

Sea level and climate changes during OIS 5e in the Western Mediterranean

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A B S T R A C T

Palaeontological, geomorphological and sedimentological data supported by isotopic dating on Oxygen Isotopic Stage (OIS) 5e deposits from the Spanish Mediterranean coast, are interpreted with the aim of reconstructing climatic instability in the Northern Hemisphere. Data point to marked climatic instability during the Last Interglacial (OIS 5e), with a change in meteorological conditions and, consequently, in the sedimentary environment. The oolitic facies generated during the first part of OIS 5e (ca. 135 kyr) shift into reddish conglomeratic facies during the second part (ca. 117 kyr). Sea surface Temperature (SST) and salinity are interpreted mainly on the basis of warm Senegalese fauna, which show chronological and spatial differential distribution throughout the Western Mediterranean. Present hydrological and meteorological conditions are used also as modern analogues to reconstruct climatic variability throughout the Last Interglacial, and this variability is interpreted within the wider framework of the North Atlantic record. All the available data indicate an increase in storminess induced by an increase in the influence of north-westerlies, a slight drop of SST in the northern Western Mediterranean, and an important change in meteorological conditions at the end of OIS 5e (117 kyr). These changes correlate well with the decrease in summer insolation and with the climatic instability recorded in North Atlantic high latitudes.

Keywords:

Sedimentary facies
Senegalese fauna
Meteorological changes
Sea surface conditions
Surface currents
Spain

1. Introduction

The Last Interglacial is correlated with Oxygen Isotope Stage (OIS) 5, and more precisely with OIS 5e. SPECMAP chronology (Martinson et al., 1987; Thompson and Goldstein, 2006) brackets the OIS 5 between ca. 130 (128–127) and 75 kyr, although data from Hawaii and Bermuda suggest an older age for the onset of the Last Interglacial period at ca. 136 kyr (Muhs et al., 2002). Nor is the timing of OIS 5e termination entirely settled, with ages of 116 to 113 kyr having been suggested as the end of this interglacial period (Stirling et al., 1998; Muhs et al., 2002).

According to high resolution ice, marine and terrestrial records, OIS 5 in the Northern Hemisphere exhibits a marked climate instability, as well as significant latitudinal variability and diachrony (GRIP Members, 1993; Kukla et al., 1997; Sanchez-Goñi et al., 1999; Knudsen et al., 2002; Kukla et al., 2002; McManus et al., 2002; Shackleton et al., 2002; Pérez Folgado et al., 2004; CAPE – Last Interglacial, Project Members, 2006). Average summer insolation throughout the Northern Hemisphere (Berger and Loutre, 1991) during the peak of the Last Interglacial (130–127 kyr) was about 11% above that of the present with a significant

latitudinal gradient, as indicated by a summer temperature anomaly 4–5° above present over the Arctic Ocean, and 0–2 °C above present in mid- and low latitudes (CAPE – Last Interglacial, Project Members, 2006). However, the final part of this interglacial is characterized by relatively low summer insolation values.

Northern hemisphere data sets (GRIP Members, 1993; Sanchez-Goñi et al., 1999; Kukla et al., 2002; Shackleton et al., 2002) indicate that after the warmest peak of the OIS 5e (ca. 128 ka), the climate underwent a progressive deterioration, firstly during the latter part of OIS 5e which registered generalized cooling prior to the onset of OIS 5d, and during the following interglacial substages (OIS 5c and OIS 5a).

In the Nordic seas, the onset of OIS 5e was characterized by a strong east–west temperature gradient (Fronval and Jansen, 1997; McManus et al., 2002), reduced during the warmest interval (ca. 126 kyr) and reaching a major sea surface temperature (SST) drop by about 116 kyr (Knudsen et al., 2002). Data from mid- and high-latitude deep-sea cores from the North Atlantic Ocean (McManus et al., 2002) show that as ice sheets began to grow near the onset of OIS 5d, the region stayed generally warm, constituting an ideal moisture source and reinvigorating thermohaline circulation. These features were probably the causes of the anomalous final part of OIS 5e, with growing ice sheets in higher latitudes and still-warm waters and climatic instability in mid-latitudes. At the end of OIS 5e, a millennial-scale cooling event (C25)

was significant in northern and North-western Atlantic latitudes as well as in the Mediterranean (Martrat et al., 2004), although this was less evident in Europe (McManus et al., 2002). However, in tropical settings there is planktonic $\delta^{18}\text{O}$ evidence of a lowering in SST (cooling event C26) not associated to any IRD (Ice Rafted Debris) peak, marking the end of the warmest peak of OIS 5e (Lehman et al., 2002).

In the Alboran Sea, located on the western margin of the Mediterranean Basin and connecting the Atlantic Ocean with the Mediterranean Sea, paleoclimatic data from ODP 977 (Pérez Folgado et al., 2004) show that OIS 5e lasted between ca. 130 kyr and 117 kyr, with a definitive cooling trend starting at 119 kyr. Analyses of Organic Rich Layers (ORL) suggest an increase in rainfall or runoff during warmer substages (i.e. OIS 5e, 5c and 5a) which was responsible for a decrease in sea surface salinity. This would in turn have enhanced water stratification, and, together with high sea surface productivity, would explain the high organic-matter content of these layers.

The sea-level highstands related to these climatic changes remain controversial, particularly with regard to their number and elevation. Interpretations of coral marine terraces in the tectonically stable coasts of Bermuda and the Bahamas are not always in agreement. Some authors point to a single prolonged highstand, with a palaeosea-level located at +5 m above present sea level (a.p.s.l.) between ca. 130 and 120 kyr (Chen et al., 1991; Muhs et al., 2002); other authors suggest two highstands with a prolonged palaeosea-level at +2.5 m and a rapid rise up to +6 m a.p.s.l. with ages of ca. 132–125 kyr and 118 kyr, with an intervening lowstand (–3 m) at ca. 125 kyr (Newmann and Hearty, 1996; Hearty and Newmann, 2001; Hearty, 2002). In the stable margins of Australia, data support one prolonged sea-level highstand (ca. 128–110 kyr) at +3 m a.p.s.l. in Western Australia (Stirling et al., 1998); and at +2 m in Southern Australia (Murray-Wallace, 2002).

In contrast, data from uplifted coasts suggest two highstands at ca. 128–120 kyr in Barbados, located at +2 and 0 m a.p.s.l. respectively (Schellmann and Radtke, 2004) and between ca. 130 and 118 kyr in Haiti, at +5 m and +2 m a.p.s.l. respectively (Dumas et al., 2006). In the Huon Peninsula (New Guinea), highstands have been reported at 134 kyr and 118 kyr (Stein et al., 1993). Recent sea-level analyses from Calabria, Italy, (Dumas et al., 2005) suggest a very different scenario. According to these authors, high tectonic uplift rates allowed an extremely detailed record of sea-level variations during the Last Interglacial, showing at least eleven minor oscillations during OIS 5e and four more during OIS 5c/5a. The chronology of these highstands points to a higher amplitude sea-level rise at 128 kyr, 122 kyr and 116 kyr during OIS 5e, and at 105 kyr and 84 kyr during OIS 5c/5a.

Once the tectonic trend is accounted for and subtracted, the reported inconsistencies concerning palaeosea-level elevation, the number of highstands and their chronology, are partially explainable in terms of the distance from earlier ice sheets; that is, in terms of the relationship between glacio- and hydro-isostatic effects in each of the settings. Data from the far field sites (Australia, Papua New Guinea) should be more accurate due to the less intense post-glacial isostatic rebound, while in the intermediate or near fields (Bermuda and Caribbean islands) glacio-isostatic unloading processes may have assumed much greater importance.

Faced with the diversity of sea-level highstand data, the Mediterranean Sea becomes a key site for understanding the connection between high and mid-latitude climatic changes in the Northern Hemisphere, as well as ocean–atmosphere interactions and their climatic implications in the Mediterranean during the Last Interglacial. Many divergences arise in the number and height of sea-level highstands in the Western Mediterranean. Although tectonic activity prevents the reconstruction of a precise sea-level curve for this basin with absolute heights, other kinds of data can be used as proxies for stating the number of highstands – another controversial and much-debated question. In this paper we attempt to synthesize palaeontological, sedimentological and geomorphological data of OIS 5 deposits from a number of Western Mediterranean countries, in order to reconstruct the palaeoenviron-

mental changes which occurred in this basin during the Last Interglacial, as well as the impact of North Atlantic climate variability on the oceanographic and meteorological conditions of the Western Mediterranean Basin.

2. Present geographical framework and location

Study sites extend all along the south and south-eastern peninsular coast of Spain, as well as in the Balearic Islands (Fig. 1), presenting important oceanographic differences driven by the general circulation in the Western Mediterranean, which also determines a variety of present temperature and salinity conditions.

2.1. Western Mediterranean circulation

The Gibraltar Strait is characterized by a water exchange of Superficial Atlantic Water, flowing towards the east, and a westward outflow of Western Mediterranean Deep Water. As Atlantic water enters into the Alboran Sea, it describes a quasi-permanent anticyclonic gyre in the West and a more variable circuit in the east (Fig. 1).

As Atlantic Water flows into the Mediterranean Sea, it forms a 100–200 m-thick layer of surface water, called Modified Atlantic Water (MAW), (Millot, 1999), or Mediterranean Waters (MWs), (Taupier-Letage and Millot, 2004; Millot and Taupier-Letage, 2005).

Modern circulation in the Western Mediterranean Basin (Fig. 1), has been extensively reviewed by Millot (1999) and Millot and Taupier-Letage (2005). The general circulation pattern involves an important thermohaline component, in a counter-clockwise sense, forced by the Coriolis Effect. After the above-mentioned eastern Alboran anticyclonic gyre, the MAW progress towards the east, along the Algerian slope to the Sardinia Strait, (Algerian Current), describing a series of clockwise coastal eddies.

As this current reaches the Sicily Channel, it bifurcates into two branches. Part of the current moves towards the Eastern Mediterranean Basin, sometimes spreading over the whole Sicily Channel and other times remaining close to the Tunisian coast. The other branch flows northwards along northern Sicily and the Italian Peninsula, surrounding the Tyrrhenian Sea, and continuing along the continental slope around the Gulf of Lyon as far as the Ibiza Channel, where it is then referred to as the Western Mediterranean Northern Current (Fig. 1).

This Northern Current, together with the Alboran anticyclonic gyres, are the main hydrographical features affecting Spanish Mediterranean coast, not only at present but probably during the Last Interglacial as well. North-westerly winds usually affect the Gulf of Lyon, inducing relatively cool surface waters. The Balearic Sea, protected by the Pyrenees, is less windy and consequently contains warmer surface waters, defining the North Balearic Front. A higher influence of north-westerlies during cold seasons in the Gulf of Lyon, forces the North Balearic thermal front towards the Balearics, so that the water becomes the warmest found anywhere in the Western Mediterranean (Millot, 1999). Part of the Northern Current continues southwards through the Ibiza Channel, but with decreasing energy, being deflected towards the Algerian Basin where it meets, between the Capes of Gata and San Antonio, the more energetic flow of more recent MAW.

In summary, the north-eastern peninsular coasts are affected mainly by the cooler superficial Northern Current that emanates from the Gulf of Lyon and moves southwards until it encounters the more recent MAW to the south of the Ibiza Channel. Conversely, southern peninsular coasts are affected mainly by the anticyclonic gyres generated by recent MAW flowing into the Alboran Sea. Meanwhile, the Balearic Islands are affected by the gyres of superficial northern currents that curl around the islands, and by the position of the thermal North Balearic Front. Taking all these features into account, we can assume a significant salinity and temperature gradient between Gibraltar and northern Mediterranean Peninsular coasts.

