Late Holocene climate variability in the Southwestern Mediterranean region: an integrated marine and terrestrial geochemical approach

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Abstract

A combination of marine (Alboran Sea cores, ODP 976 and TTR 300 G) and terrestrial (Zoñar Lake, Andalucia, Spain) paleoclimate information using geochemical proxies provides a high resolution reconstruction of climate variability and human influence in southwestern Mediterranean region for the last 4000 years at inter-centennial resolution. Proxies respond to changes in precipitation rather than temperature alone. Our archive documents a succession of dry and wet periods coherent with the North Atlantic climate signal. Drier stages occurred prior to 2.7 cal ka BP, well-correlated with the global aridity crisis of the third-millennium BC, and during the Medieval Warm Period (1.4-0.7 cal ka BP). Wetter conditions prevailed from 2.7 to 1.4 cal ka BP and after the Medieval Warm Period and the onset of the Little Ice Age. Hydrological signatures during the Little Ice Age are highly variable but consistent with more humidity that the period before. Additionally, Pb anomalies in sediments at the end of Bronze Age suggest anthropogenic pollution earlier than the Roman Empire development in the Iberian Peninsula. The evolution of the climate in the study area during the Late Holocene confirms the see-saw pattern previously shown between eastern and western Mediterranean regions and suggests a higher influence of the North Atlantic dynamics in the western Mediterranean.

Keywords: Late Holocene, moisture variability, southwestern Mediterranean, geochemical proxies, marine-terrestrial calibration.

1 Introduction

The southwestern Mediterranean region is an area of great interest for paleoclimate research, characterized by the interaction of the northern Africa subtropical and mid-latitude North Atlantic climate systems. Both have controlled climate variability since the onset of modern Mediterranean climate after the mid Holocene and helped to create the singular environmental conditions that determine the landscape, biota and human societies evolution in the area.

Geochemical archives encoded in marine and lacustrine sediments offers clues for reconstructing the environmental processes and past climate changes. In paleoceanography, geochemical proxies describe most of the processes occurring in the ocean such as paleoproductivity (e.g., Martínez-Ruiz et al., 2003), deepwater ventilation (e.g, Mangini et al., 2001) and paleotemperatures (e.g., Toyofuku et al., 2000; Cacho et al., 2006). In lakes, the use of geochemical data has been focused on atmospheric pollution (e.g. Renberg et al., 2001; Ruiz-Fernández et al. 2007) but more recently also on paleoenvironmental (e.g. Koinig et al. 2003; Eusterhues et al. 2005; Selig et al., 2007) and paleoclimate reconstructions (e.g. Moreno et al. 2007; Tanaka et al. 2007; Brauer et al., 2008; Giralt et al. 2008; Czymzik et al., 2010; Martín-Puertas et al., 2009). Nevertheless, reconstructing environmental and climate proxies from geochemical composition should be done carefully since each lake is unique, controlled to some extent by its geographic and geological setting and the interactions among external chemical inputs and internal biogeochemical cycles may greatly affect our ability to reconstruct forcing variables (Cohen, 2003).

In the southwestern Mediterranean region, several paleoclimate studies have been carried out using geochemical proxies from marine sediments, focused on abrupt climate changes since the Last Glacial Maximum (e.g., Martínez-Ruiz et al., 2003; Moreno et al., 2005; Sierro et al., 2005; Cacho et al., 2006; Jiménez-Espejo et al., 2008). However the study of the Late Holocene is still relatively poor since it requires higher resolution records for reconstructing short-term variability and only few studies are available (Martín-Puertas et al., 2008; 2009). The rapid response of lakes to changes in the environmental conditions together with relatively high sedimentation rates favor the preservation of high-resolution geochemical signals (Battarbee, 2000).

In this article, we combine geochemical information from lower-resolution marine records in the southwestern Mediterranean Sea (Alboran Sea), which provides evidences of changes in the hydrographic conditions and sea surface temperature, and higher-resolution lacustrine record in the southwest of Iberian Peninsula, which shows hydrological fluctuations in the continent and possible traces of human impact. The aim of this study is to understand the linkages between marine and terrestrial environments using geochemical proxies in order to obtain a more accurate reconstruction of the climate change dynamics in the southwestern Mediterranean region during the Late Holocene.

