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Millennial- to centennial-scale climate periodicities and forcing mechanisms in the westernmost Mediterranean for the past 20,000 yr

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ABSTRACT

Cyclostratigraphic analysis conducted on a continuous high-resolution marine record from the western most Mediterranean reveals well-identified paleoclimate cycles for the last 20,000 yr. The detrital proxies used (Si/Al, Ti/Al, Zr/Al, Mg/Al, K/Al, Rb/Al) are related to different sediment-transport mechanisms, including eolian dust and fluvial runoff, which involve fluctuations in the atmosphere–hydrosphere systems. These fluctuations are accompanied by changes in marine productivity (supported by Ba/Al) and bottom-water redox conditions (Cu/Al, V/Al, Zn/Al, Fe/Al, Mn/Al, U/Th). Spectral analysis conducted using the Lomb–Scargle periodogram and the achieved significance level implemented with the permutation test allowed us to establish major periodicities at 1300, 1515, 2000, and 5000 yr, and secondary peaks at 650, 1087, and 3000 yr. Some of these cycles also agree with those previously described in the North Atlantic Ocean and circum-Mediterranean records. The periodicities obtained at 2000 and 5000 yr support a global connection with records distributed at high, mid, and low latitudes associated with solar activity, monsoonal regime and orbital forcing. The 1300- and 1515-yr cycles appear to be linked with North Atlantic climate variability and the African monsoon system. Thus, the analyzed record provides evidence of climate cycles and plausible forcing mechanisms coupled with ocean–atmosphere fluctuations.

Introduction

A range of different paleorecords (i.e., ice cores, terrestrial and marine sediments) globally distributed (i.e., Greenland, North Atlantic and Pacific Oceans) have shown climate oscillations during the last glacial cycle on diverse timescales, resulting from interactions among the different elements of the Earth's environmental system (e.g., Broecker, 1994; Bond and Lotti, 1995; Stuiver et al., 1995; Sirocko et al., 1996; Chondrogianni et al., 2004). Most periodic variations in the Earth's climate system on long timescales have been directly related to Milankovitch forcings (mainly 20 to 400 ka) and caused by variations in the orbital cycles. Nevertheless, most cyclic patterns recognized at sub-Milankovitch timescales (<20 ka) during the late Pleistocene and Holocene in the North Atlantic regions correspond to Dansgaard–Oeschger (D–O) oscillations and Bond cycles. Extreme events of ice-rafted detritus deposition (Heinrich events, H) took place at the culminations of progressive coolings (stadials) followed by rapid warmings (interstadials) in the context of D–O oscillations during the last glacial interval, showing a periodicity of about 7000 to 10,000 yr (Heinrich, 1988; Bond et al., 1993; Dansgaard et al., 1993; Grousset et al., 1993). Furthermore, the climate quasi-periodic slowdown of North Atlantic Deep Water (NADW) production and the cold climate in Europe recorded at the millennial timescale, with an average duration of 1470 ± 500 yr, have been described as Bond cycles (Bond et al., 1993; Broecker, 1994; Bond et al., 2001).

At higher frequency timescales, interannual to decadal or even centennial climate oscillations appear to be associated with the El Niño-Southern Oscillation (ENSO), changes in the intensity of the Inter-Tropical Convergence Zone (ITCZ)—and consequently in the monsoon variability—and oceanic–atmospheric processes related to the North Atlantic Oscillation (NAO) (e.g., Sirocko, 1996; Marshall et al., 2001; Wanner et al., 2001; Marchitto et al., 2010). Even though significant climate changes also occur at longer time scales, the forcing mechanisms are still poorly understood, as well as the nature of primary or secondary cycles can be frequently controversial (Obrochta et al., 2012). Possible causes may entail non-linear responses to orbital cycles (i.e., variations in solar output/activity) (Van Geel et al., 1999; Bond et al., 2001; Kodera

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and Kuroda, 2005) amplified by a wide range of internal factors of the climate system, such as changes in the ice extent or in the sea surface freshwater balance (e.g., Denton and Karlen, 1973; Bond et al., 1997; Broecker, 2000; deMenocal et al., 2000; Gasse, 2000; Stocker, 2000; Mayewski et al., 2004). The only possibly linear response to orbital forcing would be the double insolation maximum described in tropical regions over the course of a year, producing 11,000 yr and 5500 yr periods of equatorial insolation (Berger et al., 2006).

In the case of the Mediterranean region, significant climate variations related with D–O oscillations and H events have been described (e.g., Cacho et al., 1999; von Grafenstein et al., 1999; Cacho et al., 2000; Shackleton et al., 2000; Cacho et al., 2001; Martrat et al., 2004; Moreno et al., 2004, 2005; Sierro et al., 2005; Martrat et al., 2007; Naughton et al., 2009; Sprovieri et al., 2012), demonstrating a strong link between the Mediterranean and North Atlantic climates, and with the monsoon regimen (e.g., Sánchez Goñi et al., 2008; Sprovieri et al., 2012). Furthermore, other paleoenvironmental changes such as vegetation cover, aridity conditions, productivity oscillations and the cooling of sea-surface temperature (SST) show a clear D–O variability with statistically significant cycles at 730, 1470, 3300, 5000, and 8000 yr, and harmonics for the time interval spanning 48,000 to 28,000 cal yr BP (Cacho et al., 1999; Moreno et al., 2005).

Nevertheless, climatic studies into sub-Milankovitch frequencies require a high-resolution proxy record as well as high continuity of the paleoclimate archive to identify potential signals. In this regard, this paper presents a detailed cyclostratigraphic analysis, using a range of statistically significant paleoenvironmental proxies (detrital input, redox conditions, paleoproductivity, and paleotemperature–paleosalinity), in a marine record from the Alboran Sea over the last 20,000 yr. Previous data from this core (Rodrigo-Gámiz et al., 2011) have revealed the excellence and interest of this record for this cyclostratigraphic approach. Innovative high-frequency climate periodicities at the millennial to centennial scale reveal novel insights into the timing and effect of global factors such as monsoon variability, the NAO and solar activity in the westernmost Mediterranean region.

Material and methods

Alboran Sea geochemical record: paleoenvironmental proxies

For this study we used high-resolution geochemical data from core 293G, recovered in the East Alboran Sea basin (Fig. 1) (Lat. 36′ 10.414N, Long. 2′45.280W, depth 1840 m) during the oceanographic cruise Training Through Research-12 (Comas and Ivanov, 2003). High-resolution geochemical analyses over the total length of the core (402 cm) were performed at 1.5-cm sampling intervals, obtaining a time resolution of about 75 yr/sample. Geochemical and mineralogical data from this sediment record have been reported in Rodrigo-Gámiz et al. (2011), revealing an exceptional dataset for cyclostratigraphic analyses. Major elements (Si, Al, Ti, K, Mg, Fe, Mn) and Zirconium (Zr) were measured using X-Ray Fluorescence (XRF), showing high precision with 1 sigma 1.0–3.4% on 16 data-sets at the 95% confidence level, monitored with reference materials. Trace elements (Rb, Ba, Cu, V, Zn, U, Th) were analyzed in triplicate using Re and Rh as internal standards by Inductively Coupled Plasma-Mass Spectrometry (ICP-MS) with an instrumental error of ±2% and ±5% for 50 ppm and 5 ppm elemental concentrations, respectively (Bea, 1996). Determination of stable oxygen isotope composition ($\delta^{18}O$) was carried out on the planktonic foraminifera *Globigerina bulloides* from the fraction over 125 μm using a Finnigan MAT 252 mass spectrometer with an analytical reproducibility of <0.07‰ and reported in the conventional notation with reference to V-PDB standard (Solnhofen Limestone is calibrated against NBS 19 as internal standard).

A detailed age model was established by linear interpolation between ten ^{14}C AMS radiocarbon ages in planktonic foraminifera

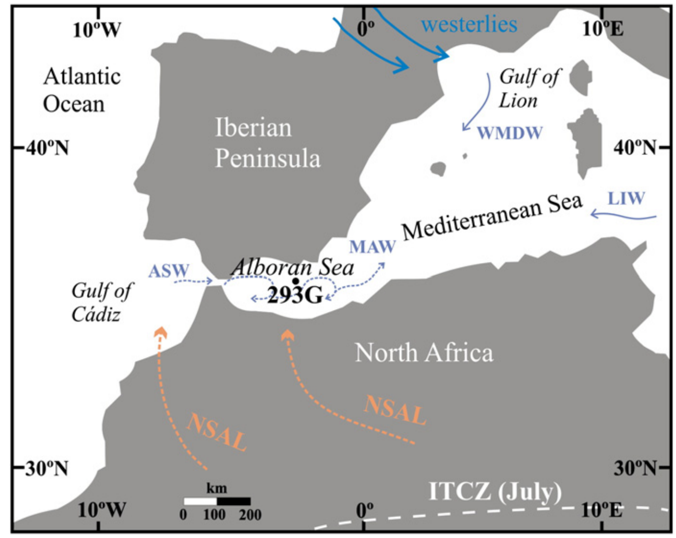

Figure 1. Iberian Peninsula map with setting of gravity core 293G in the Alboran Sea. Blue dashed arrows represent theoretical surface circulation in the Alboran Sea, influxes of Atlantic Surface Water (ASW) and Modified Atlantic Water (MAW) in the basin. Blue arrows represent westerly winds, Western Mediterranean Deep Water (WMDW) formation in the Gulf of Lion, and Levantine Intermediate Water (LIW). Orange dashed arrows indicate the main wind system over North Africa, the northern branch of Saharan Air Layers (NSAL). White dashed line show northern position of the Inter-Tropical Convergence Zone (ITCZ).

G. bulloides (>125 μm) spanning the last 20,000 yr (Rodrigo-Gámiz et al., 2011). ^{14}C AMS ages were calibrated to calendar years using Calib 6.0.2 software (Stuiver and Reimer, 1993) and the Marine09 calibration curve, with a correction for ocean surface reservoir effects of 400 yr (Reimer et al., 2009). The mean sedimentation rate, approximately 25 cm/ka, proved adequate for resolving high-frequency variability in this record.