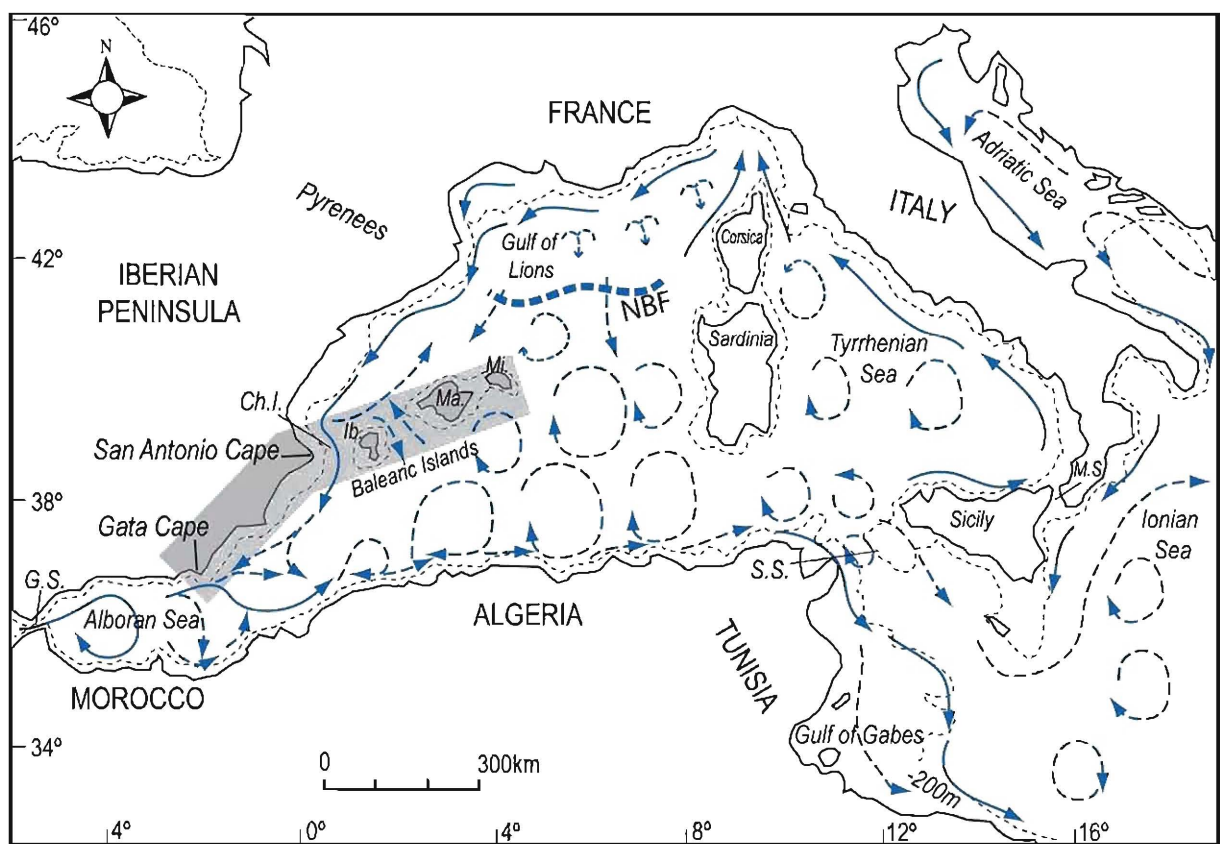


Fig. 1. Scheme of modern circulation in Western Mediterranean (from Millot, 1999), with location of studied areas. NBF: North Balearic Front; G.S.: Gibraltar Strait; S.S.: Sicily Strait; M.S.: Messina Strait, Ch.I.: Ibiza Channel. In Balearic Islands Ib.: Ibiza, Ma.: Mallorca, Mi.: Minorca.

2.2. Present sea surface conditions

As described above, modern circulation in the Western Mediterranean directly affects sea surface characteristics (temperature and salinity) in its various basins and seas. Seasonal atmospheric conditions also influence the distribution and gradient of these parameters.

The increased influence of north-westerly winds in the northern part of the Western Mediterranean during cold seasons produces a significant cooling of surface waters to temperatures <12.4 °C, with salinities of ca. 38.3 and consequently higher densities, provoking a deepening of this so-called Winter Intermediate Water (WIW). However, Western Mediterranean Deep Water (WMDW) constitutes the deepest (below 1000 m deep) and densest of Mediterranean waters (ca. 12.8 °C and salinity 38.4). Formed in the Gulf of Lyon during winter, WMDW flows out of the Mediterranean Sea through the Gibraltar Strait, where it rises in depth from ca. 2000 m to ca. 300 m.

In brief, Atlantic Water presents at Gibraltar a mean temperature of ca. 15–16 °C and salinity of ca. 36–37, and although the Mediterranean waters are seasonally either warmed (up to 20–28 °C) or cooled (down to ca. 13 °C), overall its salinity increases (up to 38–39) and thus also its density, partially due to the negative hydrological budget of this basin (Millot and Taupier-Letage, 2005).

2.3. Present meteorological conditions

Both the direction of prevailing winds and the wind stress conditions affecting these settings are highly variable. The Western Mediterranean is affected mainly by two kinds of winds, north-westerlies (from NW Europe) and south-westerlies (from Africa), both acting within a seasonal framework. Strong north-westerlies sweep across the Iberian Peninsula during cold seasons, blowing over the Western Mediterranean in a SE–E direction (Fig. 2). In summer,

weaker north-westerlies come through the Gulf of Lyon, but rotate around the Balearic Islands and the Sicily Strait towards the west, then generate easterly winds on the Spanish Mediterranean littoral, very close to the ocean–air interface (0–10 m high). The influence of winds from the SW is also reported as having been very important in the Southern Mediterranean (Magri and Parra, 2002; Moreno et al., 2002), especially during the Late Pleistocene and Holocene cold events, with enhanced Sahara dust and pollen transport being recorded. However, these winds are higher in altitude than those capable of having a noticeable influence on wave regimen.

The strongest storms are also related to various meteorological features. Mediterranean Peninsular coasts are affected by late summer or autumn Mediterranean or North African low-pressure cells, linked to significant flooding events and a consequent increase of fluvial discharge into the littoral environment. The Balearic Islands present a marked influence of north-westerlies from the Gulf of Lyon, which generate persistent rain discharges and storm wave surges.

Torrential rainfall in Spain has been related to heated sea surface waters in the Mediterranean during early autumn months, which act as a moisture source, as well as to high-pressure anticyclones centred in Western Europe, which force the flow of colder surface air over the warmer sea (Millán et al., 1995; Pastor et al., 2001).

3. OIS 5 on Spanish Mediterranean coasts

Numerous works have been done in relation to the OIS 5 on Spanish Mediterranean coasts. Such studies have relied on U-series measurements, as well as geomorphological, morphosedimentary and palaeontological analyses, to define the number and timing of the Last Interglacial highstands in Spain (Bernat et al., 1982; Brückner, 1986; Goy et al., 1986; Hillaire-Marcel et al., 1986; Hearty et al., 1986; Hearty, 1987; Causse et al., 1993; Goy et al., 1993; Zazo et al., 1993, 2003; Goy et al., 2006). Whereas

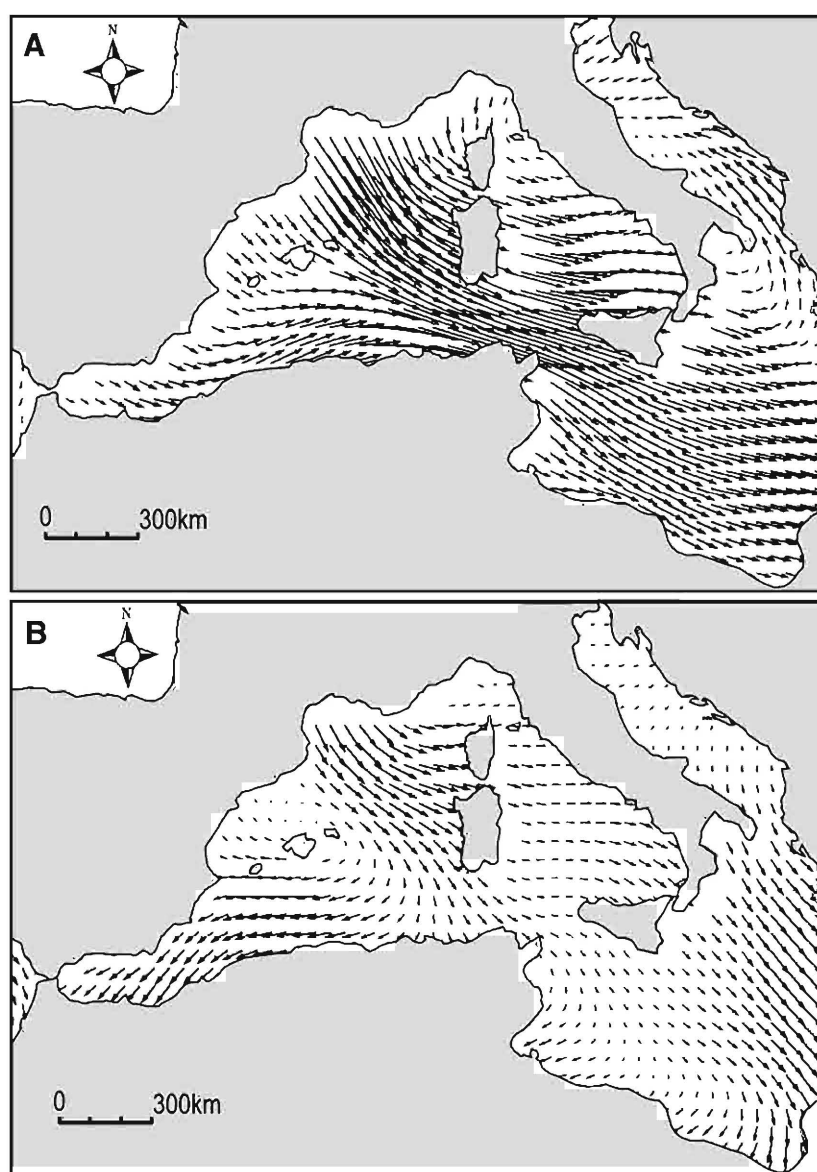


Fig. 2. Wind stress for winter (A) and summer (B) seasons (data for 1986–1992 period, based on monthly values derived from averaging daily means of the wind stress at 10 m above the air–sea interface (from Drakopoulos and Lascaratos, 1999).

the palaeontological record assists in the reconstruction of former sea surface conditions (temperature and salinity), sedimentary facies can be better applied to physiographical, meteorological (and consequently wave regimen) characteristics of earlier coastal settings.

3.1. Palaeontological record

The palaeontological record from OIS 5 can be used as a very precise tool for the reconstruction of sea surface conditions, mainly regarding temperature range, although salinity can also be inferred.

The global climatic optimum experienced during the Last Interglacial is recorded in Mediterranean settings by the presence of warm Senegalese fauna from Equatorial Africa, used as an indicator of warmer-than-present superficial marine waters (Fig. 3). The main species representing this warm fauna are: *Cardita senegalensis*, *Barbatia plicata*, *Conus testudinarius*, *Cantharus viverratus*, *Hyotissa hyotis*, *Cymathium dolarium*, *Patella safiana*, and especially *Strombus bubonius*. However, the record of this warm fauna is neither continuous nor synchronous throughout the Mediterranean, nor along the Mediterranean Spanish coast, nor even along the southern Iberian Peninsula (Atlantic vs. Mediterranean littoral), with some

Senegalese species, especially *S. bubonius*, being absent from the Atlantic settings. Consequently, from this differential distribution, we can attempt to reconstruct the changes in sea surface conditions during the OIS 5 in the littorals studied.

The entry of *S. bubonius* into the Mediterranean is controversial, given its apparent absence from marine deposits other than those of OIS 5e on central and eastern Mediterranean coasts. Nevertheless, in Spain, this particular species has been found as early as OIS 9 or OIS 11 in the Balearic Islands (Zazo et al., 2003), and during OIS 7 on peninsular coasts (Hillaire-Marcel et al., 1986; Goy et al., 1986; Zazo et al., 2003; Goy et al., 2006), with a maximum occurrence during OIS 5e. Moreover, the disappearance of this warm fauna is not coeval in the areas studied. On the Peninsular coasts examined, *S. bubonius* was present during the entire OIS 5, while in the Balearics it disappeared at the end of OIS 5e, even if some warm species did indeed still survive there (Hillaire-Marcel et al., 1996; Zazo et al., 2003).