2 Regional setting

The southwestern Mediterranean region can be defined as the westernmost basin of the Mediterranean Sea, called the Alboran Sea, and southern Iberian Peninsula and northern Morocco (Fig. 1). The area is characterized by semi-humid Mediterranean climate with warm and dry summer and mild and wetter winter. The Alboran Sea receives terrigenous sediments from both, African and European continents, as atmospheric dust and coastal/riverine inputs (e.g. Martínez-Ruiz et al., 2003). Controlled by the same climate, Zoñar Lake is one of the few permanent lakes in southern Iberian Peninsula (37°29’00’’N, 4°41’22’’W, 300 m.a.s.l.) (Fig. 1). It is highly sensitive to the precipitation regime (Valero-Garcés et al., 2006) and provides a continuous and high-resolution record of the Late Holocene (Martín-Puertas et al., 2008).

3 Materials and methods

Two marine cores from Alboran Sea basin and a terrestrial core from Zoñar Lake (Fig. 1) have been selected for this study. The maximum distance between the marine and terrestrial sites is about 300 km. The marine records selected are: the ODP Site 976C-1H in the West Alboran basin, located at 36^{o}12’N, 4^{o}18’W, 1108 m.b.s.l.; and Site TTR 300G at 36^{o} 52’55’’N, 2^{o} 17’25’’W drilled at 1860 m.b.s.l in the East Alboran Sea basin (Fig. 1). Core ODP 976C-1H was recovered at Site 976 during the ODP, Leg 161 in 1995 and core 300G during the Training Through Research (TTR) cruise 14, Leg 2 in 2004. Zoñar Lake cores were recovered with a Kullenberg corer in 2004. The composite record was obtained from correlation of five cores in the deepest area (14 m depth, cores 1A, 1B, 1C and 1D, up to 6 m long) and one in the littoral zone (6 m depth, 2A, up to 3 m long) (see Martín-Puertas et al., 2008). For the studied interval, marine cores ODP 976C-1H and 300G were sampled continuously at 2, 1.5 and Zoñar core 1B was sampled every 10 cm. Sediment samples were dried and homogenized in an agate mortar for subsequent geochemical analyses. Major elements were measured using Atomic Absorption Spectrometry (AAS) (Perkin-Elmer 5100 spectrometer) with an analytical error of 2%. Analyses of trace elements were performed using Inductively Coupled Plasma-Mass Spectrometry (ICP-MS) following HNO3 + HF digestion. Measurements were taken in triplicates by spectrometry (Perkin-Elmer Sciex Elan 5000) using Re and Rh as internal standards. Variation coefficients determined by the dissolution of 10 replicates of powdered samples were higher than 3% and 8% for analyte concentrations of 50 ppm and 5 ppm, respectively (Bea, 1996). Geochemical elements selected as proxies for this study (Mg, Sr, Rb, Zr) were normalized to Al, since Al does not show fractionation and has very little ability to move during diagenesis (Calvert and Pedersen, 1992; Pipper and Perkins, 2004). Additionally, stable oxygen isotope ratio of monospecific planktonic foraminifers (*G. bulloides*) from core 300G were also obtained. Foraminifers were cleaned in an ultrasonic bath to remove fine-fraction contamination, rinsed with distilled water, and thoroughly washed in alcohol. Stable isotopes were measured using a Finnigan MAT 251 mass spectrometer (Isotope Laboratory, Marum, University of Bremen, Germany). $\delta^{18}O$ data are relative to the PDB standard. Analytical reproducibility of the method is approximately + 0.07% (see Jiménez-Espejo et al., 2008).

The age-depth models for the Alboran basin cores have already been performed for the Late Holocene using six radiocarbon data from *G. bulloides*. The age model for the last 25.000 yr at Site ODP 976 is based on ten AMS radiocarbon ages performed on monospecific samples of *Globigerina bulloıdes* and *Neogloboquadrina pachyderma* (Combourieu Nebout et al., 2002). In this core, the last 4.0 cal ka extend the first 118 cm. In core 300G the age model for the last 13,000 yr is based on five radiocarbon data from *G. bulloides*, and the last 4.0 cal ka extend the first 118 cm from core ODP 976 (Combourieu-Nebout et al., 2009) and the first 66 cm from core 300G (Jiménez-Espejo et al., 2008). The age model validation was further supported by comparison with close well-dated records in surrounding sites based on ^{210}Pb and radiocarbon dates (unpublished data). For Zoñar Lake core, the age-depth model for the last 4.0 cal ka is based on nine AMS^{14}C dates, ^{137}Cs dating and varve counting (Martín-Puertas et al., 2008). All radiocarbon ages for the marine core were calibrated to calendar years using Calib 5.1 software (Stuvier and Reimer, 1993) and the MARINE04 calibration curve including a standard marine correction of 400 years (Hughen et al., 2004). Continental data were calibrated using the INTCAL04 curve (Reimer et al., 2004).

