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Palaeoclimate and palaeoceanographic conditions in the westernmost Mediterranean over the last millennium: an integrated organic and inorganic approach

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Abstract: Previous studies have revealed the excellence of the westernmost Mediterranean records for reconstructing climate conditions over the last two millennia. In particular, inorganic and organic proxies have revealed a coherent signal of climate and oceanographic responses during this time. Here we compare and integrate both proxy records for reconstructing climate and oceanographic conditions with focus on the last millennium. The higher temperatures indicated by lipid-based proxies during the Medieval Climate Anomaly (MCA) are coincident with drier conditions indicated by inorganic proxies. In contrast, lower temperatures and humid conditions are indicated during the Little Ice Age (LIA). The industrial period was characterized by increasing humidity in comparison with the previous LIA. However, a progressive aridification occurred since the second half of the twentieth century, coexisting with a warming trend and higher contribution of C_3 grasses. Proxy records are also interpreted to show Atlantic water inflow at AD 1450 and 1950 and an intensification of the upwelling conditions coinciding with a prolonged positive North Atlantic Oscillation (NAO) phase in the intervals AD 1000–1450 and 1960–1990. Large-scale oceanic–atmospheric circulation patterns (the NAO and the Atlantic meridional circulation) and solar irradiance variations seem to have played the major key role during the last millennium, together with anthropogenic contributions in the more recent record.

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Understanding past climate variability far beyond the historical record reached by instrumental measurements is crucial to increase the knowledge on current climate change as the basis for potential future climate projections (IPCC 2007, 2013). Palaeoclimate reconstructions of the last millennium, in which boundary conditions on the climate and natural forcing factors are representative of those of present day, can significantly contribute to our overall understanding of Earth's climate at regional and global scales (e.g. Mayewski *et al.* 2004; Wanner *et al.* 2008). These palaeo-data can be decoded using various proxies from natural recorders of climate variability such as ice cores, tree rings, coral reefs, speleothems, boreholes, peat bogs, and marine and lake sediments in regions sensitive to climate change. In this sense, the westernmost Mediterranean realm has a high scientific interest owing to its unique location, which has proved to be particularly sensitive to climatic and anthropogenic forcing (such as solar radiation, temperature and acidification, growing anthropogenic pressure and chemical contaminants) (e.g. Lionello *et al.* 2006; Durrieu de Madron *et al.* 2011; Lionello 2012). As an example, over the last millennium, the interplay of natural and human-induced environmental changes, such as natural and/or human-set fires, land-use changes and a long-term Mid- to Late Holocene climate aridification have resulted in a high degree of xerophytization in this region (e.g. Carrión *et al.* 2010).

To date, on the basis of diverse proxies, the so-called Medieval Climate Anomaly (MCA) (*c*. AD 800–1300) has been described as a notable warm period with intense droughts in some regions of the Northern Hemisphere, followed by a decline in temperature during the subsequent Little Ice Age (LIA, *c*. AD 1300–1800) (e.g. Lamb 1965; Stine 1994; Seager *et al.* 2007). In the Iberian Peninsula, high-resolution studies spanning the last millennium have been mainly based on pollen and geochemical proxies from lacustrine and marine records, which have provided evidence for hydrology and vegetation changes during the MCA–LIA transition (Moreno *et al.* 2012; Roberts *et al.* 2012, and references therein). To provide further insights into the major questions regarding the nature, spatial extent and forcing mechanisms for climate and temperature anomalies during the MCA and the LIA (e.g. Díaz *et al.* 2011; Trouet *et al.* 2012), we have combined results obtained from a wide suite of inorganic and organic geochemical and sedimentological proxies in two marine records recovered in the northwestern Alboran Sea basin, previously discussed in two recent studies (see Nieto-Moreno *et al.* 2013*a*,*b*). Although previous studies have provided new insights into palaeo-hydrology conditions for the last millennium (humid or dry conditions) in the western Mediterranean and the Iberian Peninsula (Martín-Puertas *et al.* 2010; Nieto-Moreno *et al.* 2011; Moreno *et al.* 2012), the integration of inorganic and organic

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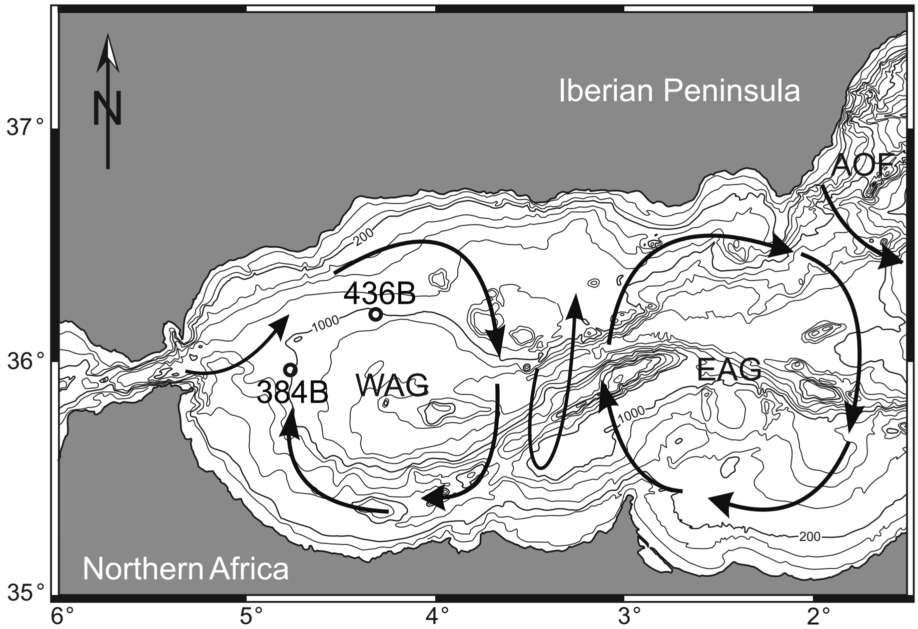