Differing distributions and abundances are also observed along the peninsular coast from Gibraltar to France, with the maximum number of specimens in OIS 5e units always occurring on the littoral fringe from Almería to Alicante (Fig. 4).

Location of referred sites	Locality	Lat./Long.	SST (°C)*	SST * annual	SSS ** (psu)	Ref. * **
	1. W Mediterranean (Spanish Coast)	41°-35° N 5° W-15° E	12 (winter) 24 (summer)	18	37	(a) (a)
	2. Gulf of Cadiz (Spanish Coast)	37°-36° N 9° -5° W	16,5 (winter) 22,5 (summer)	19, 6	35, 5	(c) (a)
	3. Azores	40°-37° N 31°-25° W	17 (Dec-Jan) 25 (Aug-Sept)	21	36	(a) (a)
	4. Morocco (Atlantic Coast)	34°-30° N 7°- 9° W	17 (winter) 22 (summer)	19, 5	~36	(a) (a)
	5. Canarias (Lanzarote and Fuerteventura)	27°-30° N 18°-13° W	19 (winter) 23 (summer)	21	36, 6	(a) (b)
	6. Cabo Verde (Sal)	15°-17° N 26°-22° W	21-22 (Jan-May) 25-26 (Sep-Dec)	23, 5	35	(a) (a)
	7. Senegal (Dakar)	14° 30' N 17° 30' W	19-21 (winter) 27-28 (summ.)	24	34	(a) (d)

Fig. 3. Distribution of living and fossil Senegalese fauna (from Zazo et al., in press). White shell: *Strombus bubonius* fossil; White shell in grey circle: living *S. bubonius*; White dot: fossil Senegalese fauna; Black dot: living Senegalese fauna; Light-blue continuous line: permanent upwelling; Light-blue dashed line: seasonal upwelling; Blue arrows: Present surface currents. References for SST (*) and SSS (**): (a) NOAA-WOA, 2001; (b) Pelegri et al., 2005; (c) Vargas et al., 2003; (d) Le Loeuff and Von Cosel, 1998 : SST and SSS stand for Sea Surface Temperature and Sea Surface Salinity, respectively.

This particular behaviour of warm Senegalese fauna, characterized by highly variable spatial and temporal distributions, can be used as a tool for reconstructing sea surface conditions and climatic variability throughout the Last Interglacial in the Western Mediterranean.

3.2. Sedimentary facies

Along Mediterranean Peninsular coasts, the OIS 5 coastal deposits are characterized by different sedimentary facies patterns that can help in the determination of climatic or environmental changes, especially in cases where particular facies require specific hydrological or meteorological conditions for their development.

3.2.1. Oolitic facies

The first part of the OIS 5e is recorded on the peninsular coasts, between Almería and Alicante (Fig. 4), by the development of oolitic dunes and beaches, the later containing *S. bubonius*. However, these facies are not represented in the OIS 5e beaches along the Atlantic coasts of southern Iberia, where coarse calcarenites and siliciclastic deposits are recorded.

Oolites are small (0.25–2 mm) spherical grains of calcium carbonate, formed by concentric lamellae of fine aragonite needles that can present either tangential or radial orientation. Although ooids occur in different sedimentary environments, tangentially oriented oolites have been reported generally to form under high-energy, normal marine conditions, whereas radial ooids have been reported to occur in “protected” coastal environments (Loreau and Purser, 1973).

Requirements for oolite formation are (a) a shallow, flat and wide coastal shelf; (b) water supersaturated with CaCO₃, probably related to warming and evaporation on the coastal shelf; (c) persistent tidal or wind-wave agitation of the grains, which facilitates first the loss of CO₂ from the system and, second, the precipitation of CaCO₃ around the grains, and (d) continuous replacement of the calcium carbonate (Lloyd et al., 1987; Wanless and Tedesco, 1993). The most extensively studied modern oolites are from the Bahamian archipelago, where Wanless and Tedesco (1993), compared the effects of tidal vs. wind-wave agitation in the type of ooids formed, and also in the sedimentary body developed. Oolite type is related to frequency of agitation, whereby regular concentric ooids, such as those from Last

Interglacial deposits in the Mediterranean, occur where there is almost continuous bottom agitation, with quiet periods not exceeding a few weeks. Irregular oolites occur where bottom agitation is not so continuous, presenting longer periods (weeks to months) of bottom stability. Regarding the sedimentary bodies, wave-generated currents may organize ooids into elongated subtidal ridges, while storm waves and wind may organize them into beach ridges and dunes adjacent to the shore.

As for sea level, in certain sites of Australia, where no modern ooid deposition occurs, oolite formation has been related to positive sea-level oscillation; that is, to the post-glacial sea-level rise (Hearty et al., 2006), or to slowed sea-level rise (Yokoyama et al., 2006), just prior to the highstand.

In the Mediterranean Basin, oolites are currently forming along the coasts of NE Africa, between the Gulf of Gabes (southern Tunisia) and the Nile Delta (Egypt) (Lucas, 1955). Here, conditions for oolite development are related to a high-energy flat and shallow shelf (1 m deepening in 200 m). Along the Egyptian coast, oolites develop close to the shoreline at shallow depths, where insolation promotes evaporation and hence carbonate precipitation, and where strong eastern and north-eastern winds promote enough wave agitation to allow oolite formation. The Gulf of Gabes, in southern Tunisia, is the only Mediterranean location where tides can reach noticeable ranges, with reported spring tides of up to 2.5 m. Here, near Djerba Island, NE and E winds as well as tidal currents supply the energy needed for oolite development. Oolitic sands form wide rounded patches, moving over sea grass prairies, which have been described by Lucas (1955) as submarine dunes rounded by the alternating ebb and flow of tidal currents twice a day.

Modern Mediterranean oolites are similar to those found in OIS 5e deposits on Iberian Peninsular coasts: tangentially oriented aragonite lamellae, very regular in shape and with a thick oolitic envelope in relation to nucleus size. However, present tidal range on the Mediterranean Spanish coast is negligible, and the absence of tidal sedimentary structures does not allow an interpretation of a different tidal range during the Last Interglacial.

Similar characteristics are also reported for Tunisian OIS 5e oolites (Lucas, 1955), although with a different nuclei nature, arrangement and shape, which the author relates to inland environmental differences

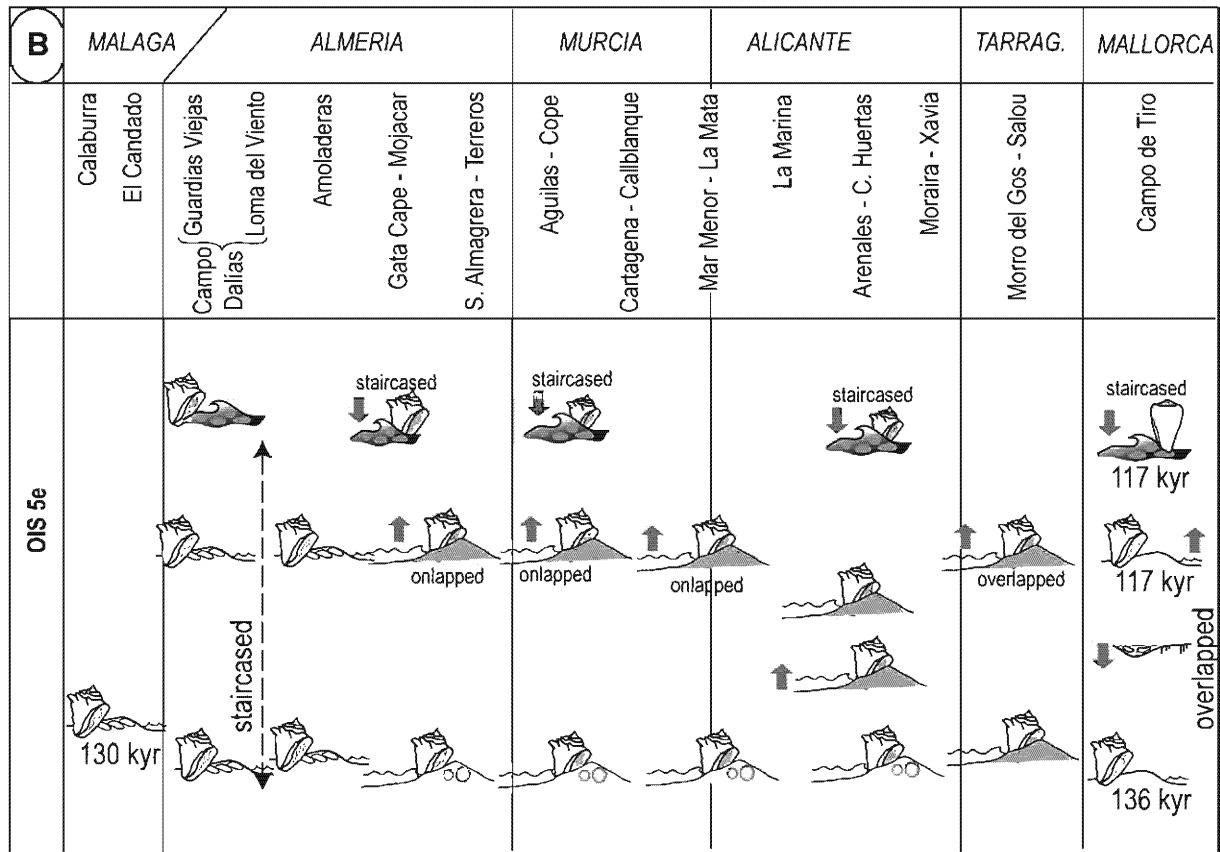
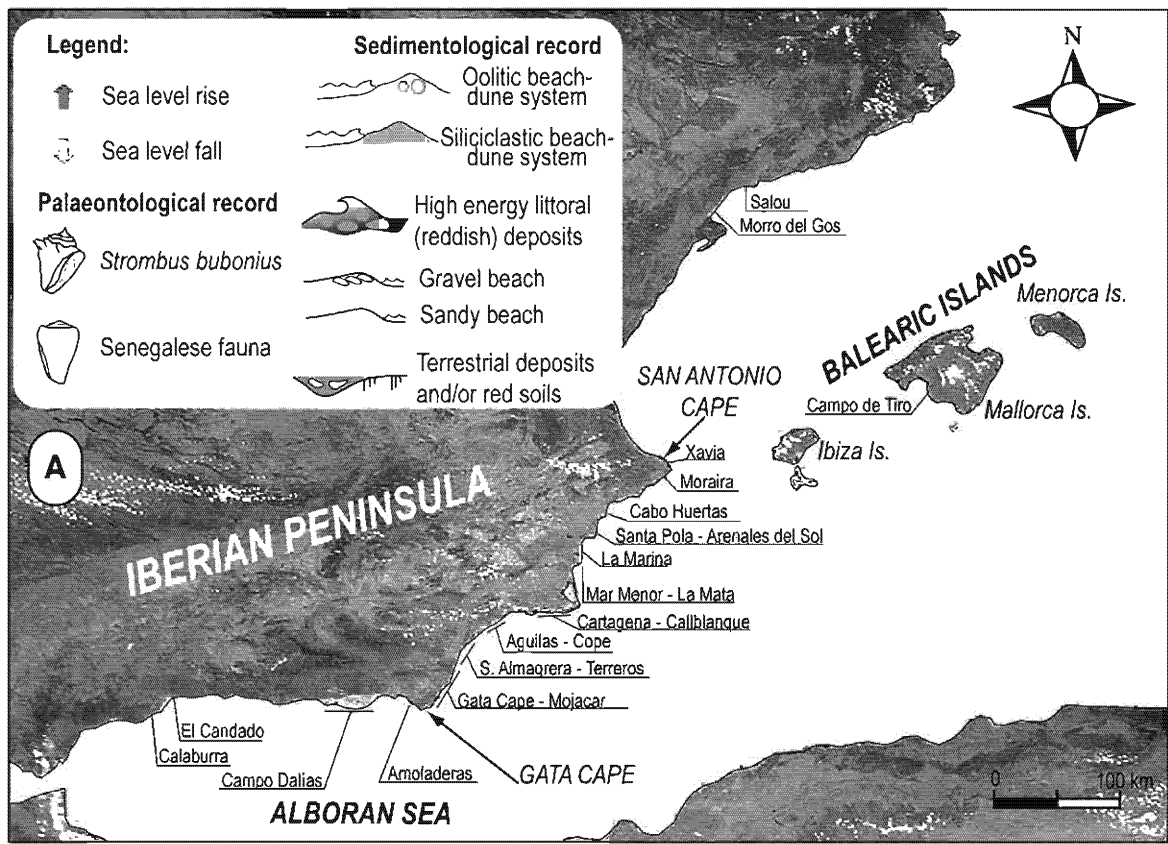