4 Paleoenvironmental and paleoclimate proxies

4.1 Alboran Sea

Climate variability at global, regional and local scale modifies the hydrographic conditions of the Alboran Sea influencing the sedimentary dynamic (Sierro et al., 2005; Llave et al., 2006; Voelker et al., 2006). Terrigenous fraction of the Alboran sediments is the sum of atmospheric dust and eroded material transported by rivers from emerged areas. The first one is mainly related to the activity of Saharan dust air masses reaching the studied area (Weldeab et al., 2003; Moreno et al., 2005) and is responsible for an enrichment of heavy minerals in the sediments (rutile and zircon) (Guieu and Thomas, 1996). Based on mineralogical composition, Zr/Al ratio has been used as an indicator of Sahara dust deposition in the western Mediterranean basin (Moreno et al., 2005). The second one, the fluvial input from the emerged areas, comes mainly from the Iberian margin in north-western Alboran Basin, but the African and Iberian margins are both possible sources in south-eastern Alboran Basin. Sediments are composed of clay minerals, quartz, and minor amounts of feldspar, dolomite and accessory minerals (Martínez-Ruiz et al., 2003). Within the clay mineral assemblages, chlorite is particularly rich in Mg; therefore Mg enrichment (Mg/Al) has been suggested as a good detrital proxy (Jiménez-Espejo et al., 2008), which could be also affected by other detrital minerals, as dolomite also common in the south Iberian margin sources. Saharan winds increase during Northern Africa and Mediterranean arid periods (Weldeab et al., 2003; Moreno et al., 2005) while contribution from the margin increases with precipitation, since it has been mainly associated with coastal/riverine process from the Last Glacial to 5.0 ka BP (Jiménez-Espejo et al., 2008). Nevertheless, during some periods of arid conditions (e.g. the Younger Dryas), increased erosion and river incision are caused by a decrease in the vegetation cover rather than fluvial runoff (Jiménez-Espejo et al., 2008).

In order to discriminate the influence of riverine input on the Mg record, we have compared Mg/Al ratio with Zr/Al ratio (Saharan winds) (Fig. 2a). For more accurate record of both processes, we have selected the Mg/Al ratio at Site ODP 976, since it is located closer to the Iberian margin and is significantly affected by fluvial discharges; and Zr/Al ratio from core 300G, where lower sedimentation rate makes this site more sensitive to Saharan dust supply (Zuñiga et al., 2008). Zr/Al ratio suggests two phases of increased aeolian input from the Sahara, prior to 2700 cal yr BP and during the LIA. Mg/Al ratio seems to have similar tendency that Zr/Al ratio between 4000 and 2750 cal yr BP and they are opposite from 2750 cal yr BP to present day (Fig. 2a). Prior 2750 cal yr BP, strengthen Saharan winds indicate an arid period and wind eroding in the African margin. From 2750 cal yr BP, opposite profile of the proxies is clear, and lower values of Zr/Al ratio together with higher Mg/Al ratio would indicate humidity increase: weaker Saharan winds and fluvial runoff. Thus, Mg/Al ratio could be reflecting riverine input and indirectly precipitation for the last 2700 years (Table 1).

Additionally, $\delta^{18}O$ data are also used in this region as an indication for sea surface temperature (SST) during the Holocene (Frigola et al., 2007; Jimenez-Espejo et al., 2008). During this time, the $\delta^{18}O$ shifts have been related to decreases in SST around 2-3 ^{o}C in the Western Mediterranean Sea (Cacho et al., 2001; Frigola et al., 2007). From our 300 G record, the $\delta^{18}O$ oscillations show certain correlation with these events (Fig. 4), as well as with others paleotemperature proxies (Cacho et al., 2001).