The multiproxy approach permitted us to select a range of proxies that configure the four main groups used in this spectral analysis:

1) Detrital group: consisting of major and trace elements/Al ratios (Si/Al, Mg/Al, K/Al, Rb/Al, Ti/Al, Zr/Al). Eolian dust from the Sahara, which significantly contributes to Mediterranean sedimentation, is highly enriched in zirconium (Zr), silicon (Si) and titanium (Ti) (Pye, 1987; Grousset et al., 1989; Brumsack and Wehausen, 1999). These elements reside in heavy minerals (zircon, quartz and Ti oxides, respectively) that are chemically resistant in weathering profiles, surviving multiple cycles of erosion and deposition; thus these elements have been successfully used as eolian proxies (e.g., Calvert and Pedersen, 2007, and references therein). Clay minerals (illite, chlorite) and feldspars are the main mineral phases determining the K/Al, Mg/Al and Rb/Al ratios, and they are predominantly derived from fluvial sediments (Chester et al., 1977; Böttcher et al., 2003). In particular, changes in the K/Al ratio are reflecting fluctuations in the relative proportions of illite, usually transported via rivers (Meunier and Velde, 2004). Feldspars survive in poorly weathered soils and its increasing abundance also results in higher K/Al and Rb/Al ratios (Pastouret et al., 1978). In Mediterranean basins, chlorite (contributing to the Mg/Al ratio) is mainly found in sediments derived from the northern Mediterranean rivers (Foucault and Mélières, 2000).
2) Redox group: variations in certain redox-sensitive trace metal ratios used (Zn/Al, Cu/Al, V/Al, Mn/Al, Fe/Al, U/Th) indicate fluctuations in deep-water oxygen content at the time of sediment deposition (e.g., Böttcher et al., 2003; Brumsack, 2006; Tribovillard et al., 2006; Calvert and Pedersen, 2007). In general, vanadium (V) is reduced to insoluble species of lower valence under anoxic

conditions, and together with zinc (Zn) and copper (Cu) enrichments, it indicates anoxic bottom waters (Calvert and Pedersen, 2007, and references therein). Uranium (U) may also form a complex with dissolved fulvic acid in hemipelagic sediments (Nagao and Nakashima, 1992) that would concentrate under anoxic conditions. Manganese (Mn) is used to identify reventilation fronts (e.g., Mangini et al., 2001; Powell et al., 2003). Iron (Fe) could be considered a detrital element, but it can also precipitate with authigenic phases, as an oxide or as sulfide, in the form of pyrite (e.g., Powell et al., 2003; Calvert and Pedersen, 2007). Enrichments in both Mn and Fe could be promoted by the diffusion of Mn^{2+} and Fe^{2+} in pore waters from anoxic to oxic layers in which such cations are immobilized. On reaching an oxidative front, these elements can precipitate into other solid phases. However, Fe/Al and Mn/Al enrichments are usually uncoupled as a result of its different behavior under oxidizing conditions (e.g., Thomson et al., 1995; Rutten and de Lange, 2003).

3) Paleoproductivity group: the Ba/Al ratio is used as a productivity proxy since barium (Ba) excess derives from authigenic marine barite in the Ba-rich intervals from the studied sediment interval (Rodrigo-Gámiz et al., 2011); it can thus be considered as a reliable indication of export production fluxes. This proxy has been successfully used in the Mediterranean for paleoproductivity reconstructions (e.g., Dehairs et al., 1987; Martínez-Ruiz et al., 2000; Wehausen and Brumsack, 2000; Martínez-Ruiz et al., 2003; Paytan et al., 2004; Gallego-Torres et al., 2007, 2011, and references therein). In the particular case of the westernmost Mediterranean, enhanced productivity during cold periods such as the Younger Dryas (YD) and the last Heinrich event has also been recorded by Ba enrichments (e.g., Moreno et al., 2004; Jiménez-Espejo et al., 2008; Rodrigo-Gámiz et al., 2011).
4) Paleotemperature–paleosalinity group: major $\delta^{18}O$ changes in planktonic foraminifera reveal paleoceanographic oscillations, including global ice volume, surface-water salinities and temperature conditions (e.g., von Grafenstein et al., 1999; Shackleton et al., 2000). Indeed, ice sheets are the main suppliers of the lighter (^{16}O) isotope into the ocean during interglacial stages, and their response to rapid climate change is almost instantaneous on the millennial scale (Rogerson et al., 2006 and references therein).

Power spectral analysis

Even though the sampling space interval along the core is constant (1.5-cm sampling resolution), variations in the sedimentation rate lead to an uneven sampling time interval. Accordingly, cyclostratigraphic analysis of the studied time series was performed for the different proxies by means of the Lomb–Scargle periodogram (Lomb, 1976; Scargle, 1982). With this method, the power spectrum is evaluated for a high number of frequencies, larger than the number of experimental data. This is a very appropriate spectral methodology when working with uneven sampling data, providing a higher resolution than the main alternatives (obtaining an even time series by interpolation, or considering the uneven time series as even with an average sampling interval equal to the mean interdistance between data). Previous research has underlined the usefulness of this methodology in applications to paleoclimate and paleoceanographic time series with uneven sampling records, even when dealing with short time series or with incidence by punctual events (Jiménez-Moreno et al., 2007; Rodríguez-Tovar et al., 2010; Pardo-Igúzquiza and Rodríguez-Tovar, 2011, 2012, 2013). In evaluating the significance of the registered spectral peaks, one appropriate method is the implemented achieved significance level using the permutation test (see Pardo-Igúzquiza and Rodríguez-Tovar, 2000, 2005, 2011, 2012 for a detailed description). Subsequently, the peaks obtained through the achieved significance level can be considered as primary, and not secondarily generated by the applied methodology. Thus, out of all the peaks registered by means of the Lomb–Scargle procedure, only those also registered in the achieved significance level were interpreted in our study with independence of their significance level.

As a conservative strategy, in order to interpret only those peaks especially significant or primary—thereby avoiding consideration of secondary cycles that could be a consequence of the spectral methodology—our analysis is focused on the cycles registered in the frequency band that shows higher possibilities for registering primary cycles. Therefore, taking into account that the sediment core spans around 20,000 yr, the cycles at the lowest frequencies, registered close to the vertical axis in the achieved significance level and calibrated as higher than 7000 yr (around 1/3 of the total time interval), were not considered. On the other hand, given the sampling interval, the cycles in the highest frequency band, calibrated as lower than 500 yr, were likewise not interpreted. That is, we took into consideration only those cycles corresponding to periodicities between 500 and 7000 yr.

Results

Spectral treatment results: achieved significance level

In general, the four main groups of proxies distinguished show a well-developed cyclic pattern in their power spectrum (Figs. 2–4). Nevertheless, different patterns of general incidence are recorded for each proxy in their power spectra, with different cycles of variable significance summarized in Table 1. Of the different groups, detrital and redox groups exhibit the best-defined cyclic patterns, with numerous peaks of very high confidence levels (usually above 99% CL). Thus, very high confidence level is established as >95% CL and high confidence level as 70–95% CL therein after.

The detrital group evidences a cyclic pattern that is particularly well developed in the lower frequency bands, corresponding to cycles calibrated from 1515 to 5000 yr (Table 1); cycles at frequencies above those corresponding to cycles shorter than 1515 yr go unrecorded for the most part. The typical fluvial proxies of this group (Mg/Al, K/Al, and Rb/Al ratios) show peaks in different frequency bands (Figs. 2A–C, Table 1). In particular, the Mg/Al ratio reflects cycles of 2000 yr at high CL, around 3000 yr and 5000 yr, both at very high CL (Fig. 2A). The K/Al ratio shows a cycle at 1515 yr (high CL), and two close peaks at very high CL around 3000 yr (Fig. 2B). The Rb/Al ratio shows main cycles at 1515 yr, 2000 yr, and 5000 yr with a relatively very high CL (Fig. 2C). The main eolian input proxies (Si/Al, Zr/Al, and Ti/Al ratios) point to a less-developed cyclicity, with just a few registered peaks of minor significance and different temporal calibration (Figs. 2D–F, Table 1). The lowest frequency cycle at 5000 yr is only characterized by the Si/Al ratio (very high CL; Fig. 2D). Meanwhile, the Zr/Al ratio presents a cycle at 3000 yr (95.1–99% CL; Fig. 2E), and Ti/Al ratio shows 1515- and 2000-yr cycles, yet with a low CL (70–80%; Fig. 2F).

The redox group reveals the best cycle pattern (Figs. 3A–F). An outstanding feature recognized for this group is the generalized peak at 3000 yr, represented at very high CL in all of the redox-sensitive elements (Table 1). Thus, this group is characterized by all the main cycles obtained (1300, 1515, 2000, and 5000 yr) to quite a significant degree, although no exclusive frequency band was observed (Figs. 3A–F, Table 1). In particular, Cu/Al and Zn/Al ratios reveal 1300- and 5000-yr cycles with very high CL (Figs. 3A, B). The V/Al ratio shows cycles at higher frequency bands at 1300 and 1515 yr (very high CL; Fig. 3C). In turn, the U/Th ratio is recorded only in the main cycle at 1515 yr (Fig. 3D). Both Fe/Al and Mn/Al ratios characterize the 2000- and 5000-yr cycles with very high significance (Figs. 3E, F).

The Ba/Al ratio characterizes the paleoproductivity group that shows cycles at 1300 and 1515 yr, with high significance level (Fig. 4A). Finally, the paleotemperature–paleosalinity group records $\delta^{18}O$ cycles at periodicities of 1300, 2000 and 5000 yr, with their significances oscillating from high to very high CL (Fig. 4B).

Discussion

Relevance of the climatic cycles obtained from the cyclostratigraphic approach

Before interpreting the cycles registered at periodicities of 5000, 3000, 2000, 1515, 1300, 1087, and 650 yr (Table 1, Figs. 2–4), it is necessary to differentiate between primary cycles and secondary harmonics, or the artifacts of primary cycles. The cycles detected at 5000 yr, 2000 yr and 1515 yr show a constant periodicity as well as a generalized record in most of the four differentiated groups (Table 1), together with a mostly very high to high significance level. We may therefore interpret them as primary in origin. Other peaks having a variable temporal calibration, less frequent record, or lower CL, such as those around 3000 yr (in the range of 2778 yr and 3125 yr) or 1087 yr, are considered to be secondary manifestations of the primary peaks at 1515 yr and 2000 yr, respectively. Interpretation of the cycles at 1300 yr and 650 yr is no easy matter; yet according to their temporal calibration, as well as the corresponding record and CL, we may infer that the cycle at around 1300 yr (between 1282 yr and 1316 yr) is primary in origin, whereas the one at 650 yr would be secondary.