Fig. 4. A: Location of OIS 5e sites along the Mediterranean coasts of Iberian Peninsula; B: Main palaeontological, geomorphological and sedimentological features of OIS 5e deposits (summarized from Zazo et al., 1981; Hillaire-Marcel et al., 1986; Goy et al., 1993; Zazo et al., 1993; Hillaire-Marcel et al., 1996; Goy et al., 1997; Zazo et al., 2003; Goy et al., 2006).

between the Last Interglacial and present-day conditions in Tunisia. Contrasting with the steady oceanographic conditions needed for regular oolite formation, unsorted and angular nuclei in Late Pleistocene units are related to significant runoff under humid climatic conditions, while the rounded and well-sorted aeolian nuclei observed in present oolites point to more persistent winds and dune formation. Along the south-eastern Spanish coast, oolitic facies from OIS 5e, usually occur as dune–beach ridge systems (Fig. 5A) reflecting an increase in wind activity, which in many cases contrasts with the gravel beach deposits that characterized earlier Interglacials (Bardají et al., 1987; Zazo et al., 1998, 2003). However, these oolitic beaches are usually located below present sea level, which can be interpreted as having been formed during the sea-level rise close to the first OIS 5e highstand. Oolitic foreshore facies outcrop in only two locations (La Marina, Alicante; and El Playazo, Almería), and there is no sedimentological evidence of a different-from-present tidal regimen. Later siliciclastic dunes replace the oolitic dunes, rather indicating a change in oceanographic or climatic conditions. The highstand associated to these siliciclastic dunes usually outcrops higher than present sea level, suggesting a sea-level rise related to the earlier oolitic unit.

3.2.2. Reddish conglomerate facies

The final part of OIS 5e and the subsequent substages (OIS 5c and 5a), are characterized by an important change in sedimentary style, representing the global climatic deterioration that followed the peak of the Last Interglacial. This climatic change is evidenced by an increase in depositional energy manifested by coarser sedimentary units and an increase in red silty–clayey matrix (Fig. 5B). These reddish deposits are represented by heterometric, strongly cemented, rounded conglomerate embedded in a red silty–clayey matrix, with abundant specimens of *S. bubonius*. These units are usually located

close to the mouth of ephemeral streams (El Cocón, Murcia; Guardias Viejas, Almería; Los Arenales del Sol, Alicante), suggesting an increase in runoff that mobilized the previously weathered superficial inland deposits and red soils.

In other locations, such as the island of Mallorca (Campo de Tiro section, Fig. 6) this environmental change is accompanied by an increase in the grain size of littoral deposits, related to higher wave energy and greater storminess (Hearty et al., 1986; Zazo et al., 2003).

4. The timing of OIS 5 in Spanish Mediterranean settings

4.1. Peninsular coasts

There are many papers devoted to the study of the Last Interglacial on the Iberian Peninsula, both on its southern Atlantic coasts and in Mediterranean settings (Stearns and Thurber, 1965; Brückner, 1986; Goy et al., 1986; Hearty et al., 1986; Hillaire-Marcel et al., 1986; Goy et al., 1993; Zazo et al., 1993; Hillaire-Marcel et al., 1996; McLaren and Rowe, 1996; Zazo et al., 2003; Goy et al., 2006, etc). Correlating various locations has been made possible by extensively detailed geomorphological mapping and facies analyses, aided by dating techniques and palaeontological information. In summary (Fig. 4), and despite the tectonic influence, what seems clear is that there were three highstands of sea level in most of the areas during OIS 5e (130–117 kyr), and one or two further highstands near the end of OIS 5 (i.e. OIS 5c/5a), when sea level in the Mediterranean is inferred to have risen once or twice to present values (Zazo et al., 2003). This is in contrast to what has been generally assumed concerning a sea level below the present for OIS 5c (ca. 100 kyr) and below or close to present for OIS 5a (ca. 100 kyr), (Chapell et al., 1996; Roy and Boyd, 1996; Pillans et al., 1998; Hearty and Kauffman, 2000).

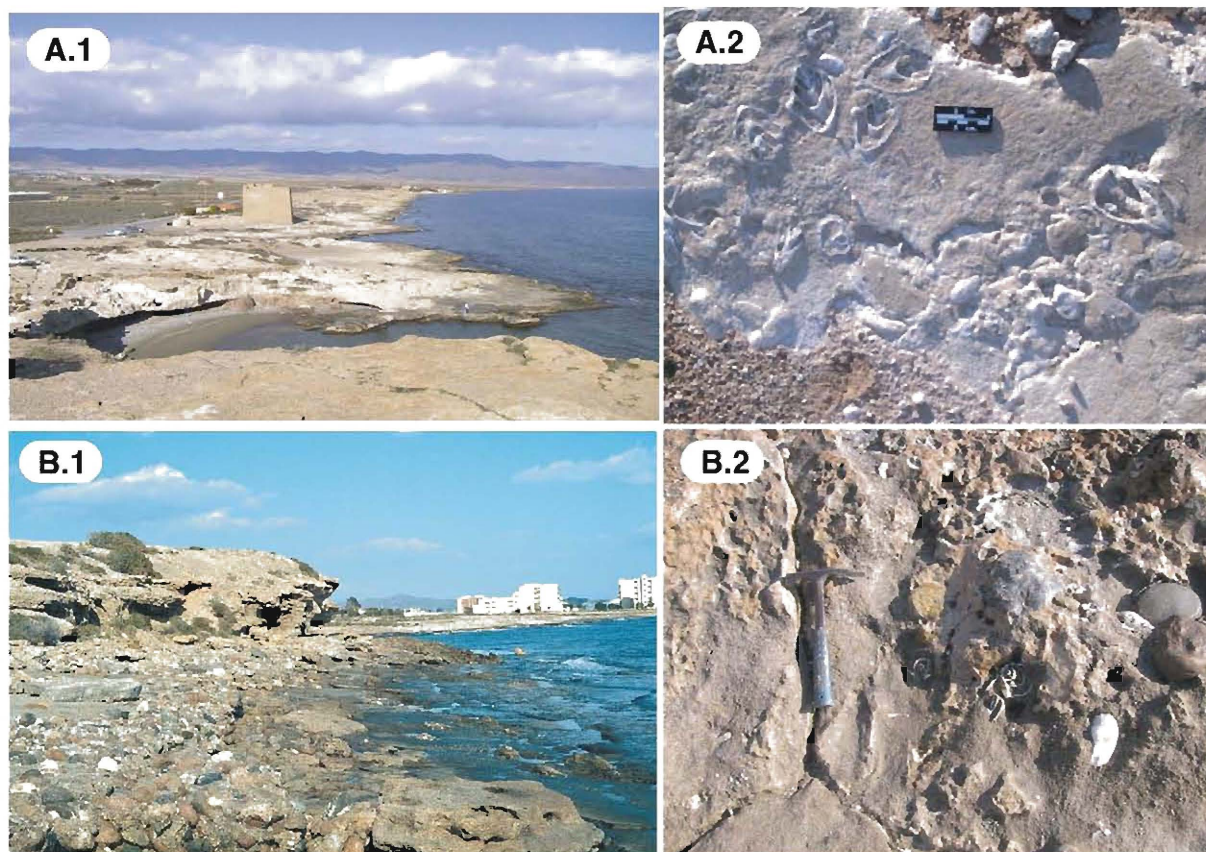


Fig. 5. A.1) Oolitic dune belt from OIS 5e (Cope Basin, Murcia); A.2) Detail of *Strombus bubonius*-bearing oolitic beach facies (La Marina, Alicante; from Goy et al., 2006); B.1) Staircased reddish marine deposits from the final part of OIS 5e (Aguilas, Murcia); B.2) Detail of the reddish facies with *Strombus bubonius* (for location see Fig. 4A).

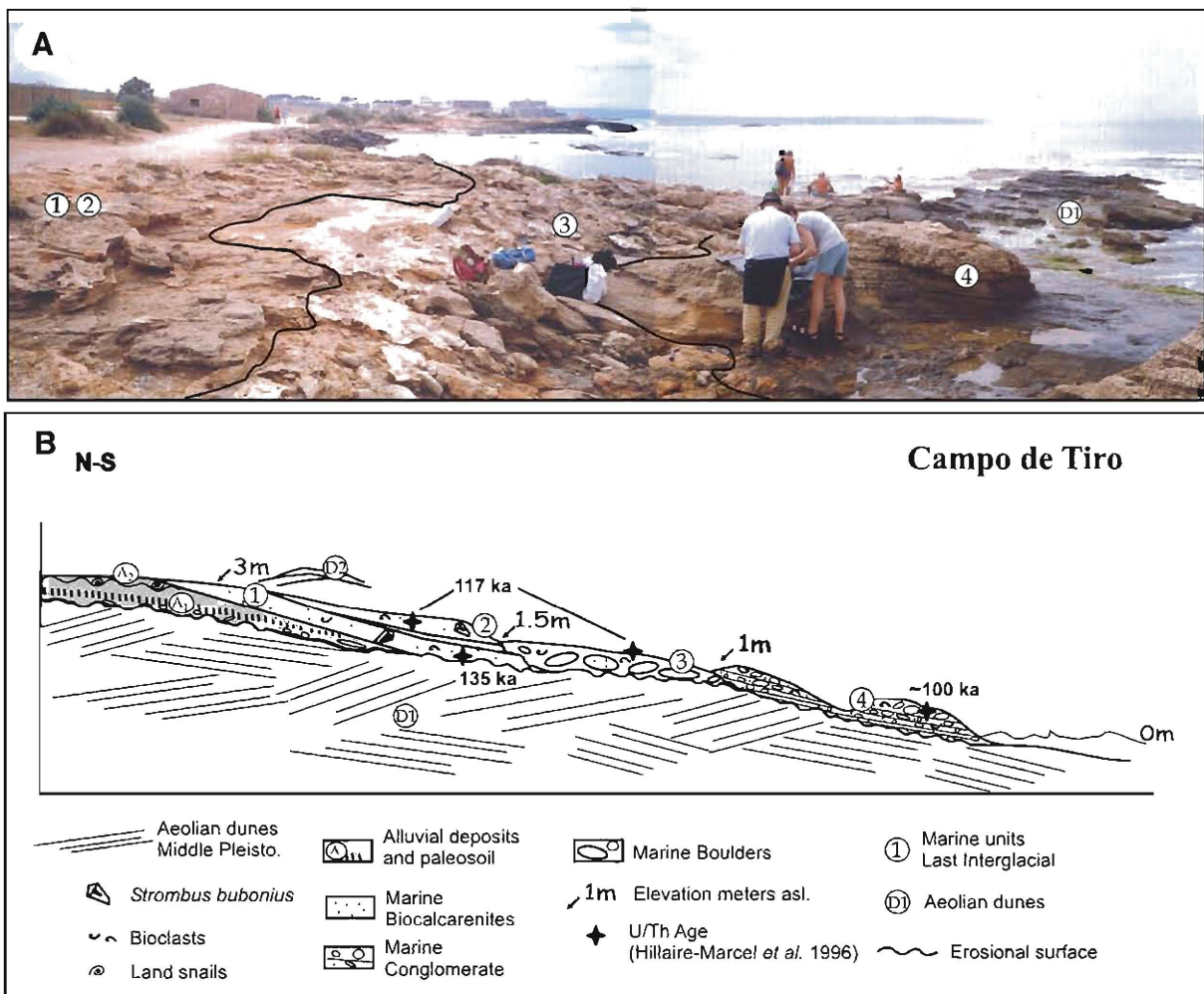


Fig. 6. Campo de Tiro Section (Mallorca, Balearic Islands); A: Panoramic view of the outcrop; B: Schematised section of Last Interglacial marine units (from Goy *et al.*, 2005; for location see Fig. 4A).

