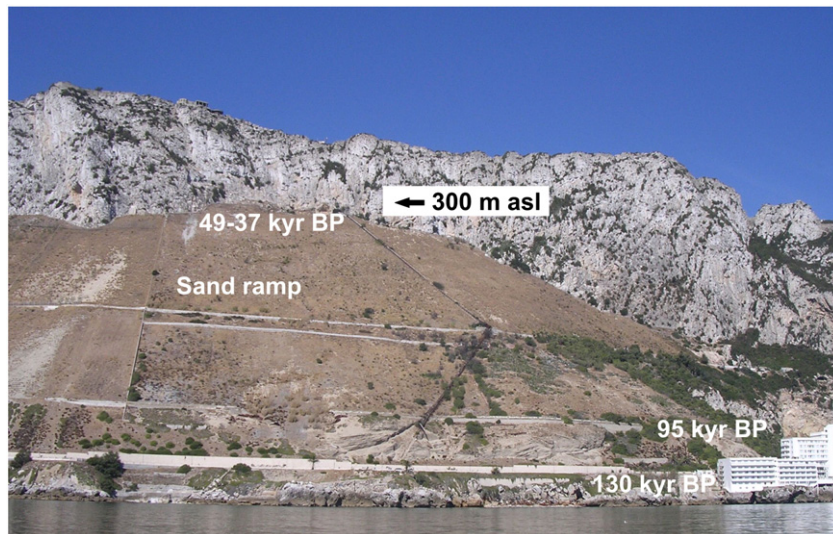


Fig. 5. Catalan Bay sand ramp (eastern side of the Rock) covering Ibx Cave (top of the ramp) and dated levels. In spite of the homogenous appearance, sand ramp is composed of consecutive arid episodes where erosion and deposits correspond to different environmental conditions.

In order to obtain shellfish resources, populations could have been moved to coastal areas such as that the lower Gibraltar cave system (e.g., Vladis Reef; Fig. 1 and Rodríguez-Vidal et al., 2011), or the Iberian Atlantic side (Fa, 2008). Although this affirmation could be coherent with the increase in marine productivity proxies during Heinrich periods (Fig. 3a), more data are needed to corroborate this hypothesis.

The last Gorham's archeological hiatus between 28.0 and 22.5 cal. kyr BP represents the transition from the last *H. spp.* populations using Mousterian industries to the first *H. spp.* Upper Paleolithic levels of occupation. We observed that this time interval is characterized by progressive cooling in SSTs (see black arrow in Fig. 2f) and winter SST below 7 °C were reached. This progressive cooling was coupled with severe droughts that occurred between 28.0 and 25.5 cal. kyr BP (e.g., Beaudoin et al., 2007). Despite the cold conditions, it is important to note that large cold-adapted fauna were almost absent in the North and South Iberian Peninsula between 31 and 26 cal. kyr BP (Álvarez-Lao and García, 2010). Another distinctive feature of this last hiatus is sea-level variation, with falls of >20 m (Siddall et al., 2003) (Fig. 4a). Simultaneously, the studied records show that the riverine input reached a minimum (Fig. 3b) and the

aeolian input reached a maximum at 25.5 cal. kyr BP (Fig. 3c), probably of the same age of the undated dune progradation episodes that almost filled Gorham's Cave entrance (Fig. 7).

Following this time interval (between 28.0 and 25.5 cal. kyr BP) and specifically during H2, the conditions became even more extreme both globally and regionally (e.g., Bout-Roumazielles et al., 2007; Jiménez-Espejo et al., 2007). The period is characterized by high atmospheric dust transport to Greenland (Rohling et al., 2003) and very cold SSTs (Martrat et al., 2004, 2007 and this study). These changes promoted intense winds from the Sahara and an increase in aeolian deposition in South Iberia (Bout-Roumazielles et al., 2007; Costas et al., 2012). This intense aeolian activity and dryness is recognized by low fluvial input in the studied marine record (Fig. 2f, g), but also throughout the entire Mediterranean, and from the western regions (e.g., Combourieu-Nebout et al., 2002; Weldeab et al., 2003; Jouet et al., 2006; Fernández et al., 2007; Naughton et al., 2009) to the Levant (Bartov et al., 2003; Vaks et al., 2007).