Fig. 1. Location of the studied cores in the Alboran basin. WAG, Western Alboran Gyre; EAG, Eastern Alboran Gyre; AOF, Almería–Orán Front.

approaches in this paper has allowed not only the elaboration of a further coherent hydrology and temperature reconstruction in this region and the characterization of the potential processes involved, but also further understanding of terrestrial and ocean responses such as possible changes in land vegetation cover, upwelling events and fluctuations in ocean circulation during this time period.

Modern climate and oceanographic setting

The westernmost Mediterranean (Alboran Sea basin) is a marginal and semi-enclosed basin connected to the Atlantic Ocean through the Strait of Gibraltar and with circulation patterns characterized by sub-basin-scale gyres and a general thermohaline circulation (e.g. Lionello *et al.* 2006; Lionello 2012; Fig. 1). Its latitudinal position characterizes the hydrological regime in this region: the temperate westerly system with associated Atlantic depressions that dominates over central–northern Europe in winter and the subtropical high-pressure belt that induces summer droughts in southern Europe and North Africa. The westerly system is associated with the North Atlantic Oscillation (NAO), which is one of the major patterns of atmospheric circulation in the North Atlantic region and determines most of the winter precipitation regime in the Mediterranean (e.g. Hurrell 1995; Trigo *et al.* 2004). The NAO alternates between a ‘high-index’ (positive NAO) and a ‘low-index’ pattern (negative NAO) with centres of action in the Icelandic Low and the Azores High. A positive NAO phase is characterized by an intensified Azores High and deeper Icelandic Low, thus stronger westerly winds transporting storms to the eastern North Atlantic and the northern European continent and leading to dry winters in southern Europe, the Mediterranean and northern Africa (e.g. Wanner *et al.* 2001; Trigo *et al.* 2002). During a negative phase of the NAO the Azores High is weaker and the Icelandic Low is shallower, thus giving rise to reduced westerly winds over the eastern North Atlantic and increasing precipitation in the western Mediterranean.

Regarding oceanographic conditions, the general thermohaline circulation in the Mediterranean Sea is determined by the exchange of waters at the Strait of Gibraltar. The surface inflow consists of Atlantic waters becoming more saline as they move eastwards, and the deep-water outflow involves Levantine Intermediate Water (LIW) and Western Mediterranean Deep Water (WMDW) formed in the Adriatic–Aegean Sea and in the Gulf of Lyon, respectively (e.g. Millot 1999; Bergamasco & Malanotte-Rizzoli 2010). The Atlantic inflow describes an anticyclonic gyre in the western Alboran Sea (the Western Alboran Gyre, WAG) with high productivity on its northern edge owing to upwelling (Fig. 1). Upwelling is mostly induced by winds (westerly winds) and by the north–south fluctuation of the Atlantic inflow related to changes in the position and shape of the gyre (e.g. Sarhan *et al.* 2000).

Proxies for palaeoenvironmental reconstructions

An increasing number of geochemical proxies relying on inorganic and organic compounds has been developed during the last few decades (e.g. Calvert & Pedersen 2007; Rosell-Melé & McClymont 2007; Eglinton & Eglinton 2008; Castañeda & Schouten 2011), and numerous studies currently apply these proxies to reconstruct environmental conditions in marine sedimentary sequences from around the world, including the westernmost Mediterranean region (e.g. Cacho *et al.* 2000; Martrat *et al.* 2007; Jiménez-Espejo *et al.* 2008; Martín-Puertas *et al.* 2010; Huguet *et al.* 2011; Nieto-Moreno *et al.* 2011, 2013*a*,*b*; Rodrigo-Gámiz *et al.* 2011, 2014). This paper arises from the integration of a wide set of some of these inorganic and organic proxies that has allowed for a more comprehensive reconstruction of environmental conditions.