4.2 Zoñar Lake

The major lacustrine response to climate change in Mediterranean areas is lake level fluctuations (Cohen, 2003). Water input to Zoñar Lake is the sum of rainfall, runoff, groundwater and springs; whereas the output is mostly by evaporation. Instrumental data during the last 20 years show that lake level fluctuation responds rapidly to changes in the precipitation (Valero-Garcés et al., 2006). Thus, hydrology of the lake is directly related to the precipitation/evaporation balance (P/E). Ion water concentration increases during phases of higher evaporation, causing aragonite and gypsum precipitation in the lake and, consequently, Sr-enrichment in sediments (Sr/Al). However it cannot be used as indicator of P/E variability trough the whole Late Holocene since aragonite precipitation only represents extreme episodes of intensive evaporation. Besides lake level rise, higher precipitation also means more watershed erosion by runoff and increases in detrital input into the lake (clay minerals, quartz, feldspar and detrital calcite). Geochemically, the allochthonous component of the sediments is composed of Al, K, Fe, Si, Ca, Rb and other trace elements associated (Martín-Puertas et al., 2009). Based on the statistical treatment carried out by these authors, we propose Rb as possible proxy for watershed erosion. Rb has been normalized to Al in order to discriminate changes in the relative contribution from different terrigenous sources. Principal Component and Redundancy Analyses (PCA and RDA) (Martín-Puertas et al., 2009) show as Rb is associated with clay minerals and controlled by the first eigenvector, which differences between detrital and endogenic. Although Al also represents the detrital component of the sediments, it, together with magnetic susceptibility and quartz, is positively related to the third eigenvector, which indicates saline to brackish environments during lower lake level (Martín-Puertas et al., 2009). This unexpected relationship could be explained as a result of the input of reworked sediments from exposed littoral zone (coarser fraction) during lower lake level stages. Moreover, it is important to distinguish between terrigenous inputs by runoff, associated with more humid conditions, and by wind erosion during arid phases. In order to test the reliability of the Rb as runoff proxy, we compare Rb/Al ratio with Sr/Al ratio (intensive evaporation phases) and the semi-quantitative lake level curve reconstructed for this lake based on multiproxy-analyses (Martín-Puertas et al., 2008) (Fig. 2b). Prior 2900 cal yr BP, Zoñar Lake dried out and palesoil developed even in the deepest basin. The onset of lacustrine deposition started at 2900-2600 cal yr BP with evaporitic facies (gypsum) and aragonite precipitation corresponding to ephemeral lake (Martín-Puertas et al., 2008; 2009). After that, Zoñar was a permanent lake until present day. Phases of intensive evaporation (Sr/Al peaks) correspond with lower values of Rb/Al ratio (lower detrital input) and, additionally, the general tendencies of this ratio reflect the most important lake level changes interpreted from the multiproxy analyses (Fig. 2b). So, we propose the variability of the Rb/Al ratio responds mostly to changes in runoff-precipitation during the last 2600 years (Table 1).

5 Chronological marker and human influence

To compare the marine and continental records at high-resolution scales we should demonstrate the compatibility of both chronological models. As chronological markers, we have used the signatures of atmospheric lead pollution during Roman Empire (2050-1750 cal yr BP) and Medieval Times (950-750 cal yr BP) defined for the North Atlantic region (Renberg et al., 2001). Fig. 3 shows Pb-enrichment in sediments (Pb/Al ratio) of Alboran Sea and Zoñar Lake records: roman lead pollution is recorded in both, but medieval signal only occurs in the Alboran Sea records. The radiocarbon data close to the Pb-enrichment in Alboran sediments supports the timing of lead pollution signature during Medieval Ages. The absence of such an enrichment in the Zoñar Lake sequence could be explained by the deposition of evaporitic facies and the occurrence of subaerial exposure periods from 1350 to 730 cal yr BP (Fig. 3) (Martín-Puertas et al., 2008). In any case, synchronous Pb peak at Roman period would validate the comparison between both records.