In addition to the global climatic impacts, at a local scale, a broad period of intense seismic activity apparently occurred during H2. Our data indicate major stalactite falls and landslides (Fig. 2) probably

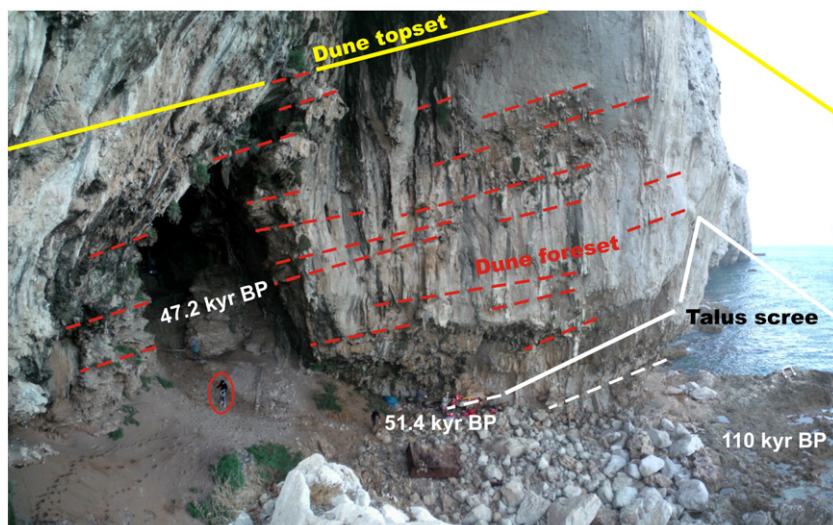


Fig. 6. Gorham's Cave entrance with dated and reconstructed cliff-front dune. White solid and dashed lines indicate rock avalanche overlying a MIS 5 marine beach. The yellow solid line represents inferred dune morphology. Red dashed lines indicate preserved dune foreset boundaries. For scale, see researcher surrounded by the red circle.