The detrital fraction of marine sediments provides a wide range of information on sediment sources (terrestrial runoff and dust transport), marine productivity and sea-floor oxygenation (e.g. Calvert & Pedersen 2007). Element/Al ratios (such as Rb/Al, Mg/Al, K/Al, Si/Al, Ti/Al and Zr/Al) have been broadly used to infer fluctuations in riverine and aeolian input into the Alboran Sea basin (e.g. Jiménez-Espejo *et al.* 2008; Martín-Puertas *et al.* 2010; Nieto-Moreno *et al.* 2011, 2013*b*; Rodrigo-Gámiz *et al.* 2011). For this study we have selected Zr as a typical aeolian proxy mainly related to zircon grains carried by wind-blown African dust, and Si representing riverine input in the form of aluminosilicates and quartz, supported by the highest correlation with Al in the selected marine cores (Nieto-Moreno *et al.* 2013*b*). Selected redox-sensitive trace element ratios (such as Ni/Co and V/Cr) and grain-size distributions have provided information about oceanographic conditions, particularly in the deep-water column. The solubility of the former elements depends on the prevailing redox conditions (e.g. Tribovillard *et al.* 2006) whereas the percentage of sortable silt (SS, 10–63 µm) correlates with faster flows and better oxygenated deep waters (e.g. McCave *et al.* 1995; Hall & McCave 2000; Rogerson *et al.* 2008).

The most widely used proxy for sea surface temperature (SST) reconstructions based on organic fossil remains is the $U^{K'}_{37}$ index

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(Brassell *et al.* 1986). This index quantifies the ratio of unsaturated ketones (alkenones) biosynthesized by haptophyte algae and has a direct relationship to average annual SST (Prahl & Wakeham 1987; Müller *et al.* 1998). The TEX_{86} index has been recently proposed to reconstruct past SST (Schouten *et al.* 2002). This index quantifies the number of cyclopentane moieties in the glycerol diphytanyl glycerol tetraethers (GDGTs) in the membrane lipids of marine Thaumarchaeota. This index has a positive correlation with SST at depths of 0–100 m (Wuchter *et al.* 2004, 2005; Kim *et al.* 2008). The most recent calibration of TEX_{86} (Kim *et al.* 2010) is based on a logarithmic function of TEX_{86} (TEX^{H}_{86}).

Other organic proxies provide a more comprehensive characterization of environmental variations. Among them, *n*-alkanes allow reconstruction of past vegetation changes (Eglinton & Hamilton 1967). These compounds are lipid components of the epicuticular waxes produced by terrestrial plants, which have been transported and are well preserved in the oceans. Environmental factors such as temperature and humidity can affect the chain-length distribution of *n*-alkanes (e.g. Schefuß *et al.* 2003). In warmer climates, land plants biosynthesize longer chain compounds whereas in cooler temperate regions shorter chain compounds are produced. Additionally, the BIT index (branched versus isoprenoid tetraether index) is a proxy for terrestrial fluvial input of organic matter into the oceans and provides further information regarding the origin of the sedimentary organic matter (Hopmans *et al.* 2004; Weijers *et al.* 2006). The diol index (Rampen *et al.* 2008) has been used as an indicator of upwelling conditions (Rampen *et al.* 2007). It is based on the relative contribution of 1,14 long-chain diols in diatoms from the genus *Proboscia*, which are abundant in upwelling regions (Sinninghe Damsté *et al.* 2003). These proxies were tested for the first time at high resolution for the last millennium in the western Mediterranean by Nieto-Moreno *et al.* (2013*a*).

Material and methods

The various techniques applied and the materials used for this integrated organic–inorganic approach are briefly presented here. For further and detailed information on the method applied as well as discussion of the ^{210}Pb and ^{14}C age–depth model we refer the reader to Nieto-Moreno *et al.* (2013*a*,*b*).

Core material, sampling, and age–depth model

The selected records came from two box-cores recovered in the northwestern Alboran Sea basin in 2008 (384B: 35°59.161′N, 4°44.976′W, 1022 m below sea level (b.s.l.); 436B: 36°12.318′N, 4°18.800′W, 1108 m b.s.l.; Fig. 1). Upon retrieval, box-cores were subsampled using PVC pipes inserted into the sediment. One liner from each box core was immediately frozen on board at −18 °C and sampled in 1 cm slices once in the laboratory. A second liner was stored in a cool room at 4 °C. Each liner was used for different analyses and sample preparation. The age–depth model was based on the activity–depth profiles of ^{210}Pb and ^{137}Cs, plus ^{14}C dates (for further details see Nieto-Moreno *et al.* 2013*b*).

Biomarker, geochemical and sedimentological analyses

Biomarkers and total organic content (TOC) were analysed on the frozen box-core at the Royal Netherlands Institute for Sea Research (NIOZ) and by SGS Minerals Services, respectively. Sediment samples (5 g dry mass) taken every 1 cm, were freeze-dried, powdered and extracted. The extracts were separated into apolar, ketone and polar fractions for GDGTs, ketone, diols, $\delta^{13}C$ *n*-alkanes, and TOC analyses (for details see Nieto-Moreno *et al.* 2013*a*).

Major and trace element and grain-size analyses were carried out on the non-frozen box-cores at the Andalusian Institute of Earth Sciences (CSIC-UGR) and the Centre for Scientific Instrumentation (CIC-UGR). Bulk sediment samples (6 g dry mass) taken every 1 cm were dried and powdered, then analysed by inductively coupled plasma mass spectrometry and X-ray fluorescence (for details see Nieto-Moreno *et al.* 2013*b*).