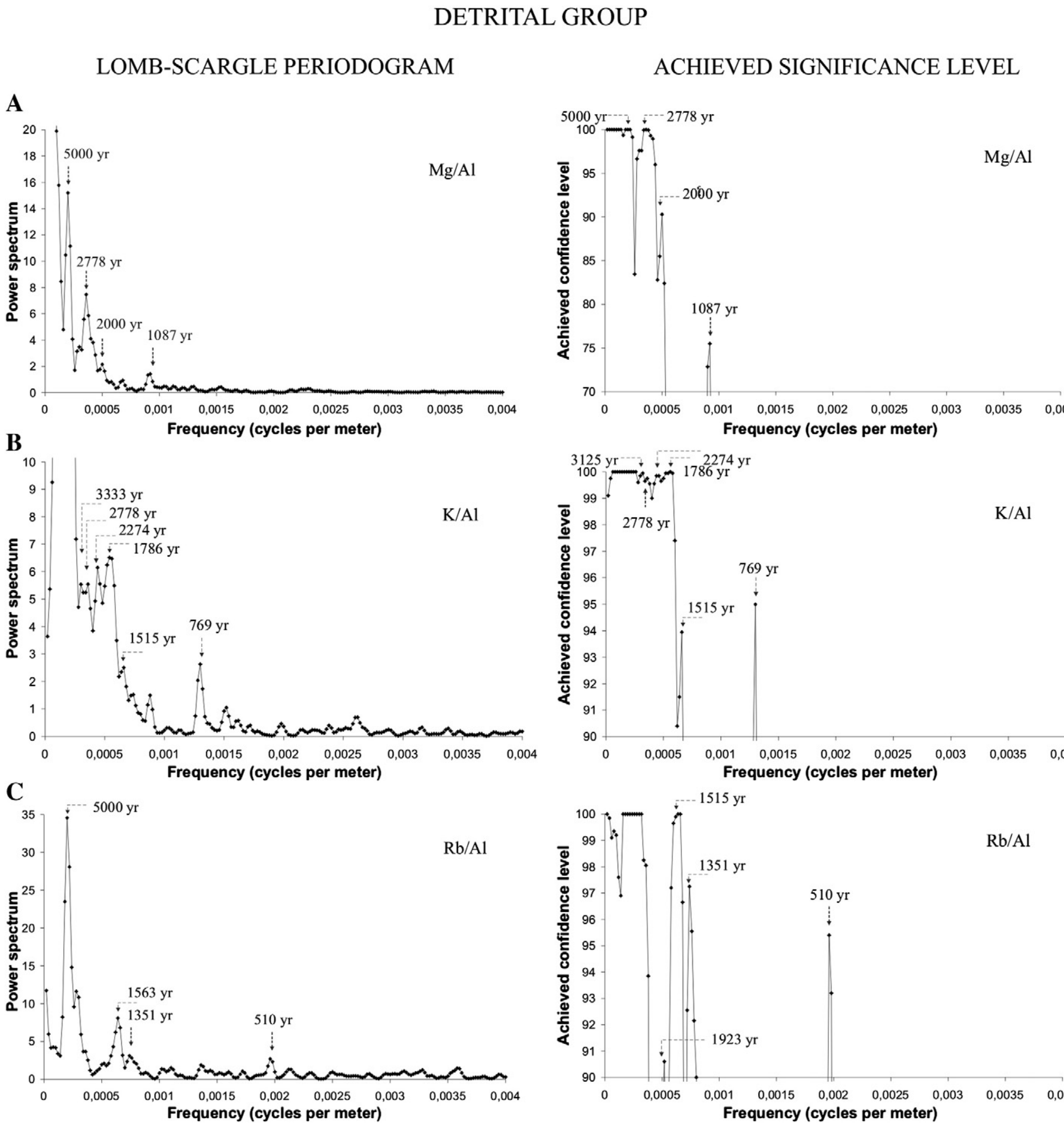

Figure 2. Power spectra for the four groups studied according to multi-proxy analysis of marine core 293G. Spectral peaks registered with Lomb–Scargle Periodogram are shown on the left; significant spectral peaks obtained with Achieved Significance Level are shown on the right.

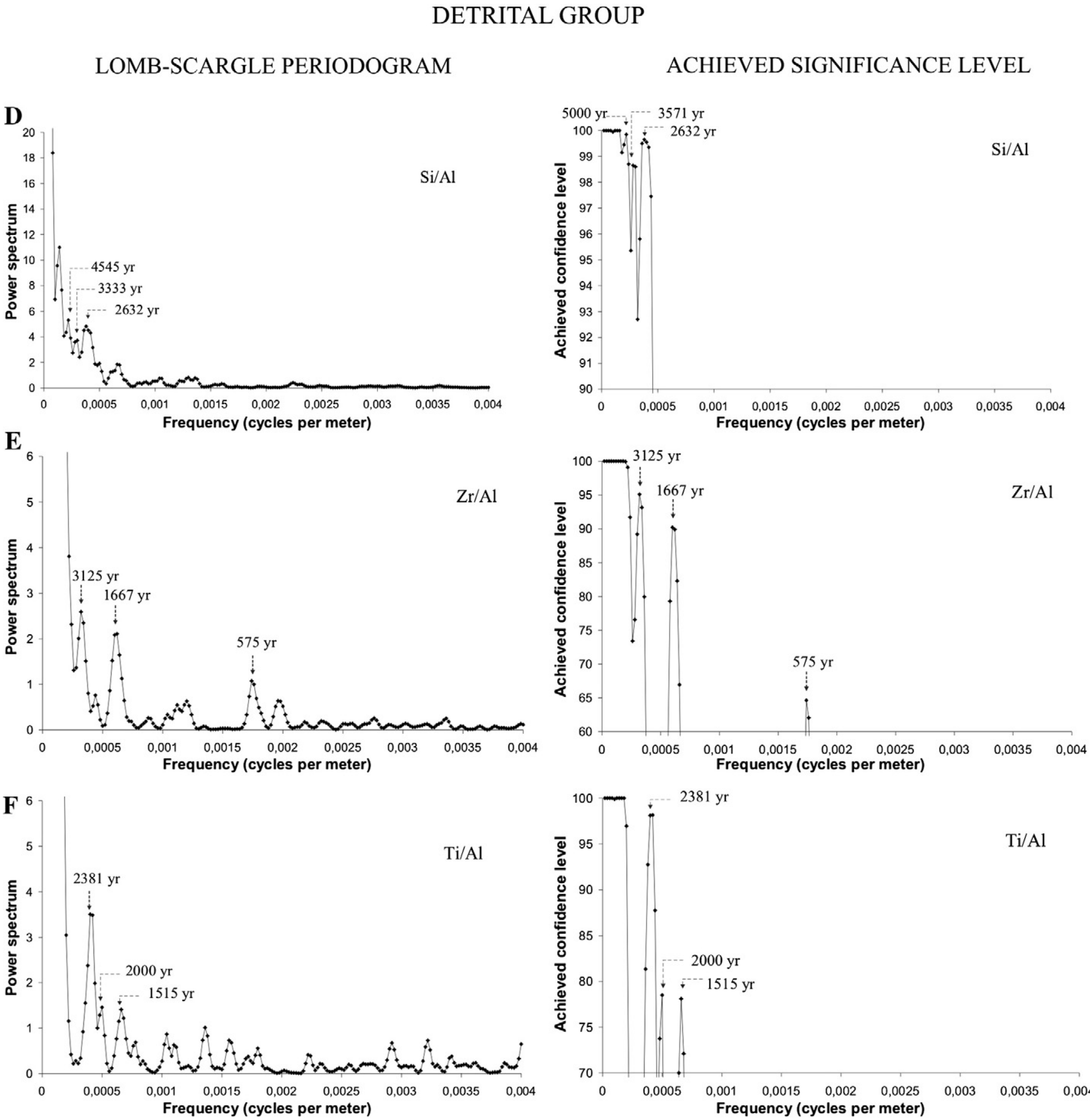

Figure 2 (*continued*).

Thus, detailed analysis of the interpreted primary peaks at 1300 yr, 1515 yr, 2000 yr, and 5000 yr, and the secondary harmonics, leads us to envisage significant paleoenvironmental implications and different forcing mechanisms when analyzing, accordingly, the groups of proxies differentiated (Figs. 5–7).

Forcing mechanisms

The 1300-yr cycle: influence of the North Atlantic waters

Paleoproductivity and paleotemperature–paleosalinity groups as well as some proxies included in the redox group (V/Al, Zn/Al, Cu/Al ratios) display a 1300-yr cycle and its secondary 650-yr harmonics (Figs. 6, 7A–B), but this cycle is not registered in the detrital group (Fig. 5). We therefore note similar periodicity between certain periods of major oxygen-depleted bottom water conditions reflected by highly significant V/Al, Zn/Al, Cu/Al ratios (Fig. 6) and major paleotemperature and paleosalinity variations ($\delta^{18}O$) (Fig. 7A). The fact that these millennial- to centennial-scale oscillations in the paleoceanographic context only affect the described proxies would point to oceanographic variations as the main origin for such cyclicity in the western Mediterranean, where this type of periodicity has not been recorded yet.

The 1300-yr cycle is not evident in most of the circum-North Atlantic climate records (Debret et al., 2007), although when recognized it has been associated with like-North Atlantic ice-rafted detritus events during the Holocene (Bond et al., 1997; Bütikofer, 2007), as well as with solar forcing (Berner et al., 2011). It is noteworthy that similar cycles around 1100 yr have been recorded by oceanographic proxy records near Iceland (Bianchi and McCave, 1999), and by summer temperature records in North American for the past 14 ka (Viau et al., 2006).

Lower oxygen levels recorded in the western Mediterranean, in turn, suggest stratification of the water column. This less intense thermohaline circulation could be triggered by different processes, such as increased riverine runoff due to an intensification of the African monsoon activity, or by a negative NAO index, among others. However, the absence of significance in any proxy that defined the detrital group leads us to discard any substantial atmospheric influence, meaning that oceanographic oscillations would be the main climate response to this cycle. Previous research suggests that a fresher Atlantic water inflow reduced the formation of the Levantine Intermediate Water (LIW) and/or the Western Mediterranean Deep Water (WMDW), weakening the Mediterranean thermohaline circulation (Rogerson et al., 2008). Lower thermohaline circulation intensity would reduce bottom-water ventilation, thereby increasing the contents in certain redox elements at this periodicity. Moreover, strong similarities with the secondary peak at 650 yr are reflected by the short SST cooling events (of about 730 ± 40 yr) previously observed during the Holocene in this region in association with short freshwater influxes (Cacho et al., 2001). One explanation for this cyclic phenomenon at 1300 yr, then, could be