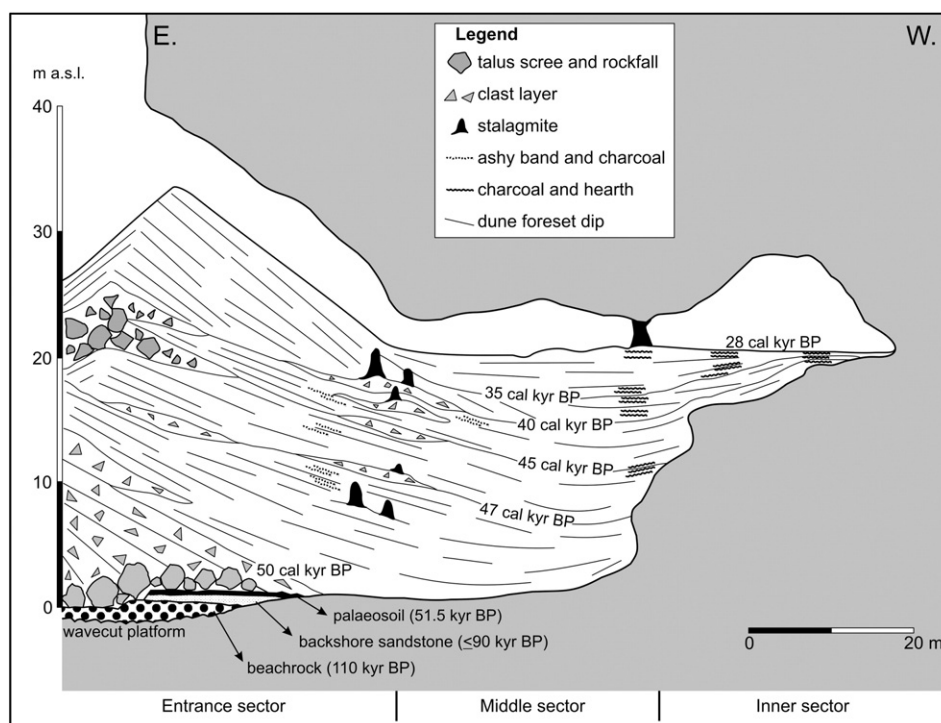


Fig. 7. Geological interpretative section of Gorham's Cave after previous publications (Waechter, 1951, 1964; Goldberg and Macphail, 2000; Pettitt and Bailey, 2000; Finlayson et al., 2006, 2008a) and this work. Middle Paleolithic occupation, morphosedimentary features and chronological evolution.

related to earthquakes (Bolt, 2004) during this time interval. Evidence of coetaneous instabilities is recognized in other geo-systems along the Cádiz coast (Gracia et al., 2008) and in two nearby archeological sites, Nerja Cave and Bajondillo Cave (Cortés-Sánchez et al., 2004; Cortés-Sánchez, 2007). In the latter, located 90 km east of Gibraltar, an instability event was dated at circa 24.3 cal. kyr BP by thermoluminescence. These events have been interpreted as paleo-seismic block falls and they are associated with a sedimentary hiatus between 24.3 and 22.1 cal. kyr BP (^{14}C -AMS) (Cortés-Sánchez et al., 2004; Cortés-Sánchez, 2007). In Nerja Cave, the fallen blocks from the ceiling indicate seismic activity between 25.6 ± 4.8 and 23.4 ± 2.3 ka (Cortés-Sánchez et al., 2004) and a sedimentary hiatus has been observed between 21 and 19 cal. kyr BP (Aura Tortosa et al., 2002). Evidence of the confluence of extreme atmospheric, hydrological, and tectonic events have also been invoked in order to explain the unusual river incision observed in the South Iberian rivers (> 15 m) at this time (Schulte et al., 2008) and the immense size of the megaturbidite ($60,000 \text{ km}^2$ and 500 km^3) deposited in the Balearic basin (Rothwell et al., 1998; Maslin et al., 2004; Owen et al., 2007).

The fluctuating environmental conditions during the stadial and interstadials though the MIS 3 and MIS 2 were also accompanied by changes in fauna. In contrast to the southern France and the Cantabrian–Catalonian regions, the south of the Iberian Peninsula was far from the favorite migration route of large mammals (e.g., Finlayson and Carrión, 2007; Álvarez-Lao et al., 2009; García-Alix et al., 2012), nevertheless, after 25.5 cal. kyr BP, cold-adapted mammals spread along the northern Iberian Peninsula (Álvarez-Lao and García, 2010, 2011). These mammals could have been a factor in new displacements along the Iberian Peninsula, despite no cold faunas has been found during this period in southern Iberia to the present.

6. Conclusions

Correspondence between terrestrial and marine records in the Gibraltar promontory and the Alboran basin point to climate and

sea level changes as major trigger for slopes instability, erosion and detrital input. Major transitions between humid and arid periods are seen during isotopic stages D–O GS-7, GI-6, and GS-6 and GI-3 to GS-3. The Gorham's Cave chronological sequence show three occupational hiatuses associated with the Heinrich periods H4, H3 and H2. The abandonments of the cave during H4 and H3 appear to be linked to the prevailing cold and arid conditions which impact local geomorphologic factors, likely to be coastal dune system activity, and enhanced tidal level variations which encouraged migrations to coastal locations. During the last described hiatus between 28 and 23 ka, a confluence of environmental variations including sea-level fall, harsh temperature oscillations, aridification, river incision processes, and marked seismic activity in the South Iberian Peninsula was the scenario where the *H. spp.* transition occurred.

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