The geomorphological relationship between coastal OIS 5e units points to a first stillstand (oolitic) not too far from present sea level or even lower, followed by a sea-level rise (onlapping siliciclastic unit) that rose to higher than present altitude, and then a rapid drop of sea level (incised reddish unit) that remained close to present level. In some locations there is evidence of a sea-level fall between the two first units, marked by the development of terrestrial deposits.

4.2. The Balearic Islands

The most extensive record of Middle and Late Pleistocene coastal deposits is found on the island of Mallorca (Hearty *et al.*, 1986; Cuerda, 1989; Goy *et al.*, 1997; Zazo *et al.*, 2003), where the Campo de Tiro Section (Fig. 6) is considered to be the type locality for Tyrrhenian (i.e. *S. bubonius*-bearing) marine deposits in the Balearics.

Since the first works of Butzer and Cuerda (1962) and Cuerda (e.g. 1989), many subsequent papers have examined aspects of the chronology, geomorphological disposition, and sea-level interpretation of these deposits (Stearns and Thurber, 1965, 1967; Hearty, 1987; Hillaire-Marcel *et al.*, 1996; Goy *et al.*, 1997; Zazo *et al.*, 2003). Summarizing all the available data, we concluded that this type section presents the most detailed OIS 5 sea-level sequence on the Mediterranean coast, recording three highstands during OIS 5e (one at 135 kyr, and two at 117 kyr). These highstands are separated firstly by lowstand reddish terrestrial facies (between Units 1 and 2, Fig. 6) and erosion resulting in the stepping of Unit 3. A third pre-Holocene

highstand (Unit 4, ca. 100 kyr) has been attributed to OIS 5c or 5a (Hillaire-Marcel *et al.*, 1996; Zazo *et al.*, 2003). This attribution is in agreement with data from phreatic overgrowths in speleothemes (Vesica *et al.*, 2000; Ginés *et al.*, 2001; Fornós *et al.*, 2002) obtained in littoral caves in eastern Mallorca. In these caves, at least two highstands are found during OIS 5e (one at ca. 130 kyr, and at ca. 116 kyr) and two more above present sea level (2–3 m), dated at ca. 105 and ca. 85 kyr and representing OIS 5c and 5a respectively (Fig. 7). Recently, Tuccimei *et al.* (2006) have published a new and more complete curve of sea-level change in Mallorca Island where three highstands have been recognised corresponding to OIS 5e (138–128.5 kyr and 122–110 kyr) and OIS 5a (84–82 kyr).

However, synthesized results of U-series analyses (TIMS), palaeontological and morphosedimentary units from Campo de Tiro exposed beach deposits, point to the occurrence of just four highstands: three during OIS 5e, at 135 kyr (Unit 1) and at 117 kyr (Units 2 and 3), and the fourth one at ca. 100 kyr (Unit 4) (Hillaire-Marcel *et al.*, 1996; Zazo *et al.*, 2003). Palaeontological content (Cuerda, 1989) shows a Senegalese assemblage, including *S. bubonius* in Units 1 and 2, which partially disappears in Unit 3, particularly *S. bubonius*, becoming similar to that of the present day, but with *B. plicata* in Unit 4. Sedimentology and geomorphological disposition of Units 1 to 3 indicate a sea-level drop and an increase in wave energy and/or storminess at the end of OIS 5e.

In summary, the available data suggest high SST in the Balearic Islands as early as OIS 9 or 11, which occurred again during the first

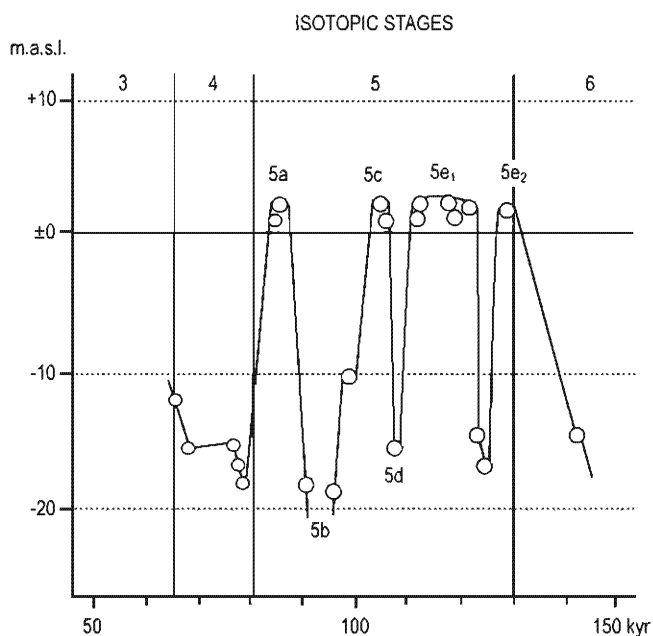


Fig. 7. Simplified eustatic curve for the Last Interglacial on Mallorca (Balearic Islands), deduced from Th/U dating on phreatic speleothems in coastal caves (after Ginés et al., 2001); (m.a.s.l.: metres above sea level).

part of OIS 5e (135 kyr), although no data from OIS 7 are currently available. The final part of OIS 5e (117 kyr) is characterized by a sudden decrease in SST, a drop in sea level, and an increase in storminess. From that time on, SST never warmed sufficiently to allow the survival of *S. bubonius*. Also notable is the absence of oolitic facies on the

island, indicating that not all of the needed requirements for oolite formation were attained on these coasts.

5. The record of OIS 5 in other Western Mediterranean countries

In order to better understand the physiographical, hydrographical and climatic conditions in the Western Mediterranean during the Last Interglacial, it is necessary to document the record of OIS 5 in the neighbouring countries of Morocco, Tunisia, Italy and France (Fig. 8).

5.1. Morocco

The record of OIS 5 in Morocco has been mostly reported for the Atlantic littoral, where most of the type sections for the marine Quaternary of North Africa are located (e.g. Lecoq, 1952; Biberson, 1958; Stearns and Thurber, 1965; Texier et al., 1986, 1994; Alouane, 2001; Occhietti et al., 2002). The sea-level record along the Atlantic littoral of Morocco presents just one highstand during OIS 5, reported on the basis of stratigraphic analyses, aminoacid racemization and Th/U dating, and ascribed to the peak of OIS 5e (128 kyr). At some locations, this level appears to be overlain by a reddish terrestrial deposit. As occurs along the Spanish littoral, the Moroccan record is also characterized by the presence of warm Senegalese fauna in deposits from OIS 5, with *S. bubonius* present in the Mediterranean sections and absent from the Atlantic coasts.

Along the Mediterranean coasts, a few outcrops of late Quaternary marine deposits are reported (Angelier et al., 1976; Brückner, 1986; Hearty et al., 1986; Alouane, 2001). From Tetouan to Al Hoceima (Fig. 8), one level pertaining to the peak (130 kyr) of the Last Interglacial has been reported, and a second one attributed to OIS 5c or 5a. However, the various authors who have studied these sections have reported neither *S. bubonius* nor oolitic facies, which probably

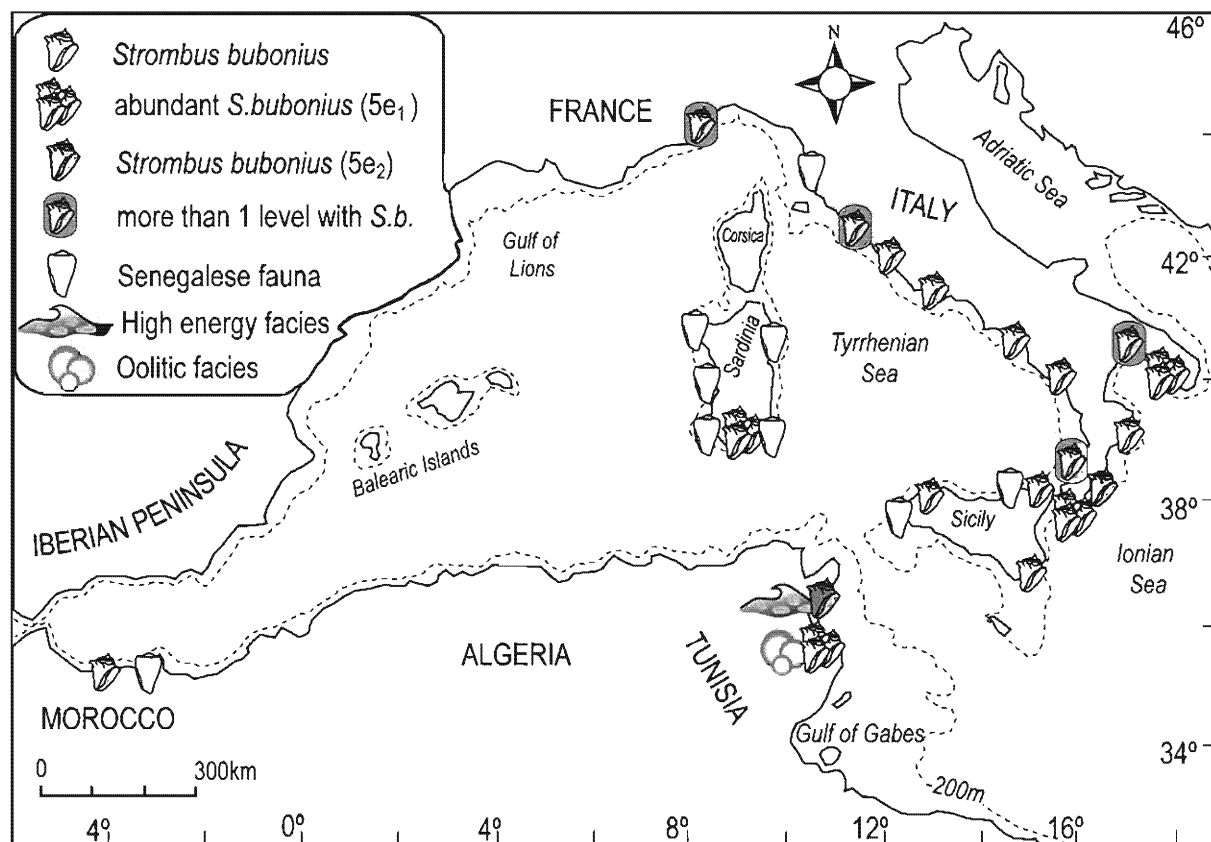


Fig. 8. Summary of OIS 5 features in Western Mediterranean countries (data from Spanish littoral in Fig. 4).