Results and discussion

The strength and reliability of our interpretation relies on the solid correlation of the above-described proxies. Our results encompass proxies from different origins that, once put together, build up a consistent climate and oceanographic picture. Thus, variables such as temperature, humidity, vegetation cover, oceanic currents or human activity are inferred from these different types of proxies and present a comprehensive climate, hydrology and oceanic signal over the last millennium. The final reconstruction is also considered in the frame of broader regional knowledge, allowing for a more precise elucidation of the processes forcing climate in this time interval.

Palaeoclimate conditions over the last millennium; causes and mechanisms

Our climate reconstruction from the marine archives is mainly based on temperature and humidity data. TEX^{H}_{86} and $U^{K'}_{37}$-derived SST values report summer SST and autumn or average annual SST respectively (Figs 2 and 3), similar to the results obtained by other studies in the western and eastern Mediterranean Sea (for further details see Nieto-Moreno *et al.* 2013*a*). In general terms, our records revealed a progressive and long-term decline of SST (punctuated by minor increases) of about 1.5–2.0 °C over the last millennium, which was rapidly reversed during industrial times and the second half of the twentieth century, when SST rose between 0.5 and 1.8 °C (Figs 2 and 3). SST values were slightly higher during the MCA than the LIA, which are indicated as the warmest and the coldest pre-industrial periods in the area, respectively (Figs 2 and 3). The LIA was characterized as a period of prevalent humid conditions, although with a dry or humid phase alternation taking place, showing decreasing or increasing trends of fluvial-derived element (Si/Zr) and higher or lower African aeolian input (Zr/Al) (Figs 2 and 3). The decreasing and increasing trend of the BIT index (indicating soil-derived organic matter by fluvial input) during the MCA and LIA reinforces the interpretation of the inorganic proxies (Figs 2 and 3). The youngest part of our record showed more humid conditions during the Industrial Period (IP) than during the previous LIA (high riverine influence and low African aeolian input shown by Si/Zr and Zr/Al ratios; Figs 2 and 3). The BIT index also indicates an increase of soil-derived organic matter in the IP compared with the LIA (Figs 2 and 3). In addition, a progressive aridification trend was revealed during the second half of the twentieth century, as shown by the sharp decrease in fluvial-derived material (Si/Zr ratio in accordance with the BIT index) and the higher aeolian input (Zr/Al ratio) (Figs 2 and 3).

Despite these dry–warm and humid–cold centennial oscillations disclosed by the integration of the inorganic and the organic proxy data, no substantial effect on the land vegetation cover is detected. On one hand, $\delta^{13}C_{WMA27-33}$ at site 436B oscillates between −32.4‰ and −30.9‰ (Nieto-Moreno *et al.* 2013*a*). Considering previously reported end-member values of −36‰ for C_3 and −21‰ for C_4 vegetation (e.g. Castañeda *et al.* 2009), our reconstruction indicates a predominant C_3 plant type during the last millennium, dominated by trees, shrubs, cool-season grasses and sedges. On the other hand, the average chain length (ACL) of *n*-alkanes at site 436B varies between 30.0 and 30.4 with no systematic changes down-core (Fig. 3). Both indices suggest that the type of vegetation has not undergone major fluctuation owing to climate variability over the last millennium (e.g. Schefuß *et al.* 2003), most probably because vegetation cover requires longer periods to fully adapt to the cyclic climate variations described above.

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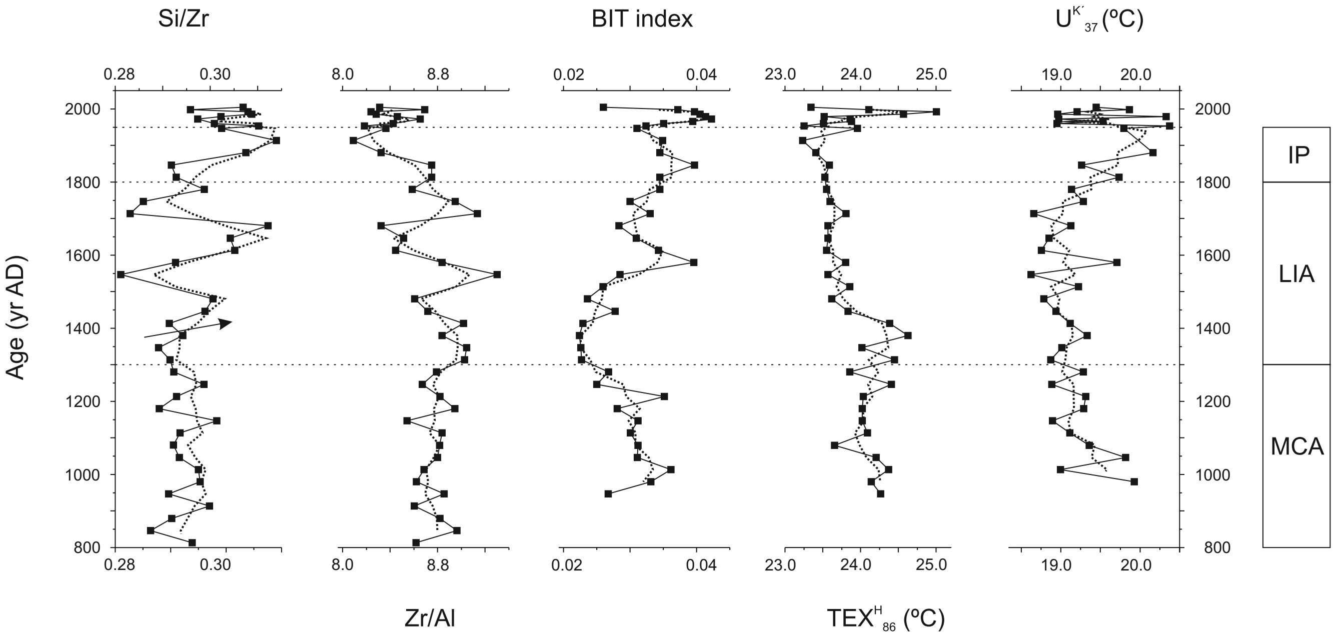