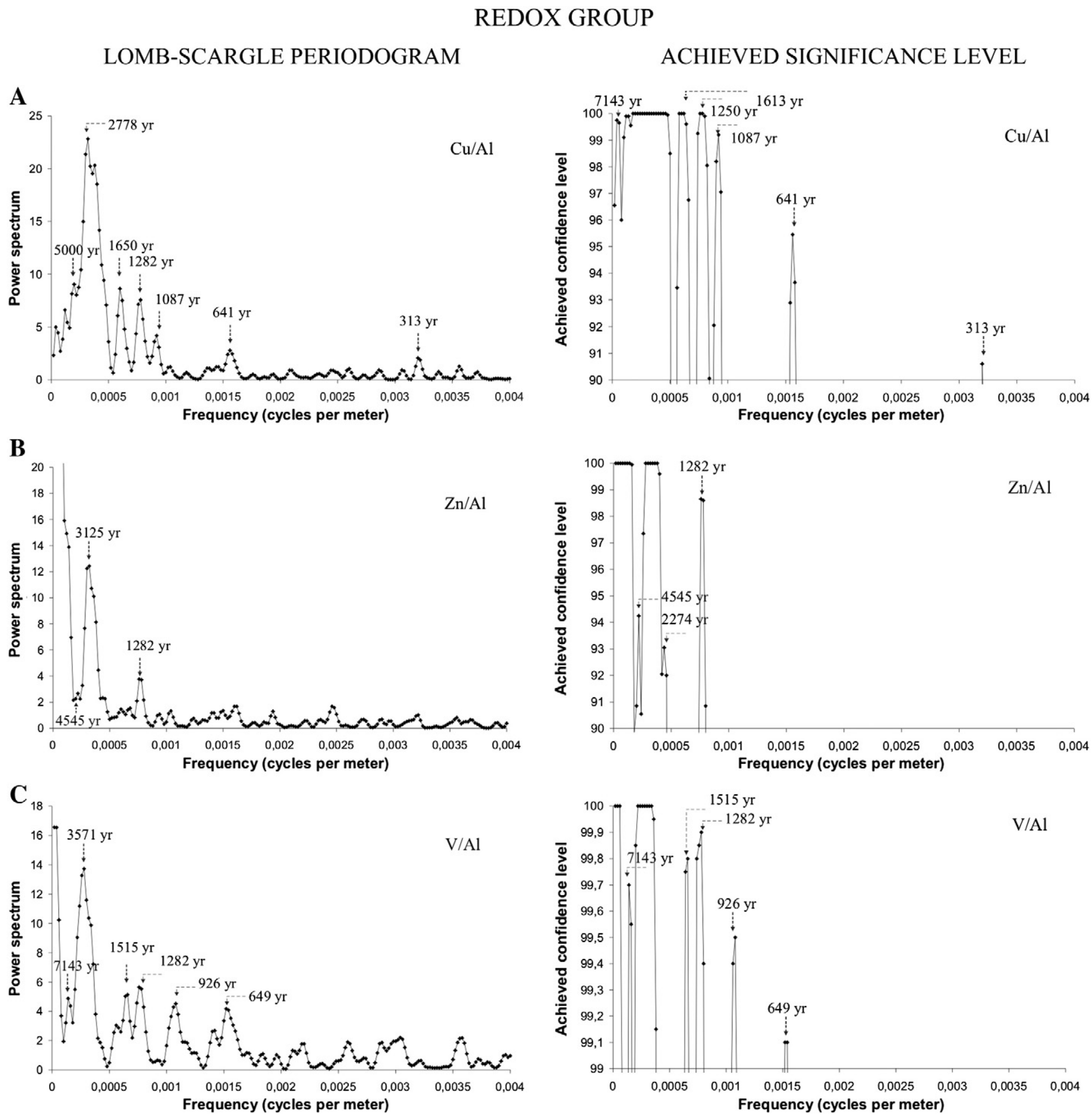

Figure 3. Power spectra for the four groups studied according to multi-proxy analysis of marine core 293G. Spectral peaks registered with Lomb–Scargle Periodogram are shown on the left; significant spectral peaks obtained with Achieved Significance Level are shown on the right.

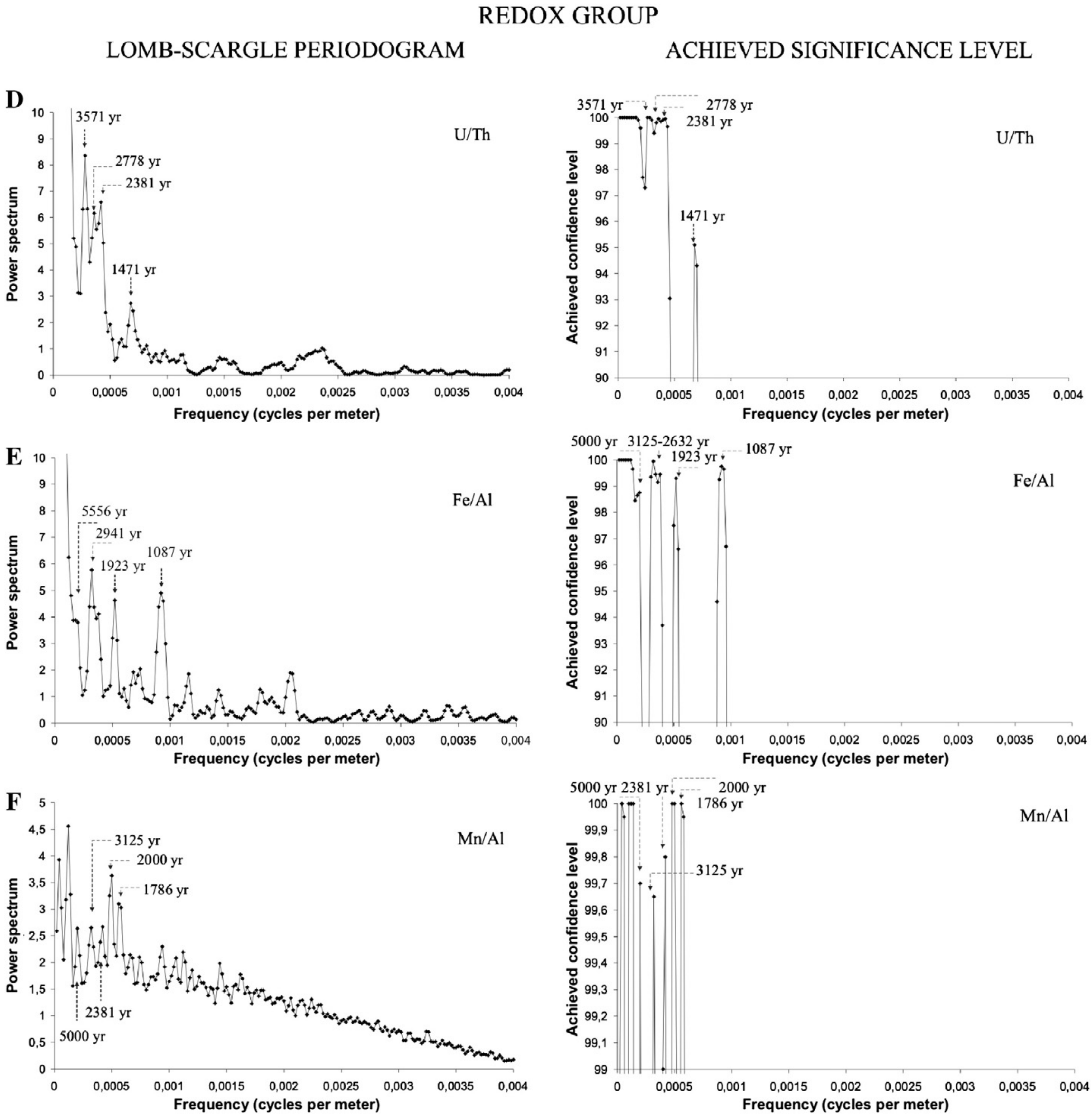

Figure 3 (*continued*).

variations in the North Atlantic thermohaline circulation with a temporary incursion of fresher subpolar Atlantic outbreaks into the western Mediterranean, as resemblance to high-latitude millennial-scale temperature fluctuations recorded in the Mediterranean between 20 and 70 ka (Sprovieri et al., 2012).

The paleoproductivity group moreover displays a statistically significant 1300-yr cycle (Fig. 7B). In this case, the paleoproductivity proxy (Ba/Al ratio) was able to record high productivity levels (e.g., Moreno et al., 2004; Jiménez-Espejo et al., 2008). The main factors giving rise to the increase in primary productivity could be: (1) major nutrient input, of both fluvial and eolian provenances; (2) major oceanographic variations such as meltwater pulses or reorganizations of main oceanographic currents in the area and/or upwelling and active productivity fronts, among others. Again, due to the fact that no increase of terrigenous material was observed in relation to the 1300-yr cycle the most likely phenomenon behind the paleoproductivity significance of this cycle is nutrient enhancement related with oceanographic variations (e.g., Packard et al., 1988; Fernández de Puelles et al., 2007). Thus, recurrent oceanic variations can be put forth as the main forcing mechanism for this cycle, promoted by changes in the nature and tempo of the North Atlantic freshwater inflow through the Strait of Gibraltar in the western Mediterranean during the last deglaciation, leading to