On the other hand, human influence can compromise the use of geochemical data as paleoclimate proxy, especially in continental records (Vannière et al., 2008). The watershed and the hydrological balance of Zoñar Lake have been directly affected by changes of the land uses and water management since the Bronze Age and particularly during the last 150 years (Valero-Garcés et al., 2006 and Martín-Puertas et al., 2008). Pb/Al peak in Zoñar Lake at 2300-2100 cal yr BP (350-150 BC) (Fig. 3), but not in Alboran Sea, could indicate early lead contamination by runoff coinciding with Rb/Al peak at 2200 cal yr BP (Fig. 2b). It was a time of enhanced mining and smelting activity by Iberian culture and increased trading with Greek and Phoenician (Rothenberg et al., 1989). During the Roman period (100 BC-AD300), human activities could have amplified the lake response to climate forcing (Martín-Puertas et al., 2009) and both drier conditions during 2100-1700 cal yr BP and spring water derivation for human consumption would have been responsible for decrease lake level, increased chemical concentration and precipitation of gypsum. Sedimentological profiles show deposition of massive facies indicative of some soil erosion during Medieval Ages (Valero-Garcés et al., 2006); however, only from the onset of the industrial revolution, anthropogenic activities cause a significant increase of the soil erosion around Zoñar Lake (Valero-Garcés et al., 2006) (Fig. 3).

6 Climate variability for the South Iberian Mediterranean region

Once we know our records can be compared chronologically and the environmental proxies are not perturbed by human influence, the marine and continental records can be used for reconstructing natural climate variability over the South Iberian Mediterranean region during the Late Holocene. Precipitation proxies (Mg/Al and Rb/Al) are well-correlated at centennial to decadal scale (Fig. 4) showing a unique signal for moisture variability in the South Iberian region, which is supported by Zr/Al ratio. From 4000 to 2700 cal yr BP, Zoñar Lake record shows clear evidences of a dry period and higher Saharan input in the Alboran basin. The drier conditions interpreted from Zoñar record and Zr/Al ratio are consistent with the global aridity crisis in the third millennium BC (Weiss et al., 1993). From 2700 cal yr BP, Mg/Al and Rb/Al ratios are interpreted as rainfall indicators. In term of humidity, both proxies define three different phases until present day: 2.7-1.5 cal ka BP; 1.4-0.7 cal ka BP; and the last 700 years. General trend of Mg/Al, Rb/Al and Zr/Al ratios suggest a progressive humidity recovery from 2700 to 2500 cal yr BP. The most humid episode occurs at ~ 2500-1700 cal yr BP, characterized by an abrupt precipitation increase and weaker winds from Africa (Fig. 4). After that, proxies indicate gradual tendency toward aridity until present day, although with some fluctuations. Precipitation decreases from 1400 to 700 cal yr BP coinciding with the Medieval Climate Anomaly (MCA). The end of MCA is marked by increase of the precipitation at 700-550 cal yr BP (AD 1250-1400) and cooling during the LIA (Fig. 4). After 500 cal yr BP (AD 1400) there are discrepancies between marine and continental hydrological signal. In Alboran Sea, there is a clear decrease of coastal/riverine input, even reaching lower values than during the MCA; however, in Zoñar Lake, although runoff also slightly decreases the LIA is wetter than the MCA. Paleoclimates records for the Iberian Peninsula (Moreno et al., 2008; Benito et al., 2010; Morellón et al., 2009) and Morocco (Esper et al., 2007) show that the LIA was wetter than the MCA, in agreement with Zoñar record. This observation would suggests that the age model from the core ODP 976C-1H is not sufficiently well constrained for the last 500 yr.