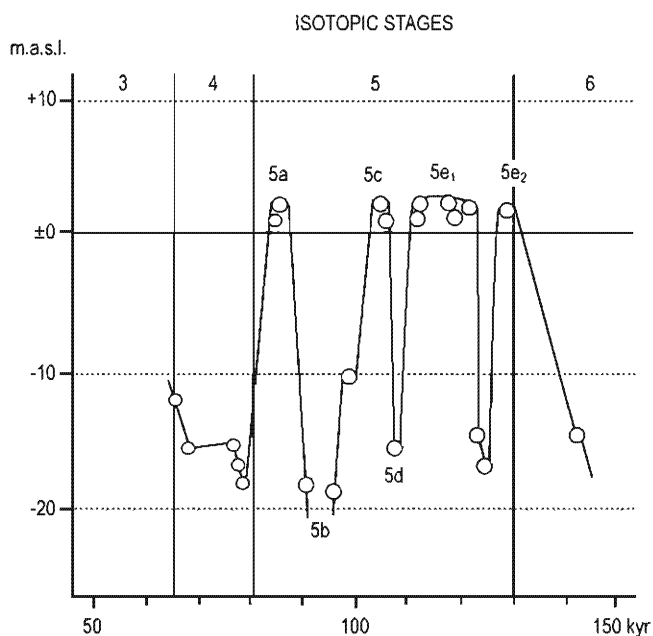


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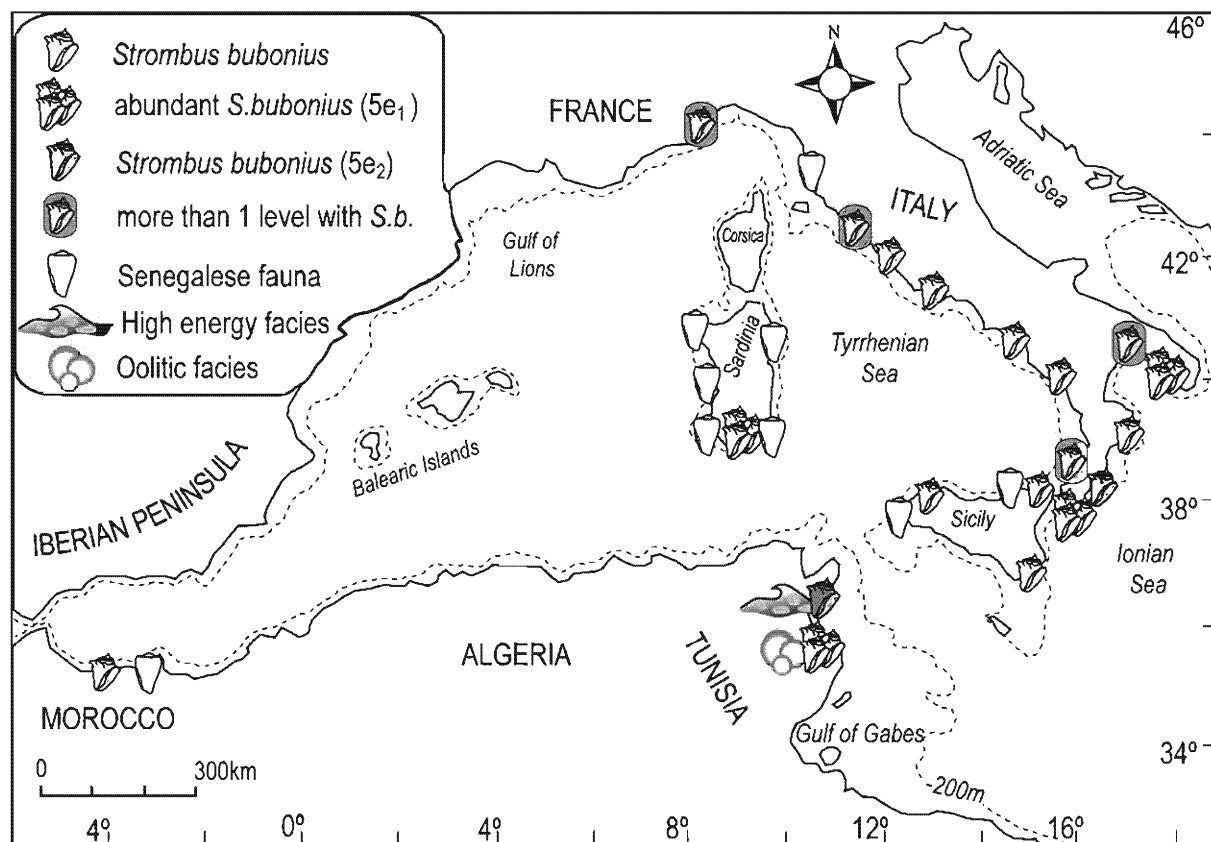


Fig. 8. Summary of OIS 5 features in Western Mediterranean countries (data from Spanish littoral in Fig. 4).

reflects sea surface conditions different from those characterizing the Spanish coasts at similar latitudes.

The first reported *S. bubonius*-bearing marine deposits (Alouane, 2001) appear near Saïdia, where a beach level located at +5–10 m was dated by Th/U (Angelier et al., 1976) and aminoacid (Hearty et al., 1986), yielding ages of 120 kyr and 126 kyr respectively, and corresponding to the peak of OIS 5e. This same level is also recognised in the Beni Saïd area, at a similar height and dated at ca. 130 kyr (Brückner, 1986).

5.2. Tunisia

Pleistocene marine formations in Tunisia were first described by Paskoff and Sanlaville (1976, 1980), who identified three stratigraphic marine formations along the eastern coast: Douira, Rejiche (separated by an intervening paleosol) and the more recent Chebba Formation, the two last units bearing *S. bubonius* (Fig. 9). The older *S. bubonius*-bearing marine unit exhibits a bioclastic and oolite beach–dune regressive sequence. A higher-energy conglomeratic deposit, erosively encased within the earlier unit, composes the second *S. bubonius*-bearing formation.

Mahmoudi (1987) and Mahmoudi et al. (1987a) established a new stratigraphic definition of these units, combining the two newer formations (former upper Rejiche and Chebba Fts.) into just one characterized by the presence of *S. bubonius*, but with significant intraformational erosive contact and a marked change in depositional style, from oolitic to conglomeratic (Fig. 9).

The climatic reconstruction made by Mahmoudi et al. (1987b) for this Last Interglacial unit implies warmer SST than present and significant wind action during the deposition of the oolitic *S. bubonius*-bearing unit, with episodic storms indicated by the boulder beaches eroded into this oolitic unit. Temperature determinations made by these authors on a specimen of *S. bubonius* from the oolitic unit, show a value 2–4 °C higher than present in these littorals.

Recent research on raised Pleistocene marine deposits in SE Tunisia (Jedoui et al., 2002, 2003), based on U-series dating of *Ostrea*

shells, suggests the possibility of two highstands of sea level during the Last Interglacial (Fig. 9). The first (147–140 kyr) is recorded by a siliciclastic unit without *S. bubonius*, and the second (110–100 kyr) characterized by oolitic facies and abundant *S. bubonius* shells.

5.3. Italy

The sites where *S. bubonius*-bearing beach deposits were first described in the Mediterranean lie along Italian coastlines, more precisely in Sardinia. The term Tyrrhenian was coined (Gignoux, 1911; Issel, 1914) to name these fossiliferous beds that occurred between the Sicilian and the Holocene. Subsequently, Bonifay and Mars (1959), subdivided it into three different stages: Paleotyrrhenian (with banal fauna), Eutyrrhenian (with *S. bubonius*) and Neotyrrhenian (with Senegalese fauna but no *S. bubonius*). Therefore, the presence of this particular species was restricted to the Eutyrrhenian. Nowadays, there is a general consensus in associating the Eutyrrhenian with OIS 5e, assuming the absence of *S. bubonius* in levels other than that of OIS 5e. However, Bonadonna and Bigazzi (1970) reported ages of 177 ± 30; 127 ± 13 and 90 ± 8 kyr, for three levels with *S. bubonius*, separated by erosional phases, in the Cerveteri area (Central Italy).

A recent compendium on the Last Interglacial sea-level highstand in Italy (Ferranti et al., 2006), includes an extensive database of all reported marine deposits from the OIS 5e. Although the authors assume that the presence of *S. bubonius* is exclusive to the OIS 5e, with a unique highstand at ca. 125 kyr average, data from earlier investigations suggest the occurrence of multiple highstands and less strict timing.

The northernmost record of *S. bubonius* is reported in Liguria (Federici and Pappalardo, 2006) where Stearns and Thurber (1967) and De Lumley (1969) mentioned the occurrence of different levels with *S. bubonius*, dated at 170 ± 35, 160 ± 34, 95 ± 5 and 60 ± 5 kyr. In Lazio, in the area of Cerveteri, Hearty and Dai Pra (1987) report the occurrence of at least three different beaches with *S. bubonius* at different heights. In Calabria (Dumas et al., 2005), *S. bubonius* has been

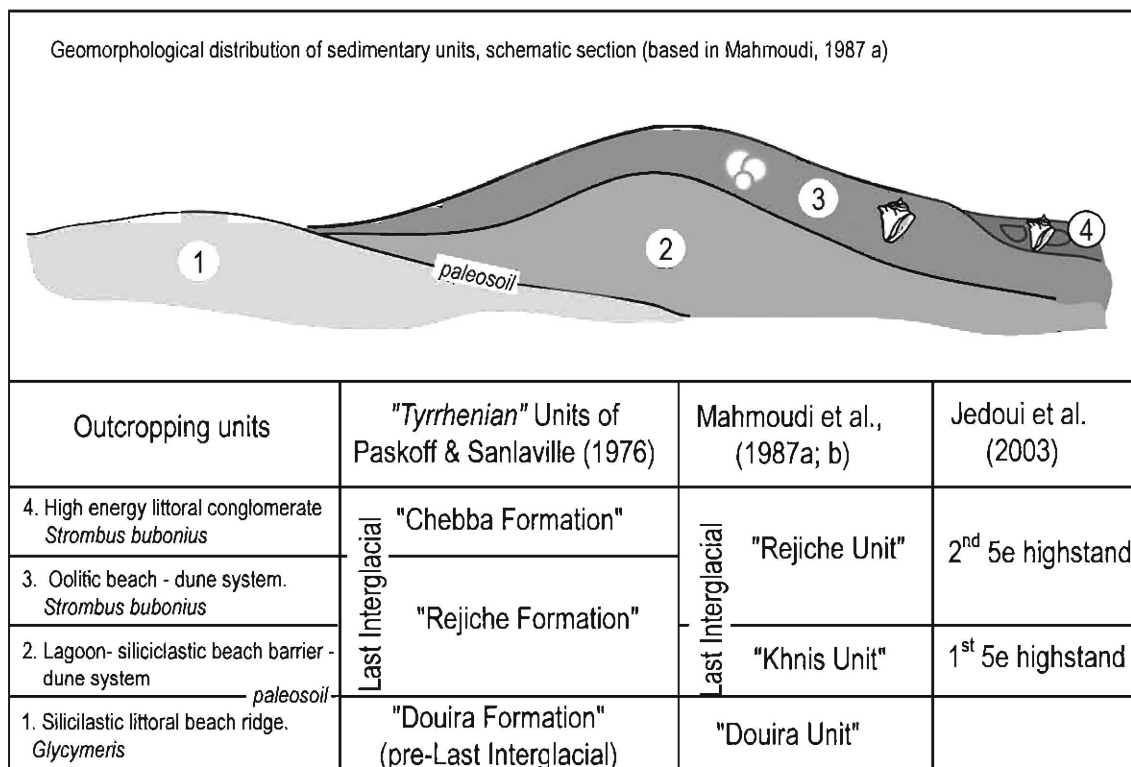


Fig. 9. Last Interglacial sedimentary units in Tunisia, and chronological interpretation according to various authors.

reported as occurring at 116 and 101 kyr. Mauz (1999) also reports TL-ages of *S. bubonius*-bearing marine layers from Tuscany, clustered around ca. 100 kyr and ca. 116 kyr.

In summary, the published data suggest that *S. bubonius* on the Italian coasts seems not to be exclusive to the peak of OIS 5e, but appears before (160–180 kyr) and remains afterwards (116 kyr, 90 kyr, perhaps 60 kyr?). This is very similar to the situation on the Iberian Peninsula. The same data also support the occurrence of at least two different highstands during OIS 5e. Sedimentological descriptions of *S. bubonius*-bearing deposits do not mention oolitic facies, and therefore it should be inferred that the required conditions for oolitic formation did not exist along Italian coastlines.