Fig. 2. Age–depth profile of detrital proxies (Si/Zr and Zr/Al ratios), BIT index, TEX^{H}_{86} and $U^{K'}_{37}$-based sea surface temperatures (SST) for core 384B (squares). MCA, Medieval Climate Anomaly; LIA, Little Ice Age; IP, Industrial Period. Dotted line indicates the three-point running mean of Si/Zr and Zr/Al ratios, BIT index, TEX^{H}_{86} and $U^{K'}_{37}$-based SST.

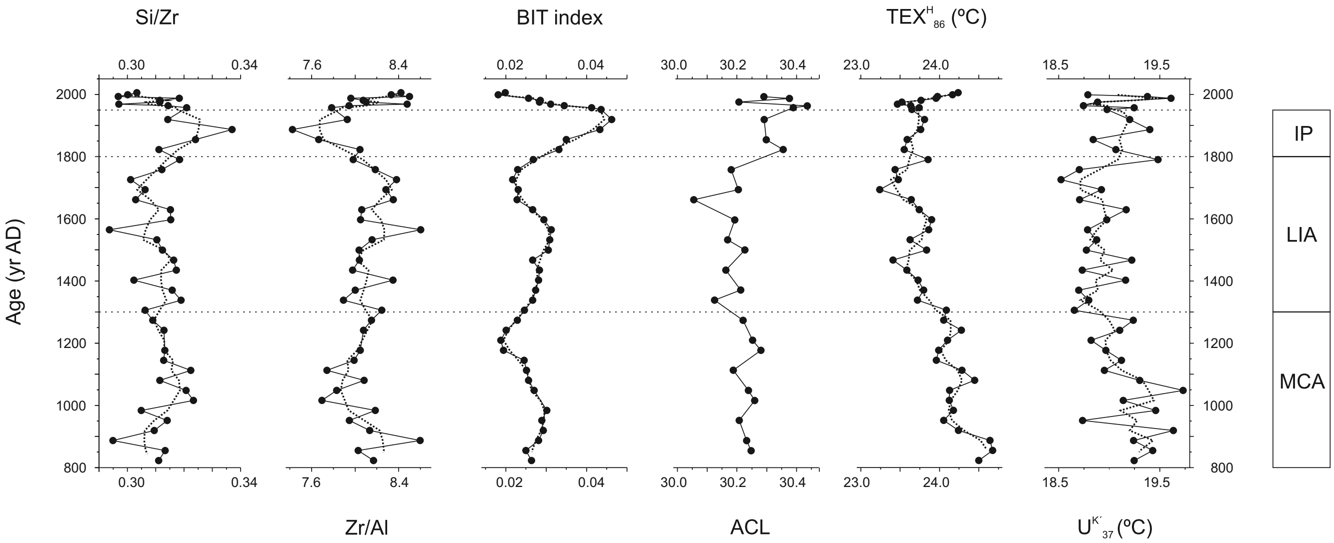

Fig. 3. Age–depth profile of detrital proxies (Si/Zr and Zr/Al ratios), BIT index, average chain length (ACL), TEX^{H}_{86} and $U^{K'}_{37}$-based sea surface temperatures (SST) for core 436B (circles). MCA, Medieval Climate Anomaly; LIA, Little Ice Age; IP, Industrial Period. Dotted line indicates the three-point running mean of Si/Zr and Zr/Al ratios, BIT index, TEX^{H}_{86} and $U^{K'}_{37}$-based SST.