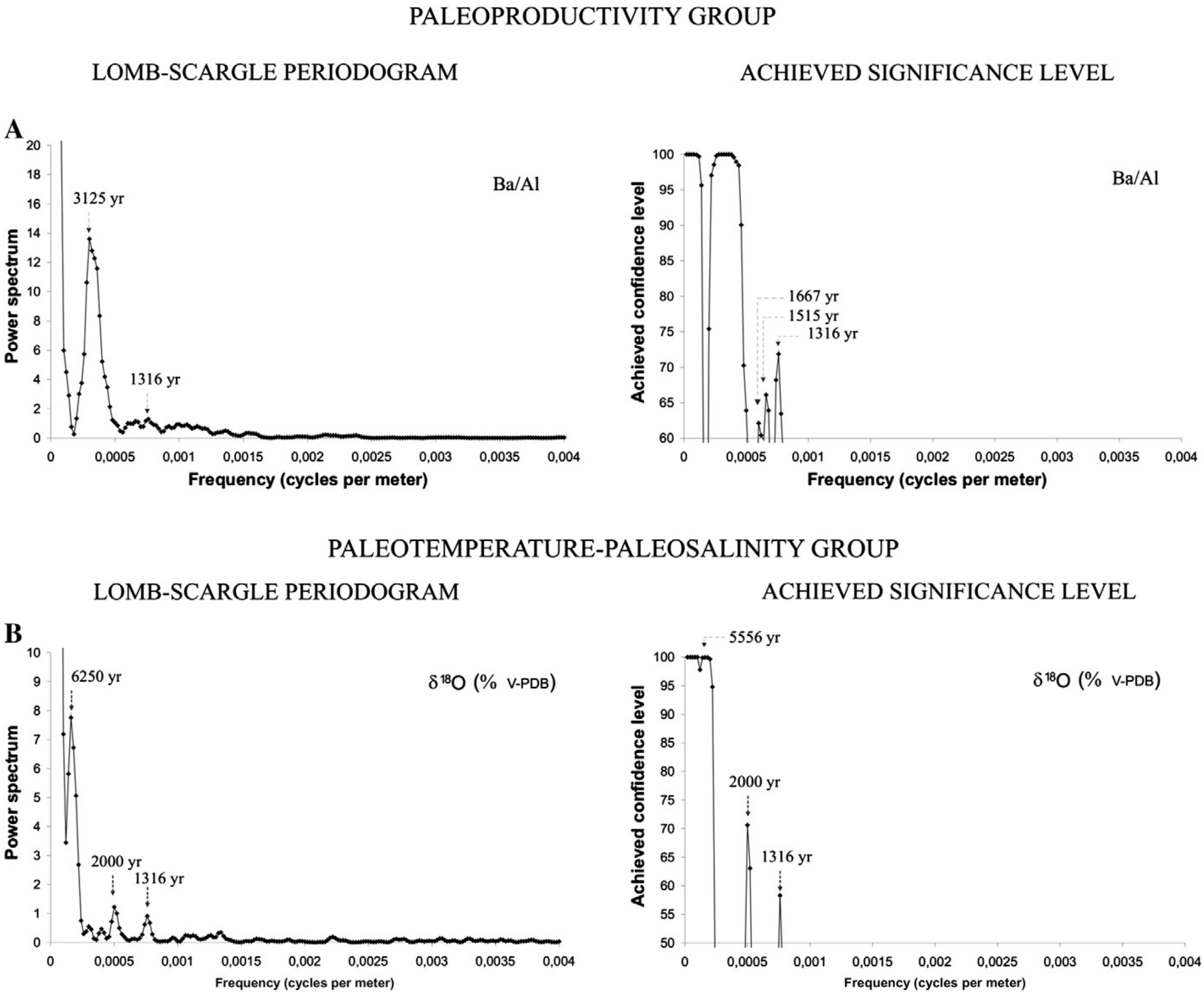

Figure 4. Power spectra for the four groups studied according to multi-proxy analysis of marine core 293G. Spectral peaks registered with Lomb–Scargle Periodogram are shown on the left; significant spectral peaks obtained with Achieved Significance Level are shown on the right.

stratification of the water column most likely via reduction of WMDW formation, and hence a weakening of the thermohaline circulation (Fig. 8A).

The 1515-yr cycle: North Atlantic thermohaline circulation, global ice volume and/or NAO and ITCZ migrations

The primary cycle at 1515 yr—as well as a corresponding secondary cycle at 3000 yr—is clearly detected in all the main proxy groups described (Figs. 5–6, 7B). This cycle might be equivalent to the cycles described by Bond et al. (1992, 1993) in North Atlantic ice-core records, with a periodicity of 1470 ± 500 yr. Cycles with this short-term periodicity have been reported as millennial-scale changes superimposed on the orbital climate evolution in the circum-North Atlantic region (Bond et al., 1997, 2001; Mangini et al., 2007), and have been described previously in the western Mediterranean during the last glacial cycle and the Holocene (Cacho et al., 1999, 2000; Moreno et al., 2005; Martrat et al., 2007; Fletcher et al., 2013). Gasse (2000) proposed such fluctuations to be feedbacks between changes in insolation and oceanic or atmospheric circulation. Despite being well recognized in the Northern Hemisphere, the origin of such periodicities during the Holocene remains unclear (Debret et al., 2007). Wavelet analysis recently performed over Atlantic, Mediterranean, Pacific and circum-Antarctic paleorecords spanning the Holocene indicates that the 1500 yr climate cycles may be associated with oceanic internal forcing, and not only with variations in solar output (Debret et al., 2007, 2009; Fletcher et al., 2013) since these solar variations have shown different periodicities during the early and late Holocene. Moreover, it has been recently proposed that the original 1500-yr cycle could be even an admixture of the 1000- and 2000-yr cycles, as was observed within the Holocene at diverse locations (Obrochta et al., 2012).

All the proxies included in the redox group signal this cycle as having a high degree of significance (Table 1, Fig. 6). Redox proxies have proven to be particularly sensitive to variations in the Mediterranean thermohaline circulation over the last 20 ka (e.g., Jiménez-Espejo et al., 2008). This circulation is a key factor for our understanding of the evolution of the Modified Outflow Waters from the Mediterranean towards the Atlantic, which could play a major role in North Atlantic circulation resumption (Voelker et al., 2006; Toucanne et al., 2007). Rogerson et al. (2008) proposed that changes in surface layer buoyancy, the Gibraltar Strait section and sea level could be a main mechanism underlying the aspiration of deep water and thermohaline circulation during the last glacial cycle. Yet according to this model, only two major changes in

Table 1
Major peaks in dark gray and their probable secondary peaks in white obtained for each selected proxy from core 293G. Confidence levels (in %) for the particular peak (in year, yr) obtained with spectral analysis are indicated.

Group	Variable	Temporal cycles (yr)						
		5000	3000	2000	1515	1300	1087	650
Detrital	K/Al		>99 (3125, 2778)		90.1–95 (1515)			
	Ti/Al			70–80 (2000)	70–80 (1515)			
	Zr/Al		95.1–99 (3125)					
	Si/Al	>99 (5000)						
	Mg/Al	>99 (5000)	>99 (2778)	90.1–95 (2000)			70–80 (1087)	
	Rb/Al	>99 (5000)		90.1–95 (1923)	>99 (1515)			
Redox	Fe/Al	95.1–99 (5000)	>99 (2941)	>99 (1923)			>99 (1087)	
	V/Al				>99 (1515)	>99 (1282)		>99 (649–1)
	Zn/Al	90.1–95 (4545)	>99 (3125)			95.1–99 (1282)		
	U/Th		>99 (2778)		95.1–99 (1471)			
	Mn/Al	>99 (5000)	>99 (3125)	>99 (2000)				
	Cu/Al	>99 (5000)	>99 (2778)			>99 (1282)	>99 (1087)	95.1–99 (649–1)
Paleoproductivity	Ba/Al		>99 (3125)		<70 (1515)	70–80 (1316)		
Paleotemperature–paleosalinity	$\delta^{18}O$	>99 (5556)		70–80% (2000)		<70 (1316)		

deep water ventilation might be expected, one during the increase of deglacial meltwaters at 14.5 cal ka BP (Termination 1a), and the other related to the deep water formation during the 8.2 cal ka BP cold event (Rogerson et al., 2008). The presence of significant 1500-yr periodicity therefore suggests a more complex scenario involving cyclic changes in deep and/or intermediate water masses in the Alboran Sea.

Among the detrital group, typical fluvial proxies (K/Al, Mg/Al and Rb/Al ratios) display these periodicities, and some eolian input proxies (Ti/Al and Zr/Al ratios) also record the major cycle and its secondary peak (Fig. 5). The presence of some minerals formed at low weathering conditions indicates enhanced aridification over the Sahara region and further supports an atmospheric intensification of the northern branch of the African wind system transporting, latitudinally, eolian dust to the western Mediterranean. Such an interpretation of the detrital mineral oscillations recorded is thus supported by recent models where low rainfall conditions in North Africa are triggered by the southward migration of the ITCZ (Lee et al., 2011), and fluvial proxies come from poorly drained soils of the lower sectors of equatorial and tropical rivers.

The ITCZ northward/southward displacements have been identified in diverse paleorecords, including African lakes (Tierney and Russell, 2007) and Asian monsoon precipitation (Wang et al., 2001; Cai et al., 2010). Other atmospheric perturbations with high wind intensities at this frequency oscillation were documented in Greenland ice-core records by an increased concentration of sea salt and terrestrial dust in the atmosphere during the Holocene (O'Brien et al., 1995).

Periodical changes between wet–dry conditions observed in the western Mediterranean can be explained by variations in the position of the Atlantic jet stream and the equivalent negative and positive NAO modes (Trigo et al., 2002). NAO variations have been described at centennial scales (Trouet et al., 2009) and NAO-like mechanisms have been also invoked to explain SST-cooling events recorded in the western Mediterranean (Cacho et al., 1999). Similar periodicities at 1750 yr have been also documented in the Mediterranean vegetation record during the Holocene in relation with the sensitivity to ocean and solar forcing factors (Fletcher et al., 2013). This teleconnection may be related with the presence of cold or warm surface waters over the North Atlantic region, affecting the northward/southward westerly displacements, and coupled with Atlantic inflow salinity and temperature changes (Trigo et al., 2002; Moreno et al., 2005; Trouet et al., 2009). In addition, Atlantic SST cooling bears an impact on the African climate by strengthening the subtropical cell pressure, affecting both the aridity of dust source areas and the intensity of the dust-transporting trade winds (deMenocal and Rind, 1993). This SST record from northwestern Africa (deMenocal et al., 2000) demonstrates a clear oceanic imprint with the 1500-yr internal period, well expressed during the late Holocene (Debret et al., 2009). The same periodicity has been reported in sea-surface salinity oscillations and rainfall patterns in Asian monsoon areas (Wang et al., 1999; Sarkar et al., 2000).

The 1515-yr periodicity can also be seen in the Ba/Al ratio of the studied sediments (Fig. 7B). Though the $\delta^{18}O$ signal was not recorded as significant in this cycle (Fig. 7A), redox sensitive elements, detrital fluctuations and paleoproductivity conditions suggest a strong oceanic–atmospheric impact. These productivity variations could be associated with a greater supply of nutrients and a well-mixed water column triggered by the formation of surface cold water that increased oxygenation of the water column linked to the intensification of wind systems over the western Mediterranean (Bassetti et al., 2010). The spectral $\delta^{18}O$ values are in agreement with a lack of relationship between the described Bond cycles and ice sheet volume, as proposed previously by Debret et al. (2007). Moreover, the proposed collapse of thermohaline circulation during Heinrich 1 in the western Mediterranean (Sierro et al., 2005), the presence of African surface currents in the Gulf of Cadiz during the last glacial maximum and YD (Rogerson et al., 2006), and local isotopic gradients in the western Mediterranean (Jiménez-Espejo et al., 2008) could mask the $\delta^{18}O$ signature of the 1515-yr periodicity. Millennial-scale events in the Atlantic Portugal margin also showed different responses in the oxygen isotope signal from benthic vs. planktonic foraminifera (Shackleton et al., 2000). Minor oxygen variability in the Gulf of Cadiz has additionally been related with long-term stable temperature and salinity properties of the Mediterranean outflow through the LIW contribution (Voelker et al., 2006).