6. Interpretation and discussion

Palaeontological, sedimentological and geomorphological data of OIS 5e on the Spanish littoral (Fig. 10) support the statement of more than one sea-level highstand, while there is not a general consensus about the number and duration of highstands in the other Western Mediterranean countries. Different sea surface and meteorological conditions could be related to a different Western Mediterranean response to changing global climate throughout this particular stage. However, tectonic activity in all of the coastal settings studied does not allow absolute sea-level heights during all these highstands to be formulated, and we can only deduce relative changes.

6.1. Sea-level record

OIS 5 presents four or five sea-level highstands along the studied Spanish littoral depending on the location (Zazo et al., 2003). On Mallorca (Balearic Islands) three highstands have been reported for OIS 5e (one at 135 kyr, and two around 117 kyr), and one more for OIS 5c/5a (at ca. 100 kyr), all of them in the same section, (Hillaire-Marcel et al., 1996). The geomorphological distribution of these units shows that after the first highstand (135 kyr) sea level suffered a relative fall, as evidenced by the deposition of reddish terrestrial deposits. The overlapping of the second highstand points to a higher sea level at 117 kyr, but with a rapid and sudden fall marked by the staircasing of the third highstand, also at 117 kyr.

The highstand record is greater along the Peninsular coast, where up to three highstands have been reported for OIS 5e in Alicante (La Marina), three in Almería and at least two in Murcia. As for sea level, the geomorphologic distribution of the sedimentary units also suggests a higher sea level during the deposition of siliciclastic systems than during the deposition of oolitic units, and also a sudden drop at the end of OIS 5e, evidenced by the incised development of the reddish unit.

To the north of Cape San Antonio (see Fig. 4), there is a general lack of raised marine terraces from OIS 5. The only available data are from Xabia and Moraira (Fumanal et al., 1993), where an OIS 5e oolitic beach has been recovered in a core drill at –15–6 m below sea level, with the associated dune belt cropping out along the present coastline. An overlying siliciclastic dune–beach system has been attributed to the OIS 5 in general, given the lack of reliable dating for this unit. To the north of Cape San Antonio, reported data are scarce for Last Interglacial sea-level highstands, with only two reported sites of outcropping marine terraces, in Morro de Gos and Salou (Tarragona). Both studies (Zazo et al., 1981, 1987) point to the occurrence of two highstands during OIS 5 with an intervening terrestrial deposit, but without any precise timing.

6.2. Sea surface conditions

Sea surface conditions during OIS 5, particularly temperature, can be estimated by the presence or absence of significant Senegalese fauna, especially *S. bubonius*. The present distribution of this warm fauna along the eastern north Atlantic Ocean (Fig. 3), indicates that this faunal assemblage requires a mean annual SST of around 23–

24 °C, never below 19–21 °C in the cold winter season, and salinity around 34–35 psu. Oceanic surface currents distribute the warm fauna in larval stage, and so their survival and settlement depend on the precise sea surface conditions of the coastal settings into which they arrive. Therefore, the presence of Senegalese warm fauna, particularly *S. bubonius*, in Mediterranean settings during the warm stages of OIS 5, must be considered as a good proxy for the reconstruction of some former palaeoceanographic physical and chemical parameters.

This species is widely represented all over the studied locations at the beginning of OIS 5e, disappearing at the end of this stage in the Balearic Islands, but surviving during the entire OIS 5e and later, during OIS 5c/5a, on the Peninsular coasts of Almería, Murcia and Alicante (Fig. 10). The abundance of *S. bubonius* is considerably greater in deposits from OIS 5e than in those associated with subsequent highstands, even disappearing in some locations (e.g. Mallorca) at the end of OIS 5e, where only the accompanying Senegalese fauna is recorded. Only two *S. bubonius* sites have been reported north of Cape San Antonio (two superimposed levels at Morro del Gos, and a single level at Salou).

6.3. Meteorological conditions

Meteorological conditions throughout the entire Last Interglacial can be inferred from the analyses of sedimentary facies and their comparison with modern analogues. Different facies can be attributed to differing wave energy or wind stress, or even increased runoff.

The Peninsular and insular Mediterranean coasts during the Last Interglacial were characterized by diverse sedimentary environments. Oolitic dune systems developed at the beginning of OIS 5e on Peninsular coasts, but the spatial distribution of outcrops seems to be bracketed between Cape Gata and Cape San Antonio on the Peninsular coast and on Ibiza and Formentera in the Balearic Islands (Fig. 4). According to modern analogues, and in the absence of significant tidal range, these morphosedimentary units require a strong, constant wind activity to be able to generate both the oolites and the associated dune belts. The N–S orientation of these “oolitic sectors”, suggest that the wind framework capable of ensuring these physiographical conditions would have been one of prevailing easterlies, blowing very close to the air–sea interface, at the beginning of OIS 5e, just prior to and during the sea-level highstand. Other important winds in the Mediterranean area at this time, such as those from the SW, able to transport great amounts of pollen and dust from the Sahara, would not have been so effective in inducing the constant wind required to induce persistent wave energy.

With regard to the pattern of currents, we can imagine a hydrologic scenario during the Last Interglacial similar to that of the Present Interglacial. Although the specific mechanisms are still to be understood, oolites were formed along these sectors, coinciding with the area where present Modified Atlantic Water and Northern Current interact. This mixing of water masses could have created some precise geochemical conditions that favoured oolitic development. To the north and south-west of this “bracketed area” no oolitic formation has been reported, even for areas where wide, shallow coastal shelves also occur.

A similar orientation of the coastal outline occurs in Tunisia, where wide oolitic dune–beach systems characterize the peak of the Last Interglacial. This fact can be interpreted as evidence of considerable eastern-wind activity during this period.

Comparing this with present wind distribution (Fig. 2), we can observe that during the summer the prevailing winds in these coastal sectors are currently from the east. Nevertheless, the fact that oolites and dunes formed during the Last Interglacial in places where these sedimentary features are absent suggests strong wind activity during the Last Interglacial, probably warmer than that which currently prevails in the Western Mediterranean.

Sedimentary environments changed dramatically at the end of OIS 5e, or in subsequent substages, in many locations around the Western Mediterranean. On Spain's Peninsular Mediterranean coasts, oolitic dune–beach systems are replaced either by siliciclastic dune–

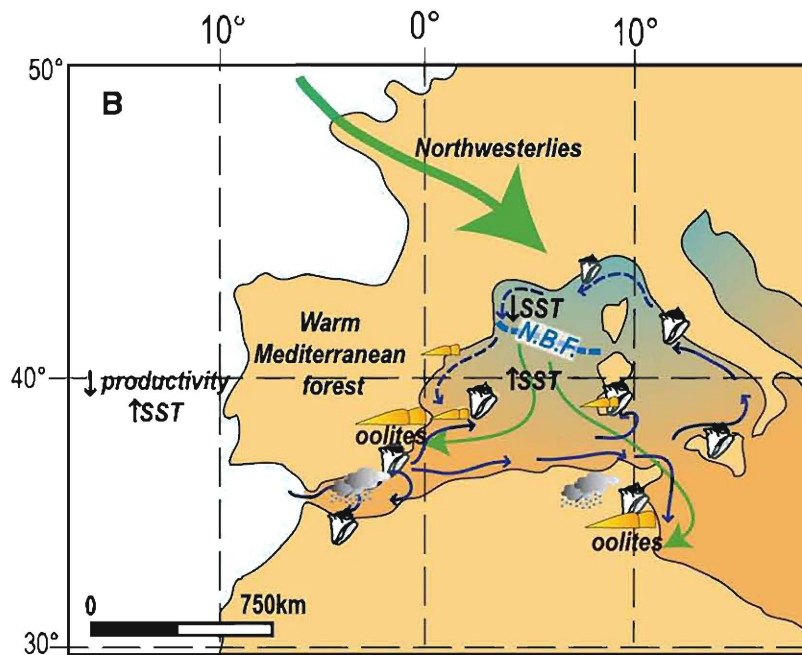
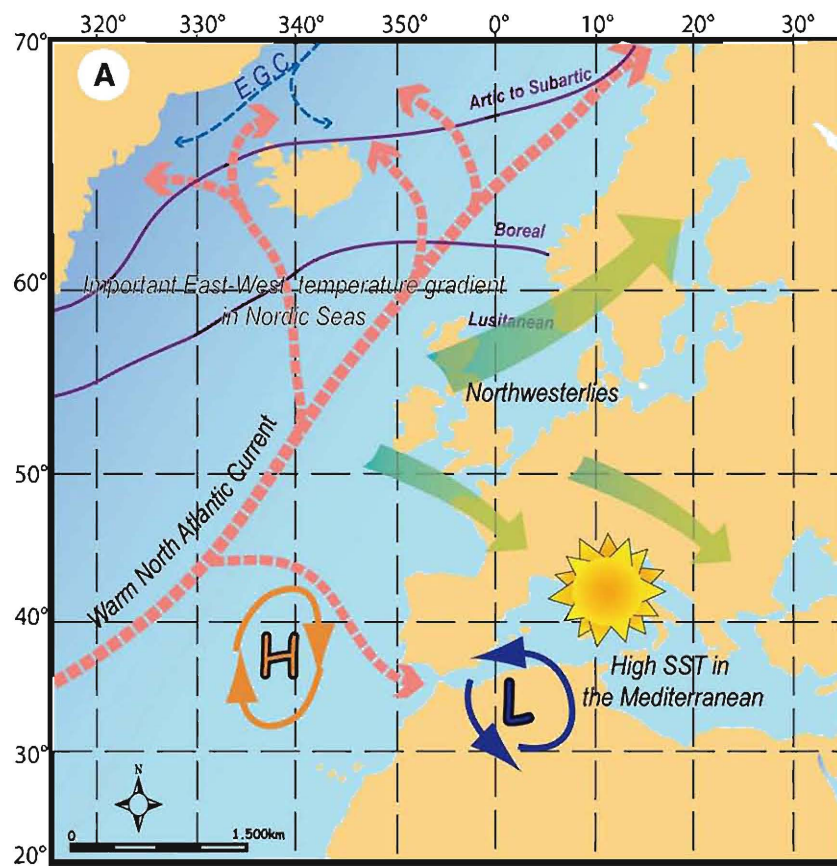


Fig. 10. A: Reconstruction of atmospheric-oceanographic scenario in Northern Hemisphere during the peak of OIS 5e, (mod. from Knudsen et al., 2002); E.G.C.: Eastern Greenland Current; Solid blue lines indicate the distribution of Arctic, sub-Arctic, Boreal and Lusitanian microfaunal assemblages; Green arrows: north-westerlies pattern; H-L: High and Low-pressure cells respectively; Red dashed arrowed lines: inferred path of warm North Atlantic Current. **B:** Western Mediterranean conditions during the peak of OIS 5e (ca. 130 ka), with indication of *Strombus bubonius* occurrence and special sedimentological features. Data from Iberian Peninsula vegetation and offshore Portugal from Sanchez-Goñi et al. (1999); Green arrows, prevailing winds (interpreted from modern pattern after Drakopoulos and Lascaratos, 1999); Blue arrows: inferred circulation pattern, N.B.F.: North Balearic Front (interpreted from modern analogue, from Millot, 1999); Pluviosity in Alboran Sea after Pérez Folgado et al. (2004); Tunisia data after Lucas (1955) and Mahmoudi (1987); Sea Surface Temperature interpreted by palaeontological distribution.

beach systems or by reddish clayey conglomerates. These reddish facies suggest an important meteorological change marked firstly by an increase in inland runoff, carrying away the previously formed red

soils, and secondly by an increase in storminess that can erode and round the boulders embedded in the red matrix. On Mallorca, this change is also characterized by an increase in storm activity, and