These results are in agreement with previously published material for the Iberian Peninsula. Lacustrine reconstructions based on geochemical and biological proxies have indicated xerophytic vegetation and lower lake levels during medieval times (Moreno *et al.* 2012, and references therein). Pollen analyses of marine (Combourieu-Nebout *et al.* 2009) and terrestrial records (Jalut *et al.* 2000, 2009) also revealed forest cover regression during this time interval. In contrast, more humid conditions and mesophytic vegetation were found in the following centuries (Moreno *et al.* 2012; Roberts *et al.* 2012, and references therein). Maximum lake levels occurred during the nineteenth century whereas declining lake levels associated with warmer climatic conditions are found during the twentieth century (Morellón *et al.* 2011). Tree ring data in the Spanish Pyrenees showed higher temperatures than average in the fourteenth and fifteenth centuries and an unprecedented warming in the twentieth century (Büntgen *et al.* 2008). Instrumental data confirm a decrease in rainfall and moisture availability in the Mediterranean basin throughout the twentieth century, along with more frequent and severe drought episodes (Sousa *et al.* 2011). Furthermore, recent work based on geochemical proxies in high-resolution marine records from the Algerian–Balearic basin have revealed higher aeolian African input and reduced riverine influence during the MCA and opposite trends during the LIA (Martín-Puertas *et al.* 2010; Nieto-Moreno *et al.* 2011; Moreno *et al.* 2012).

Over the last millennium global surface temperature reconstructions have indicated that all regions experienced a long-term global cooling trend followed by recent warming during the twentieth century, except on Antarctica (PAGES 2k Consortium 2013). Overall global surface temperatures were higher at the end of the twentieth century than during the medieval highs. Global manifestations of a warm medieval period followed by a cool LIA have been likewise confirmed, although the specific timing of these intervals varies from site to site, resulting in regionally specific temperature departures from an underlying global cooling trend (PAGES 2k Consortium

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2013). On a millennial time scale, natural forcings such as orbital and solar variability as well as volcanic activity have been regarded as major causes influencing global climate, in particular natural orbitally induced cooling during the Mid- to Late Holocene (e.g. Wanner *et al.* 2008; PAGES 2k Consortium 2013; Moffa-Sánchez *et al.* 2014). Among the most plausible mechanisms inducing climate anomalies during the MCA and the LIA in the Northern Hemisphere, an interplay of external forcings (solar irradiance, volcanic activity) and climate system internal variability (NAO variability and changes in the Atlantic Meridional Overturning Circulation (AMOC)), and/or a combination of these, has been proposed (e.g. Trouet *et al.* 2009, 2012; Díaz *et al.* 2011; Olsen *et al.* 2012; Moffa-Sánchez *et al.* 2014). The NAO has also been proposed to modulate natural climate variability at decadal to centennial scales in the Mediterranean region (Trouet *et al.* 2009). A prolonged positive mode, characterized by stronger westerly winds transporting storms farther to the north and resulting in dry winters in the Mediterranean and northern Africa during the MCA (AD 1000–1450), alternates with weakened winds bringing storms to the Mediterranean and northern African region (negative mode), thus triggering humid winters during the LIA (e.g. Trigo *et al.* 2002, 2004). During the last century (AD 1960–1990), unprecedented strongly positive NAO phases have been recorded (Hurrell 1995; Rodó *et al.* 1997). These prolonged periods with anomalous positive NAO phases and stronger westerly winds associated, may have enhanced the AMOC, as was proposed for the MCA over Europe (Trouet *et al*. 2009, 2012).

Our SST reconstruction for the pre-industrial period is consistent with Northern Hemisphere surface temperature reconstructions from instrumental and high-resolution proxy data and attributed to orbitally induced cooling during the last millennium (Wanner *et al.* 2008; Wahl *et al.* 2010; PAGES 2k Consortium 2013). Warmer and drier conditions during the MCA and colder and humid conditions during the LIA correlate with other records in the Iberian Peninsula and the western Mediterranean, and seem to be promoted by the modulation of the NAO as proposed by Trouet *et al.* (2009) to explain the see-saw anomalies occurring in the North Atlantic–European realm during the last millennium.

The rapid reversed warming trend depicted by SST since industrial times is also in agreement with Northern Hemisphere surface temperature reconstructions (Wahl *et al.* 2010; PAGES 2k Consortium 2013). Our results also show warmer temperatures during the second half of the twentieth century than during the last millennium similar to these Northern Hemisphere reconstructions. Recent model simulations have failed to reproduce the observed warming only using natural forcings (solar output and volcanic activity) and have produced good simulations of the warming over the past century when including human factors such as the effects of increasing levels of anthropogenic greenhouse gases (IPCC 2007, 2013).

Additionally, drier conditions (higher aeolian input and reduced riverine influence) during the second half of the twentieth century coexist with higher land-derived contribution from C_3 grasses (increased ACL values) (Fig. 3). This apparent contradiction was most probably caused by the increase in agricultural activities and changes in land use in the region. Thus, for the most recent period, the geochemical record overlaps natural and anthropogenic activity affecting not only the temperature record (owing to increasing anthropogenic greenhouse gas emissions) but also the detrital record owing to land use and soil cultivation.

Palaeoceanographic conditions over the last millennium; causes and mechanisms

Concerning oceanic processes, our record at site 436B shows that the last millennium in the westernmost Mediterranean was characterized by sediments deposited under mostly moderate hydrodynamic energy conditions and oxygenated bottom waters (Fig. 4). This is supported by the uniformity of the particle-size distribution (mainly clay fraction, 50–75%), minor fluctuations of redox-sensitive elements (V/Cr and Ni/Co ratios) and the diol index (0.2–0.5) (Fig. 4). Although marine productivity is not particularly enhanced in the region during the studied interval (as shown by the narrow range of variation of TOC: 0.7–1%; Fig. 4), organic matter preserved in the sediment is mainly formed within the basin, with minor input of terrestrial material, as shown by low BIT values (<0.05) (Figs 2 and 3).