7 South Iberian Mediterranean Archive and its connection with the Northern Hemisphere climate changes.

As we have shown above, our environmental proxies are mostly driven by changes in precipitation; nevertheless humid conditions have been related to cooling phases in northern-central Europe and the Mediterranean region during the last three millennia (Magny, 2004; Mauquoy et al., 2008). The occurrence of lower SST in Alboran Sea fit quite well with both cool pulses in the western Mediterranean (Frigola et al., 2007) and global polar cooling described by Mayewski et al. (2004) (Fig. 4); however there are some disagreements, which could be induced by the influence of other climate factors on the isotopic signal. Attending to global and regional cool episodes, it can be observed that the association cool/wet and warm/dry conditions do not occur always in this region. The most humid period recorded during the Late Holocene (2.5-1.7 cal ka BP) coincides with two cool pulses for the western Mediterranean -M2 and M1- (Frigola et al., 2007) and also lower SST for Alboran Sea (Fig. 4). This period has been recognized as a cool and wet episode in the North Atlantic region associated with solar forcing, which started at 2.8 cal ka BP (Bond et al., 2001; van Geel et al., 1999), e.g.: northern Europe (Bond and Lotti, 1995), Greendland (Stuvier et al., 1995) western-central Europe (Magny, 2004), Demark (Mauquoy et al., 2008), The Netherland (van Geel et al., 1996) and NW Iberia (Bernárdez et al., 2008). On the other hand, cool and dry periods have been reconstructed for 3.4-2.7 cal ka BP and 1.2-1.0 cal ka BP (Mayewski et al., 2004). Pollen data from the Iberian Peninsula (Jalut et al., 2000) and marine core ODP 976C-1H (Combourieu Nebout et al., 2009) suggest aridity prior 3000 cal yr BP and during the MCA coinciding with lower precipitation reconstructed (Fig. 4). Arid conditions in southwestern Mediterranean region are in concordance with central Europe (Magny, 2004) (Fig. 5b). The onset of the last cool episode -the LIA- (600-200 cal yr BP) is characterized in both Alboran and Zoñar records by a sharply increase in precipitation, but it is followed by a slight decrease in precipitation, also recorded in central Europe (Magny, 2004) and NE Spain (Morellón et al., 2009). However, more humid condition are also evidenced in central-western Europe (high lake level, Magny et al., 2007) (Fig. 5b, green bars) and northern-western Europe (peat bog developments, Mauquoy et al., 2008; and glacial advances, Nesje et al., 2008) showing hydrological discrepancies in the western part of the European continent.

The most recent precipitation reconstruction for the Late Holocene in west-central Africa is based on the record of Sahara dust flux (Mulitza et al., 2010). These authors reconstruct weaker Sahara dust emissions, more fluvial deposits and humid conditions ($^{18}\delta O_{carbonates}$) during 3150-1750 cal yr BP in response to more continental precipitation; a gradual Sahara dust strengthening until 1000 cal yr BP together with higher values of $^{18}\delta O$ indicating tendency toward aridity. For the last 700 cal yr BP, isotope composition suggests humidity recovery; however, Saharan dust influx also increased because of changes in land uses (Mulitza et al., 2010). Increasing Saharan dust is also recorded in Alboran basin during the last 700 years (Fig. 5c).

The Late Holocene climate variability over the Eastern Mediterranean shows opposite humidity conditions (Fig. 5d): a wet period from 3500 to 3000 cal yr BP and 1700-1000 cal yr BP and aridity for 3000-1700 cal yr BP and 800-270 cal yr BP. The MCA was humid in the Eastern Mediterranean (Schilman et al., 2001; Wick et al., 2003; Jones et al., 2005, 2006; Neumann et al., 2007) and the LIA shows some fluctuations and regional variability since it is recorded as humid (Issar, 1998; Dragoni, 1998) but also dry (Bar-Matthews et al., 1998).

Comparison among southwestern Mediterranean, north-central Europe, West Africa and eastern Mediterranean regions suggests that moisture variability in the study area is more similar to west-central Europe and West Africa than the eastern Mediterranean region during the Late Holocene. Opposite temperature and precipitation pattern between western and eastern Mediterranean, has already been evidenced by several authors during the Holocene (Rimbu et al., 2004; Roberts et al., 2008; Felis and Rimbu, 2010; Touchan et al., 2010).

8 Conclusions

Changes in geochemical composition of sediments from the Alboran Sea and Zoñar Lake records are used to reconstruct environmental changes in response to humidity conditions in the South Iberian Mediterranean region during the Late Holocene. The robust chronological control of marine and continental proxies allows a comparison and integration of both records at centennial to decadal scales. Since 2700 cal yr BP, changes in precipitation have controlled the detrital sedimentation in both depositional environments allowing the reconstruction of moisture variability based on geochemical proxies. The two archives record four main stages for the Late Holocene: i) an arid period prior 2.7 cal ka BP, ii) moisture recovery and wettest conditions for 2.5-1.7 cal ka BP, iii) a gradual decrease in precipitation and driest conditions during the MCA (1.4-0.7 cal ka BP) and iv) more humid conditions and hydrological instability during the last 700 years. The southwestern Mediterranean region climate evolution correlates better with the climate variability in western-central Europe and West tropical Africa rather than eastern Mediterranean supporting a seesaw pattern for the Mediterranean region during the Holocene. Additionally, evidences of Pb-enrichment in sediments from the terrestrial record during the Late Bronze Age suggest early anthropogenic pollution.