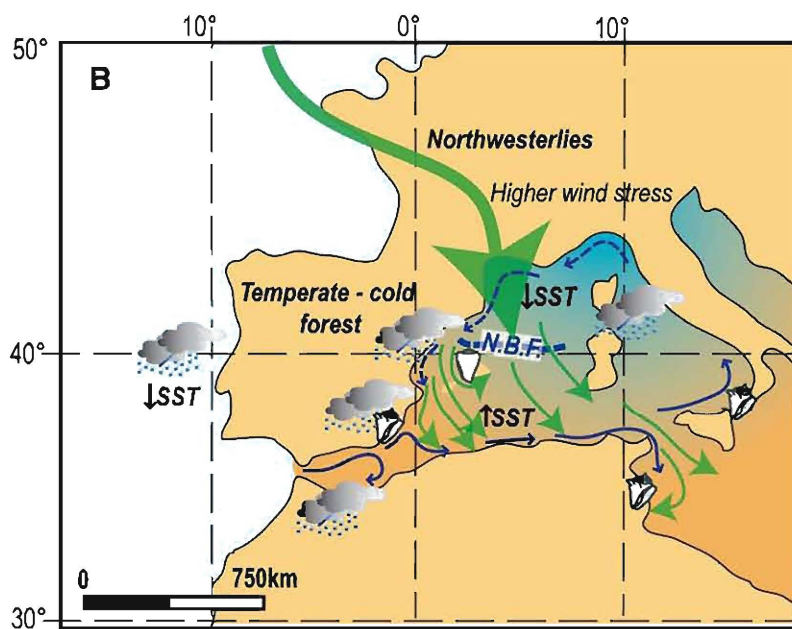
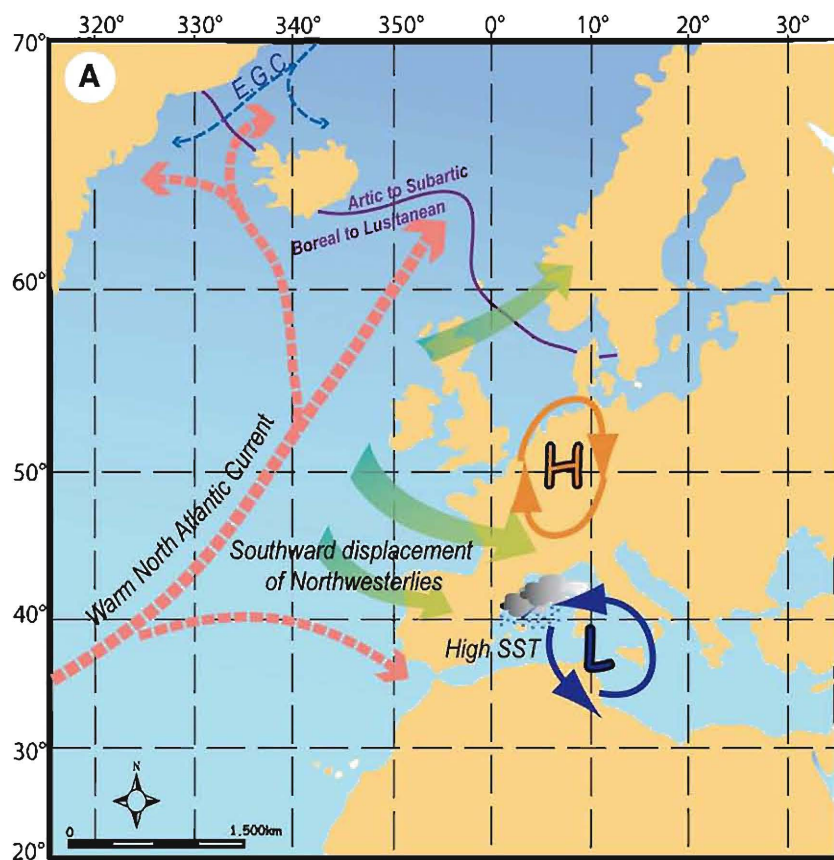


Fig. 11. A: Reconstruction of atmospheric-oceanographic scenario in Northern Hemisphere at the end of OIS 5e (ca. 116 ka); B: Western Mediterranean conditions at the end of OIS 5e (see Fig. 10 for symbols and data sources; Northern Morocco, data from Alouane, 2001).

dating carried out on these levels indicate that this change occurred in a very short time span, at 117 kyr.

6.4. Correlation with North Atlantic climatic variability

The correlation of all of these key features with North Atlantic climatic variability and the assessment of high and mid-latitude responses to global climate change is a complex task.

During the warmest peak of Last Interglacial, high summer insolation in the Northern Hemisphere induced a stronger influence of the North Atlantic Current in the Nordic Seas, with a more westward location of this current (Fig. 10A), which could have strengthened the significant sea surface temperature gradient recorded by microfungal assemblages (Knudsen et al., 2002). This oceanographic situation in the Nordic latitudes induced weaker north-westerly winds in Western Europe, allowing a persistent

southward location of Azores High and high SST in the Western Mediterranean, favoured by the prevailing anticyclonic conditions. The increase in runoff or rainfall suggested by the development of ORL (Organic Rich Layers) during the warmer OIS 5e substages in the Alboran Sea (Pérez Folgado et al., 2004), could have caused variations in the basin's hydrological budget and hence in SSS.

Higher sea surface temperature in Atlantic waters and the flow of warmer waters into the Mediterranean led to the expansion and flourishing of warm fauna (mainly *S. bubonius*) along Mediterranean coasts, especially along the Almería-Alicante littoral, where a higher number of highstands bearing *S. bubonius* and a greater abundance of this species are recorded. This record is also significant on the coasts of Tunisia and Tyrrhenian coasts of Italy, being more reduced in the Ligurian Sea, the Gulf of Lyon and on the Mediterranean coasts of Morocco. This differential distribution and abundance must be due to a difference in sea surface conditions, probably related to the hydrological framework and to spatial differences in the hydrological budget. Using the present-day circulation pattern (Millot, 1999) as a modern analogue (Fig. 1), we suggest that locations with a more abundant record of warm fauna would have been directly influenced by fresher Atlantic waters, whereas localities that present fewer specimens, were subject to a greater influence of the cooler and saltier Northern Mediterranean Current. Consequently, the deepening of the cooler NMC would have taken place to the north of Cape San Antonio, at a more northerly position than today's. Seemingly, a northern position of the Balearic Front (Fig. 10), determined by the northward influence of north-westerlies, was responsible for SST distribution, and consequently the distribution of warm fauna.

Compared with the present situation, meteorological conditions during the warmest peak of the Last Interglacial could be attributed to the summer wind stress scenario recorded at 10 m above the air-sea interface (Fig. 2). In this scenario, the influence of north-westerlies is not so marked, promoting a wind flow from the Gulf of Lyon to the south, where it rotates in a westward direction and induces a marked influence of eastern winds on the littorals of SE Spain and E Tunisia.

Given the lack of evidence for a different-from-present tidal range in the sedimentary record of outcropping oolitic beaches, we assume a wind-driven wave energy as the trigger for oolite formation. In this sense, the N-S orientation of these coastal sectors where oolites developed leads us to suggest a persistent influence of eastern winds as the main driving mechanism.

These eastern winds would have been strong and persistent enough to promote high wave energy that, together with the slowed sea-level rise near the highstand of the peak of OIS 5e, favoured the formation of an oolitic shoal in front of these littorals. Data from the Alboran Sea (Pérez Folgado et al., 2004) and from Tunisia (Lucas, 1955) support an increase in rainfall or runoff at this time. However, vegetation on the Iberian Peninsula was characterized by Mediterranean species typical of a warm and seasonally humid climate, and Eastern Atlantic waters in these middle latitudes presented high SST (Sanchez-Goñi et al., 1999).

At the end of OIS 5e (116–117 kyr) this scenario started to change (Fig. 11A). The Northern Hemisphere received lower summer insolation during the second half of the Last Interglacial marine highstand (CAPE Last Interglacial Members, 2006). Ice sheets began to grow and, although high latitudes remained warm (McManus et al., 2002), the flow of the warm North Atlantic Current to the Arctic Ocean was also reduced (Knudsen et al., 2002). This situation led to a steeper temperature gradient in Nordic Seas (Knudsen et al., 2002), and to a southward displacement of enhanced north-westerlies over Europe, which then began to sweep across the Iberian Peninsula. A vegetation shift towards a temperate-cold forest (oceanic climate) resulted, linked to the enlargement of the European cyclonic zone to include South-western Europe (Sanchez-Goñi et al., 1999). The southward migration of a branch of the warm North Atlantic Current at the end of OIS 5e could be responsible for the recorded increase in SST off

Portugal (Sanchez-Goñi et al., 1999), and the entry of this warmer water into the Mediterranean where *S. bubonius* or Senegalese warm fauna still survived.

A weaker and latitudinally lowered Azores High favoured the southern migration of the north-westerlies (Fig. 11A), promoting a probably persistent winter-like wind stress scenario (Fig. 2) in the Gulf of Lyon. These features would likely have triggered the sudden, and considerable, environmental changes recorded in the Western Mediterranean. Southern displacement of north-westerlies was probably linked to a southern displacement of the North Balearic Front, inducing cooler waters in the Gulf of Lyon, and warmer waters from the Balearics to the south. However, SST was slightly lower in these islands, as we have a sudden faunal change recorded at 117 kyr (Hillaire-Marcel et al., 1996; Zazo et al., 2003), with an initial record of *S. bubonius*, and then its rapid disappearance. This change is recorded on the island of Mallorca by two different morphosedimentary units dated at 117 kyr. The first represents a higher highstand and higher SST (*S. bubonius* record), while the second represents a sudden drop both of sea level (lower highstand) and of SST (warm Senegalese fauna, but no *S. bubonius*).

This drop in sea level is also recorded along the Peninsular Spanish coasts, where this *S. bubonius*-bearing marine unit usually appears incised into the earlier one. Even in Tunisia, although not all researchers regard it as an independent highstand, a sudden drop in sea level, together with an increase in storminess, is recorded at the end of the OIS 5e (Paskoff and Sanlaville, 1980; Mahmoudi et al., 1987a,b).

The previously-mentioned change in the trajectory of North-westerlies also influenced the prevailing winds in the Western Mediterranean, promoting a persistence of northern winds in a situation similar to a continued winter-like scenario (Fig. 2), with significant wind stress. These strong north winds were probably responsible for the registered increase in storminess at 117 kyr in the Balearics.

In contrast, present-day catastrophic rain discharges are linked with anticyclonic highs in western Europe, which push cold air masses to the south, and cyclonic low pressure in the warm Western Mediterranean area (Millán et al., 1995; Pastor et al., 2001), enabling an important recharge of moisture. These current meteorological conditions are probably similar to those that caused the increase in rainfall, erosion of older red soils, and fluvial discharge represented by the reddish facies conglomerates at the end of OIS 5e along Spanish Peninsular coasts.

7. Conclusions

The palaeontological, sedimentological and geomorphological records of OIS 5e deposits in the Western Mediterranean, allow the proposal of a model for the connections between this basin and high-latitude climatic changes in the Northern Hemisphere, in comparison with modern analogues.

High-resolution ice, marine and terrestrial records of OIS 5e in the Northern Hemisphere show a marked climate instability which is reflected in the Mediterranean setting by important faunal and sedimentological changes. Geomorphological analyses allow the identification of different sea-level highstands.

During the warmest peak of Last Interglacial (OIS 5e), the Nordic Seas experienced a northward influence of warm North Atlantic Current, which could have reached Arctic or sub-Arctic areas. The northern influence of north-westerlies could have facilitated the predominance of eastern winds in the Western Mediterranean, promoting strong wave energy along east-facing littorals of Iberian Peninsula and Tunisia, where oolitic shoals developed, and where oolitic dune-beach systems developed. High sea surface temperature is evidenced by the presence of Senegalese fauna, specifically *S. bubonius*.

The end of the OIS 5e, is characterized by a decreasing influence of the warm North Atlantic Current in high latitudes, and by a southward migration of north-westerlies which induced a strong northern-winds influence in the Western Mediterranean. Here, SST remained warm but the area experienced an increase in both storminess and runoff.

In summary, sedimentology, palaeontology and geomorphology of OIS 5e deposits in the Western Mediterranean can be considered a useful tool in the reconstruction of ocean-atmosphere interactions as the driving mechanisms of environmental changes.

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