A remarkable decrease in redox-sensitive elements took place at AD 1450 (lasting until 1900) and after AD 1950 (low V/Cr and Ni/Co ratios), which coincides with coarser sediments (most abundant fine silts at this site) and more variable sortable silt (SS) values during the LIA and the second half of the twentieth century compared with the preceding MCA and IP respectively (Fig. 4). The diol index depicts a declining trend in the same time intervals as the inorganic proxies (after AD 1450 and 1950) (Fig. 4). These conditions (low V/Cr and Ni/Co ratios and coarser grain size) are indicative of better oxygenated bottom waters and faster bottom currents, which can be attributed to a reinforcement of the WMDW. In contrast, two marine records from the Algerian–Balearic basin (*c*. 2500 m b.s.l. depth) revealed faster bottom currents and intense hydrodynamic conditions during the MCA and opposite palaeoceanographic conditions during the LIA based on the same proxies (redox-sensitive elements and grain-size distribution) (Nieto-Moreno *et al.* 2011). Nieto-Moreno *et al*. claimed enhanced WMDW formation promoted by the intensification of northwesterly winds towards the Gulf of Lyon during prolonged positive NAO phases, and collapse of WMDW formation owing to weaker and southward displaced westerly winds during prolonged negative NAO phases. We propose a different oceanographic mechanism triggering a more vigorous WMDW current during the LIA and the second half of the twentieth century at site 436B. Although the Algerian–Balearic basin is close to our study area, there is a significant difference in water depth (2500 m v. 1100 m). The WMDW flows from its source area filling the lowermost part of the water column from east to west, and spilling over the Strait of Gibraltar. However, its outflow can be favoured by uplifted effects on the WAG, where site 436B is located. Some researchers have verified that intensification of the WAG is able to raise deeper waters from a layer between 500 and 700 m depth (García-Lafuente *et al.* 2009; Naranjo *et al.* 2012; Sánchez-Garrido *et al.* 2013), allowing WMDW to rise and flow out of the basin on shallower depths. Likewise, we suggest a similar mechanism affecting deep waters after AD 1450 and 1950 in our record, owing to an enhanced surface inflow of Atlantic waters entering the Mediterranean Sea and intensifying the WAG (Fig. 1).

Atlantic freshwater incursions into the Mediterranean Sea through the Strait of Gibraltar have been previously explained by ice-sheet collapses during times of reduced North Atlantic Deep Water (NADW) production (Sierro *et al.* 2005; Rogerson *et al.* 2010). Reduced NADW induced changes in the AMOC linked to freshwater discharge into the North Atlantic from the melting Greenland ice sheets as a response to the long-term decline in summer insolation in the Northern Hemisphere during the LIA (Bond *et al.* 1997, 2001; Wanner *et al.* 2008, 2011; Sicre *et al.* 2014). Such reduced NADW (and thus intensified Atlantic injection into the Mediterranean) has been reported for the MCA–LIA transition (*c*. AD 1450). Trouet *et al.* (2012, and references therein) described a 10% reduction of NADW, and an abrupt slowdown of AMOC from AD 1915 to 1935 at high latitudes, affecting middle latitudes 3–7 years later. This has been modelled based on a coupled general circulation model (GCM; Lin *et al.* 2014). Thus we point to a slowdown in NADW as the driving mechanism triggering these oceanographic conditions for the two above-mentioned events.

Concurrently, the diol index points to a reduction of the upwelling conditions after AD 1450 and 1950 at site 436B. An intensification

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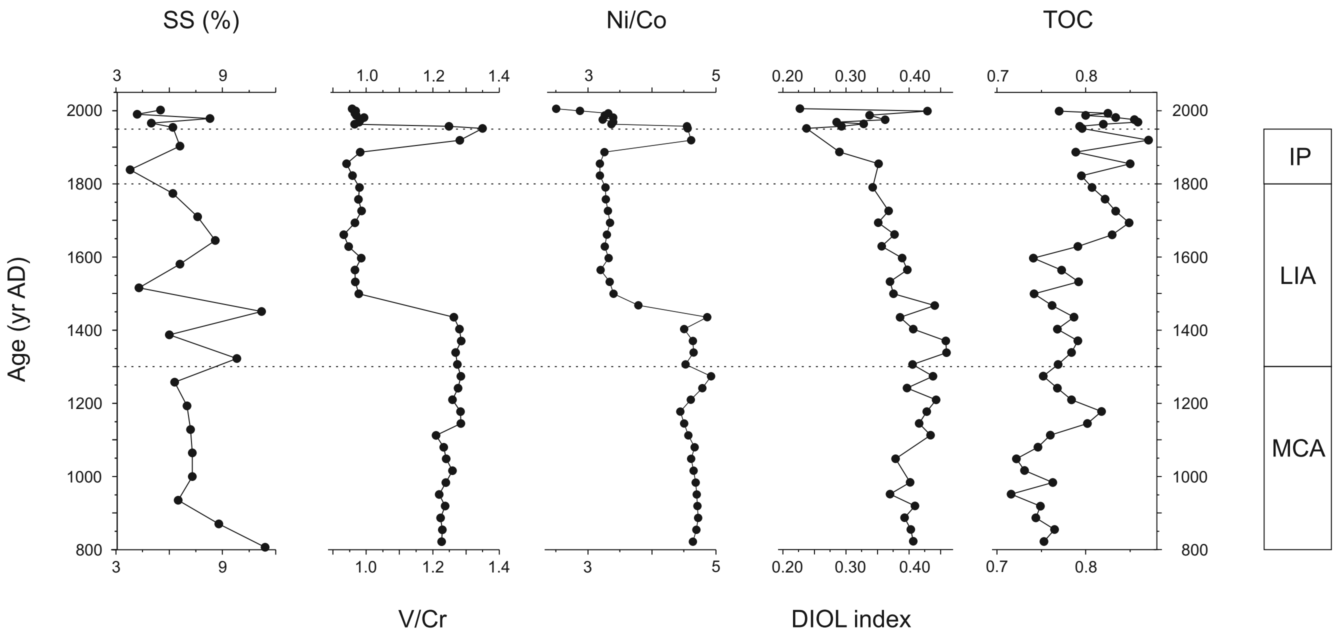