For all these reasons, the 1515-yr cycle registered in the western Mediterranean record would evidence a rapid response in the oceanic and atmospheric systems given the different proxies described, though to a lesser extent on the isotopic signal since the last glacial maximum. The forcing mechanisms related to this noteworthy period may very well be directly linked to North Atlantic thermohaline circulation and atmospheric changes in the North Atlantic realm. Aside from altering the properties and volume of the inflowing North Atlantic surface waters, the trigger mechanism would have modified the intensity and

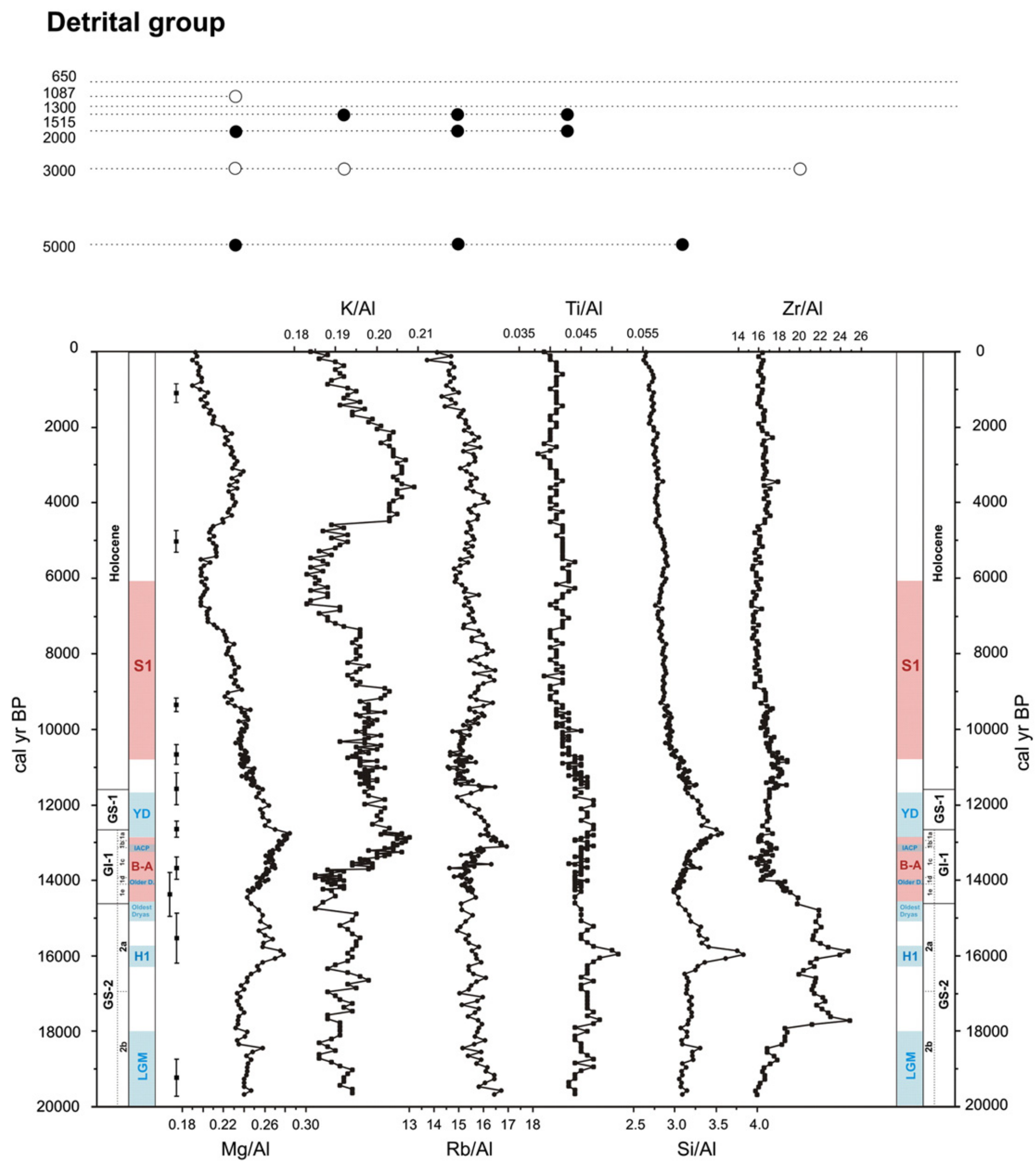

Figure 5. Major and secondary peaks obtained in the four groups presented as geochemical proxy profiles versus calibrated ^{14}C ages (element/Al ratios for major elements and element/Al ratios $*10^{-4}$ for trace elements). The upper panel shows all the cycles described, indicating the primary cycles with black circles and the secondary ones with white circles recognized in each proxy. Black squares show the ten AMS ^{14}C dates with 2σ error bars. Light red boxes indicate warm periods Bölling-Alleröd (B–A) and last Sapropel deposition (S1) in the eastern Mediterranean time interval. Light blue boxes indicate main cold periods, last glacial maximum (LGM), last Heinrich event (H1), Oldest Dryas, Older Dryas, Intra-Alleröd Cold Period (IACP) and Younger Dryas (YD) time intervals. According to NGRIP terminology (Lowe et al., 2008), white boxes indicate Greenland stadials (GS-1, GS-2) and interstadials (GI-1).

position of atmospheric pressure gradients as determined by the NAO influence and the ITCZ migrations in North Africa, with the consequent displacement of the monsoon rain belt, thereby changing the Mediterranean pluvial regime and the wind systems (Fig. 8B). These atmospheric and oceanographic thresholds hence affect the WMDW and LIW formations, and they leave their imprint in redox proxies with better or poorer deep-water ventilation, as well as in the productivity conditions.

The 2000-yr cycle: high- to low-latitude climate variability linked to variations in solar activity and the monsoonal regime

The 2000-yr cycle, and its secondary peak at 1087 yr, is significant in three groups, namely detrital, redox, and paleotemperature–paleosalinity (Figs. 5–7A). The fluvial proxies in particular (Mg/Al, Rb/Al ratios) are significant among the detrital element group, though the Ti/Al ratio is also characterized (Fig. 5). Elevated Ti/Al ratios are expected in eolian-derived material from North Africa. However, the increase in this ratio in conjunction with typical fluvial proxies suggests a combined transport phenomenon. Chemical cycles during Pliocene sapropel formation reveal the same Ti/Al ratio anomaly, attributing the increase to westward-directed transport from continental sources of basaltic rocks rich in Ti contents located in the east (Wehausen and Brumsack, 2000). The cycle could thus be interpreted as prevailing humid conditions with major terrigenous input due to river runoff (Mg/Al, Rb/Al ratios) and dust pulses from the eastern Mediterranean borderlands.

During the Holocene, similar millennial-scale climate oscillations have been recognized in locations from the North Atlantic area and elsewhere, most likely related to long-term solar forcing variations (Debret et al., 2009, and references therein). The 2500-, 1660- and 1000-yr cycles are explained by solar activity fluctuations based in ^{10}Be and ^{14}C cosmogenic isotopes, being the 2500-yr cycle identified during the whole Holocene, while the other two only occur during the early Holocene (Debret et al., 2009). Therefore, the identification of the 2000-yr cycle likely derives from the larger time period considered

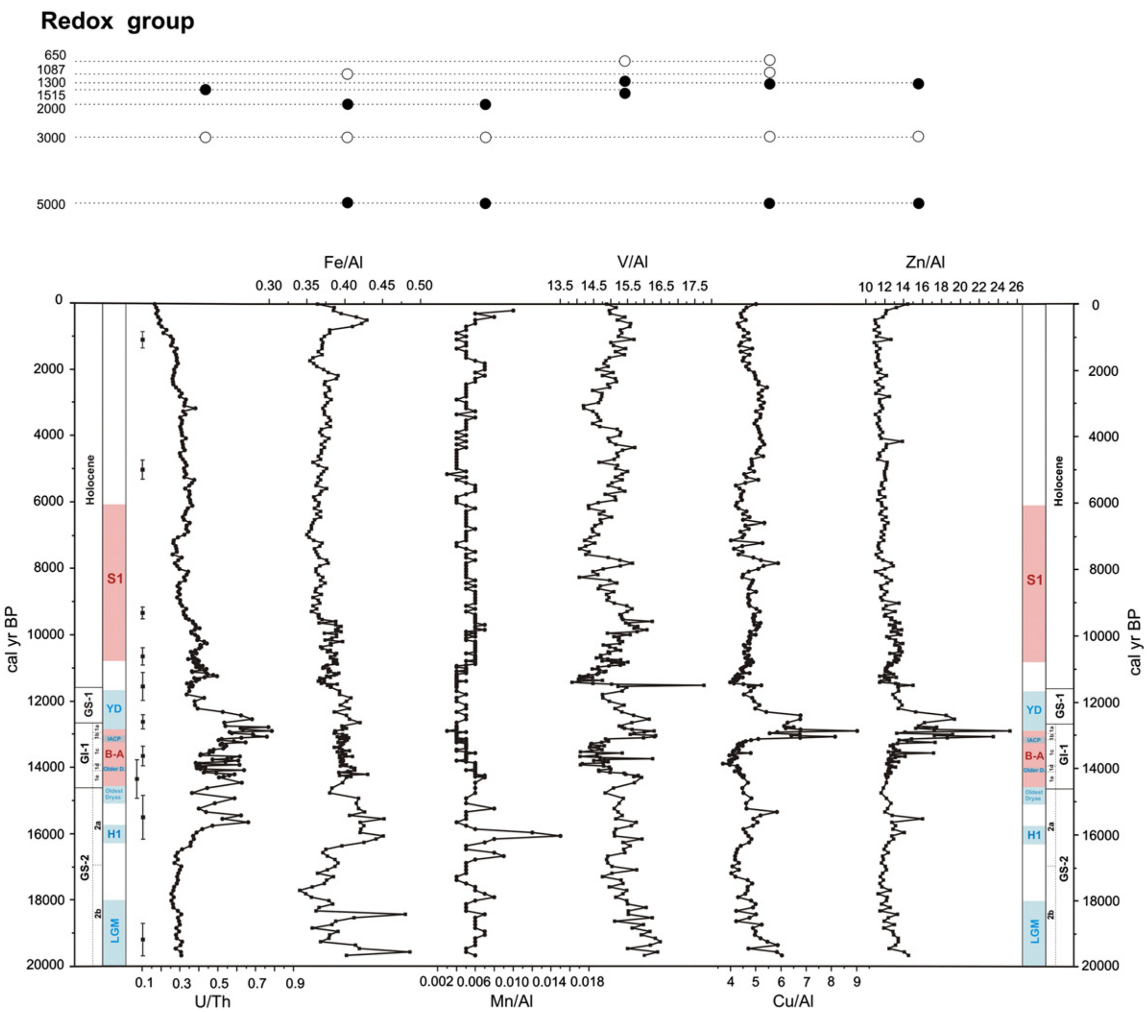

Figure 6. Major and secondary peaks obtained in the four groups presented as geochemical proxy profiles versus calibrated ^{14}C ages (element/Al ratios for major elements and element/Al ratios $*10^{-4}$ for trace elements). The upper panel shows all the cycles described, indicating the primary cycles with black circles and the secondary ones with white circles recognized in each proxy. Black squares show the ten AMS ^{14}C dates with 2σ error bars. Light red boxes indicate warm periods Bölling-Alleröd (B–A) and last Sapropel deposition (S1) in the eastern Mediterranean time interval. Light blue boxes indicate main cold periods, last glacial maximum (LGM), last Heinrich event (H1), Oldest Dryas, Older Dryas, Intra-Alleröd Cold Period (IACP) and Younger Dryas (YD) time intervals. According to NGRIP terminology (Lowe et al., 2008), white boxes indicate Greenland stadials (GS-1, GS-2) and interstadials (GI-1).

in this case (i.e. the last 20 ka) and hence the forcing mechanism would not be merely triggered by solar variations.