Fig. 4. Age–depth profile of grain size distribution (sortable silt; SS), redox proxies (V/Cr and Ni/Co ratios), upwelling conditions (diol index) and palaeoproductivity proxies (total organic carbon; TOC) for core 436B (circles). MCA, Medieval Climate Anomaly; LIA, Little Ice Age; IP, Industrial Period.

of the upwelling conditions is evidenced over the MCA and the second half of the twentieth century, coinciding with prolonged positive NAO modes (Hurrell 1995; Trouet *et al.* 2009, 2012). Vargas-Yáñez *et al.* (2008) pointed out the positive correlation between the NAO index and the westerly wind-induced upwelling in the Alboran Sea basin. Because positive NAO phases are characterized by stronger westerly winds transporting storms to the eastern North Atlantic and northern Europe (Wanner *et al.* 2001; Trigo *et al.* 2004), the intensification of the upwelling conditions revealed by the diol index seems to be induced by a different mechanism. On the other hand, Moulin *et al.* (1997) reported enhanced African dust transport into the Mediterranean during positive NAO phases promoted by winter Mediterranean cyclones, which would be restricted during negative NAO phases. Our records also show higher aeolian input during the second half of the MCA and the twentieth century (Figs 2 and 3). Also, the highest African aeolian input of the last 4000 years has been recorded in marine gravity-cores from the Algerian–Balearic basin during the MCA (Martín-Puertas *et al.* 2010; Nieto-Moreno *et al.* 2011; Moreno *et al.* 2012). This is further supported by the decreasing trend of the diol index observed during the LIA and the industrial period (Fig. 4), which corresponds to development of the negative mode of the NAO. Our records in the Alboran Sea basin and other records in the Algerian–Balearic basin (Martín-Puertas *et al.* 2010; Nieto-Moreno *et al.* 2011; Moreno *et al.* 2012) also reveal these time intervals as prevalently humid periods, with increasing freshwater input and declining aeolian input. Therefore, we suggest that the intensification of the upwelling conditions is promoted by Mediterranean cyclogenesis rather than by the westerly wind system associated with the North Atlantic storm tracks.

Conclusions

The combination of diverse inorganic and organic proxies allowed a multi-variable environmental reconstruction of the westernmost Mediterranean region. Si, Zr, TOC, TEX^{H}_{86}, $U^{K'}_{37}$ and BIT index showed consistent climatic signals of warm and mostly dry phases alternating with humid and cold periods. Dry–warm and humid–cold conditions during the Medieval Climate Anomaly (MCA) and the Little Ice Age (LIA) respectively, seem to be promoted by solar irradiance variations and the modulation of the North Atlantic Oscillation (NAO) in the westernmost Mediterranean.

At the same time, comparisons of the diol index, sortable silt and redox trace elements permitted the identification of oceanographic events that, in turn, might have been related to broader scale climatic fluctuations. In fact, additional natural forcing mechanisms such as the possible weakening of the rate of production of North Atlantic Deep Water (NADW) might have been also involved, as indicated by our records at AD 1450 and 1950. Winter Mediterranean cyclogenesis during a prolonged positive mode of the NAO during the MCA and the second half of the twentieth century also induced an intensification of the upwelling conditions as well as major African aeolian input into the basin, again supporting the connection between oceanographic and climatic processes.

Finally, the integration of $\delta^{13}C_{n\text{-alkanes}}$ and average chain length (ACL) with TEX^{H}_{86} and $U^{K'}_{37}$-derived sea surface temperatures and detrital input proxies allowed us to recognize overlapping anthropogenic forcing in the more recent record from the unprecedented rise of temperatures and the enhanced contribution of C_3 grasses, probably owing to increasing greenhouse gas emissions from human activities and progressive aridification and soil erosion owing to changes in land use.

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