During older periods, frequency spectra from lacustrine records in central Italy (Lake Albano) and northern Greece evidence cyclic periods at 2000 yr and 2500 yr, respectively (Chondrogianni et al., 2004; Kloosterboer-van Hoeve et al., 2006). This cycle and its secondary peak at 1087 yr present similarities with periodicities recorded in $\delta^{18}O$ values from the GISP2 ice core during the late Pleistocene, with periodicities of 1050 yr (Stuiver et al., 1995). Likewise, the 1150-yr period is reportedly characteristic of SW monsoonal variability in the Arabian Sea (Sirocko et al., 1996). In northwestern Africa, marine records present a periodicity in the terrigenous signal of 900 yr over the past 9000 yr, comparable to the temperature variation in Greenland, suggesting a transitional area between the influences of the African monsoonal system and the North Atlantic climate (Kuhlmann et al., 2004). In this sense, recent models also highlight the role of the Atlantic Multidecadal Oscillation and the natural fluctuation of the Atlantic Meridional Overturning Circulation in modulating the variation of the ENSO–monsoon system (Chen et al., 2010).

In addition, a 2300-yr spacing is recorded in the Aegean SST and winter/spring intensity of the Siberian High (GISP2 K^{+} record), which suggests solar modulation of the climate recognized in the ^{14}C record and in worldwide Holocene glacier advance phases (Rohling et al., 2002). Moving from the Equator toward the Southern Hemisphere, spectral analyses of diverse paleorecords (Bütikofer, 2007) determine periodic surface temperature variations at around 2000 yr in the Tropical Pacific Ocean (Stott et al., 2004; Bütikofer, 2007) and in SE Australia (McGowan et al., 2010) in relation with solar irradiance variations.

Therefore, the Mediterranean cycle recognized at 2000 yr, and at around half this time span, suggests a direct atmospheric link with high- (North Atlantic), mid- (monsoon region), and low-latitude (Pacific Ocean) climate variability, supposedly influencing the whole Mediterranean region. The reasons underlying this regular climatic fluctuation are not clear. Yet a recurrence of cold climatic phases in Greenland ice cores, and in terrestrial records from Europe, North Africa and the Southern Hemisphere, could be linked to variations in solar activity (Maunder-type oscillations) (Van Geel et al., 1999). Accordingly, the coincidence of variations in cosmogenic isotopes (^{14}C and ^{10}Be) with climate changes during the Holocene, and the upper part of the last glacial period, imply that the climate system is far more sensitive to small variations in solar activity than is generally believed. Simulation models also show that the response in atmospheric parameters to irradiance forcing can be characterized as the direct response of a system with a large thermal inertia in parameters such as surface air temperature, monsoon precipitation and glacier length (Weber et al., 2004).

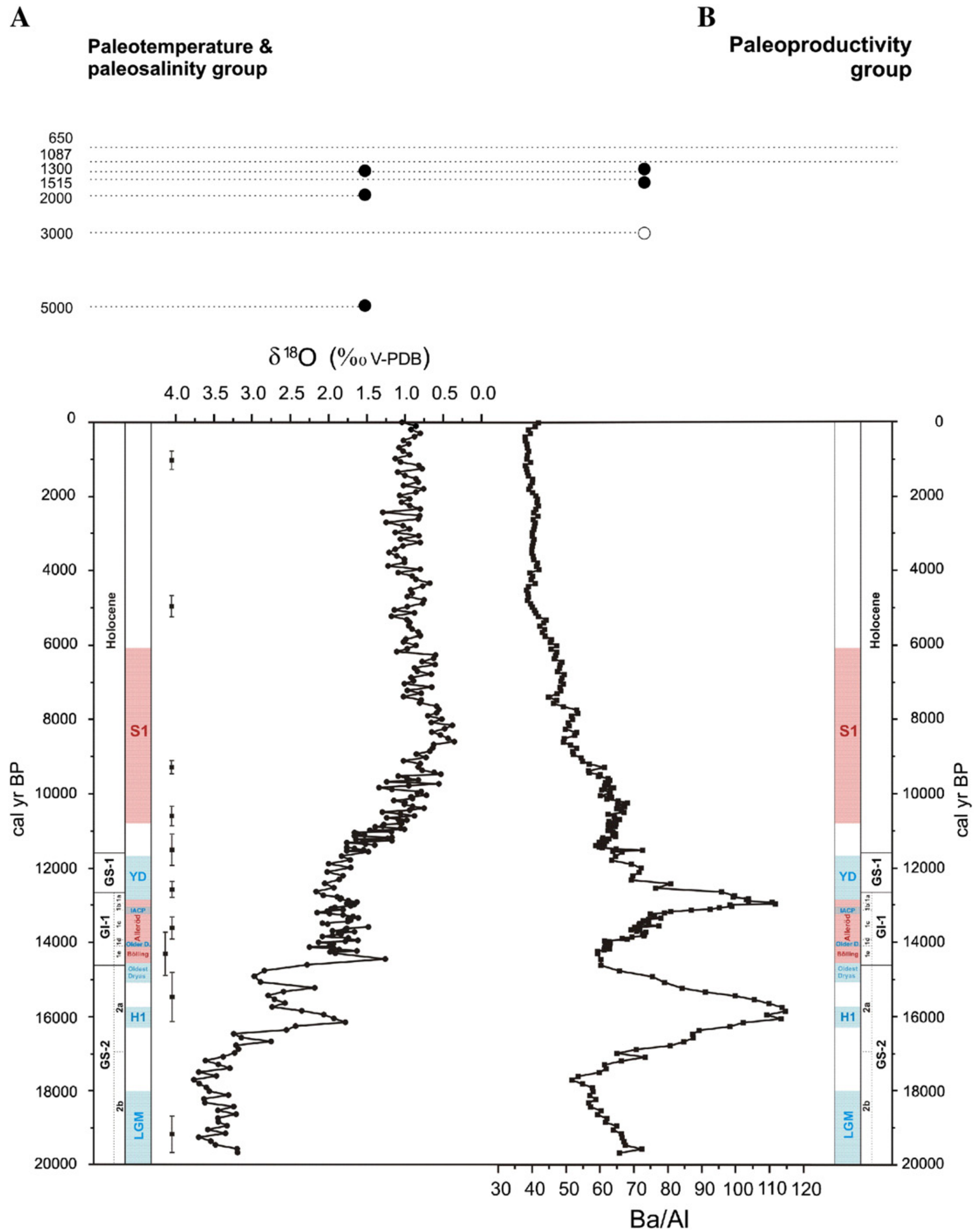

Figure 7. Major and secondary peaks obtained in the four groups presented as geochemical proxy profiles versus calibrated ^{14}C ages (element/Al ratios for major elements and element/Al ratios $*10^{-4}$ for trace elements). The upper panel shows all the cycles described, indicating the primary cycles with black circles and the secondary ones with white circles recognized in each proxy. Black squares show the ten AMS ^{14}C dates with 2σ error bars. Light red boxes indicate warm periods Bölling-Alleröd (B–A) and last Sapropel deposition (S1) in the eastern Mediterranean time interval. Light blue boxes indicate main cold periods, last glacial maximum (LGM), last Heinrich event (H1), Oldest Dryas, Older Dryas, Intra-Alleröd Cold Period (IACP) and Younger Dryas (YD) time intervals. According to NGRIP terminology (Lowe et al., 2008), white boxes indicate Greenland stadials (GS-1, GS-2) and interstadials (GI-1).

In terms of paleoceanographic and climate conditions, the redox group presents the highest confidence level for this cycle, and $\delta^{18}O$ oscillations are also highly significant (Figs. 6, 7A). The $\delta^{18}O$ oscillations may result from the high sensitivity of ice sheets to increasing solar radiation as a main forcing mechanism triggering this periodicity. SST variations, especially higher during summer, would intensify Mediterranean cyclogenesis and associated floodings (Trigo et al., 2002), reinforcing the oceanic–atmospheric teleconnections. Obtained detrital proxies are also coherent with northerly moisture transport toward the Saharan–Sahelian belt and the monsoonal front displacement (Gaetani et al., 2010). The influence of the African monsoon fluctuations has been seen in flux oscillations of the Nile (Skliris et al., 2007; Blanchet et al., 2013). A major Nile input would reduce the formation of LIW, whereas low Nile input would reduce surface dilution in the Levantine basin, increasing LIW formation. Such changes in temperature and related salinity could also strongly affect the seasonal stability of the Mediterranean water column, altering the bottom-water oxygen conditions (e.g., Sparnocchia et al., 1994; Skliris et al., 2007) and marine ecosystems (Cartes et al., 2011). In this sense, isocronus redox variations in the western and eastern Mediterranean have been documented around 7.4 cal ka BP (Jiménez-Espejo et al., 2007; Blanchet et al., 2013). Therefore, the oceanic response to insolation forcing due to

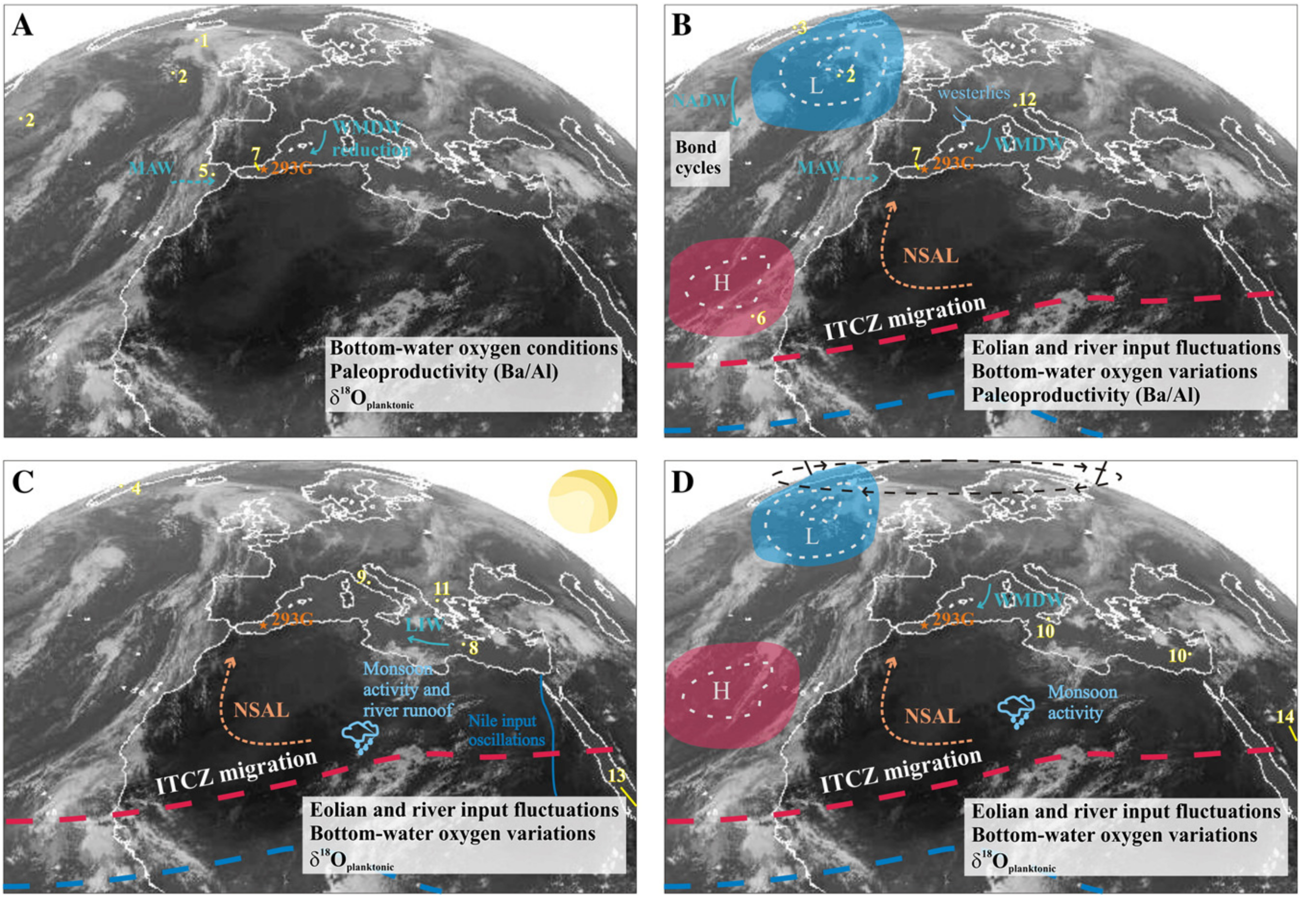

Figure 8. Scheme of the main climate teleconnections and proxies associated with (A) 1300 yr, (B) 1515 yr, (C) 2000 yr, and (D) 5000 yr periodicities obtained in the power spectra on marine record 293G from the westernmost Mediterranean Sea. A) The 1300-yr cycle appears to be mainly driven by changes in the nature of the Atlantic water inflow and the Western Mediterranean Deep Water formation. B) The 1515-yr cycle is associated to variations in North Atlantic thermohaline circulation, ice volume and atmospheric conditions. C) The 2000-yr cycle suggests variations in solar activity as the main driving factor, affecting moonsonal regime, riverine input and Deep and Intermediate Mediterranean Water formation. D) The 5000-yr cycle is directly linked to orbital forcing influence and monsoon dynamics. Numbers indicate other paleorecord locations cited in the manuscript that recognize similar periodicities. Greenland and North Atlantic Ocean: (1) Bianchi and McCave, 1999, (2) Bond et al., 1997, 2001, (3) O'Brien et al., 1995, (4) Stuiver et al., 1995; Gulf of Cadiz: (5) Voelker et al., 2006; Tropical West Africa: (6) deMenocal et al., 2000; Europe and Mediterranean Sea: (7) Cacho et al., 2001; Moreno et al., 2005, (8) Rohling et al., 2002, (9) Chondrogianni et al., 2004, (10) Becker et al., 2005, (11) Kloosterboer-van Hoeve et al., 2006, (12) Mangini et al., 2007; Arabian region: (13) Sirocko et al., 1996, (14) Fleitmann et al., 2003. NADW: North Atlantic Deep Water. MAW: Modified Atlantic Water. WDMW: Western Mediterranean Deep Water. LIW: Levantine Intermediate Water. ITCZ: Intertropical Convergence Zone.

solar irradiance variations is strongly modified by internal feedback processes, as Holocene climate models and marine records would indicate (Weber et al., 2004; Fletcher et al., 2013).

In summary, the obtained 2000-yr cycle in the western Mediterranean appears to be forced not only by solar-derived activity variations but also by the subsequent monsoonal intensification. The African monsoon regime would yield an impact on Mediterranean thermohaline circulation, affecting intermediate and deep-water formation as well as water column stabilization (Fig. 8C) as the multi-proxy analysis has evidenced.

The 5000-yr cycle: orbital forcing influence and monsoon dynamics

The 5000-yr cycle presents high significance in the detrital, redox, and paleotemperature–paleosalinity groups (Figs. 5–7A). Once again, this periodicity corresponds to an important generalized mechanism, affecting both oceanic and atmospheric response systems at high and mid-latitudes. This cycle is in agreement with significant temperature oscillations and changes of the polar circulation index recorded in the GISP2 ice core (Grootes and Stuiver, 1997; Mayewski et al., 1997). This comes to further support the existence of a strong link between the rates of deep-water ventilation (with significant high Fe/Al and Mn/Al ratios) and the intensity of high-latitude atmospheric circulation reflected in major eolian input (Si/Al ratio) in the western Mediterranean region (Figs. 5, 6). In addition, changes in the deep-water convection produced in the Gulf of Lion by cold and arid conditions can be detected using the n-hexacosanol/n-nonacosane index, directly influenced by the intensity of northwesterly winds as previously described in this region (Cacho et al., 2000) or by changes in the oxygenation associated with bottom current intensity in the western Mediterranean (Martrat et al., 2007).

In the monsoonal areas (Asia and Africa), pronounced variations at periods of about 10,000 yr and 5000 yr have been related with runoff variations in response to the precessional forcing (Berger et al., 2006; Tuenter et al., 2007). Climate model simulations have also shown that wetter conditions were probably caused by changes in the Earth's orbital parameters that increased the amplitude of the seasonal cycle of solar radiation in the Northern Hemisphere, enhanced the land–ocean temperature contrasts, and thereby strengthened the African summer monsoon (Kutzbach et al., 1996). Therefore, this cycle is the only one that could have a direct relationship with an orbital forcing response. During precession maxima, boreal summer insolation is low and the desert area expands, as reflected by the Si/Al ratio; thus, the surface albedo increases whereas the surface air temperature decreases (lower temperature contrast between land and ocean). In consequence, the African monsoon response is a general reduction in precipitation and hence in runoff (Tuenter et al., 2007). Minor amounts of precipitation during precession maxima can, however, increase river runoff input as well, meaning statistically significant Mg/Al and Rb/Al ratios as fluvial proxies, since the soil retains less water. Such a scenario—where major desert expansion implies major Saharan dust export/supply but with some sporadic rainfall—could be the main reason why we observe a significant response in the detrital group, especially in the two fluvial proxies (Mg/Al, Rb/Al ratios) and the typically eolian-delivered elements such as Si/Al ratio (Fig. 5). These runoff oscillations at sub-Milankovitch time-scales, every 5000 yr, produce variations in $\delta^{18}O$ within the western Mediterranean as well, and in the redox conditions, particularly in terms of Fe/Al, Mn/Al, Zn/Al, and Cu/Al ratios, due to oscillations of the water column stratification (Figs. 6, 7A). A decrease in precipitation or African monsoon could give rise to major salinity in the surface water lens of the western Mediterranean, together with lower temperatures and a drier climate favoring the WMDW formation; this implies more ventilated bottom water conditions during precession maxima. The opposite situation would be reflected during precession minima, favoring stagnant bottom water in conjunction with the increase in the African monsoon.

High-frequency climate variability at 3000-5000 yr timescales in the eastern Mediterranean has been previously related to changes in Saharan dust supply (Becker et al., 2005). Enhanced dust deposition over the Mediterranean, correlated with the cold intervals of the millennial–scale D–O oscillations, suggests that the Atlantic pressure system (i.e., NAO) may also have played a critical role in varying the wind strength and/or aridification of northern Africa. In addition, the establishment of the modern ENSO band characterized by increased El Niño frequency could have caused significant monsoon weakening by the southward migrations of the ITCZ after around 5400 cal yr BP (Haug et al., 2001), which may in turn be regulated by orbitally induced insolation in the tropical oceans (Fleitmann et al., 2003). The 5000-yr cycle is therefore strongly related to orbital forcing as the main mechanism, while also accompanied by monsoon variations due to ITCZ migrations and shifts in the modes of the present-day NAO that influence the western Mediterranean cyclicity (Fig. 8D).

Conclusions

The high sedimentation rates of the marine record from the westernmost Mediterranean, Alboran Sea, have allowed us to establish novel high-periodicity cycles at millennial to centennial scales for the last 20,000 yr in this location. The paleoenvironmental cyclicities obtained exhibit noteworthy spectral periodicities of varying statistical significance for the range of the different multi-proxy groups. Main periodicities at 1300, 1515, 2000, and 5000 yr plus secondary harmonics at 650, 1087, and 3000 yr suggest different forcing mechanisms as favored hypothesis of these periodic climate oscillations. The 1300-yr cycle is principally recorded in the Mediterranean paleoceanographic context, pointing to the influence of North Atlantic freshwater inflow to the Alboran Sea. All the groups described show a 1515-yr cycle equivalent to the Bond cycle in the North Atlantic; however, it is less significant in the isotopic signal, probably due to a lagged response of the ice sheets to these cyclic oscillations at the time interval studied. These high frequency bands appear to be linked to North Atlantic thermohaline circulation, changes in the intensity and NAO-like pattern and ITCZ migrations. Although the 2000-yr cycle is not reflected by many proxies, it suggests generalized climate variability in the Mediterranean region, with variations in solar activity and monsoonal teleconnections between high and low latitudes as main forcings mechanisms. The cycle at 5000 yr corresponds, then, to a generalized periodicity and is the only one presenting a direct relationship with an orbital forcing response. Therefore, the obtained spectral periodicities provide evidence that serves to reinforce the strong connection between North Atlantic climate and monsoonal variations in the western Mediterranean context, and further supports the extreme sensitivity of this region to cyclic climate changes.

These cyclical alterations will also affect future climate responses over the westernmost Mediterranean, particularly sensitive to oscillations in the water column thermal-salinity stratification, bottom-water oxygenation, and detrital input fluctuations derived from river runoff or major eolian dust pulses forced by the NAO mode and ITCZ migrations over North Africa. In addition, natural volcanic eruptions and the current warming trend exacerbated by greenhouse emissions should be also accounted in future climate scenarios.

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