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Table 1

Proxy	**Source**	**Environmental process**	**Forcing variable**	**Validity (cal yr BP)**
Mg/Al ratio	Alboran ODP976	Fluvial runoff	Precipitation	2700 to present
Zr/Al ratio	Alboran 300G	Saharan winds	Precipitation *	4000 to present
$\delta^{18}O$	Alboran 300G	Sea Surface Temperature	Temperature	4000 to present
Rb/Al ratio	Zoñar Lake	Runoff	Precipitation	2600 to present
Pb/Al ratio	Alboran 300G Zoñar Lake	Lead pollution	Human impact	4000 to present

*Inverse relationship between the proxy and the variable

Figure captions:

Table 1: Geochemical proxies applied for this study from Alboran Sea and Zoñar Lake sediments.

Figure 1: Map of continental and marine core sites.

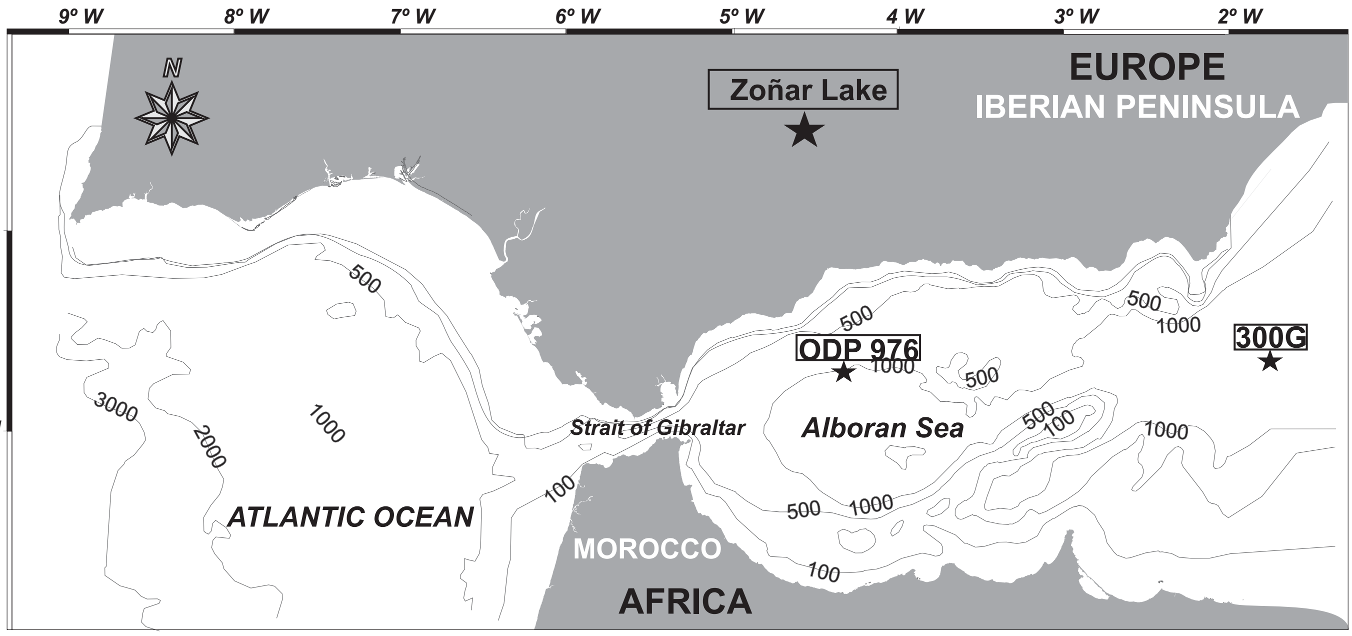
Figure 2: (a) Alboran paleoenvironmental proxies: in blue, Mg/Al ratio from core ODP976 sediments as indicator of Iberian riverine inputs into Alboran basin; in red, Zr/Al ratio from core 300G as Saharan dust inflow. (b) Zoñar paleoenvironmental proxies: in blue, Rb/Al ratio as detrital input into the lake; in red, Sr/Al ratio as ion water concentration (Martín-Puertas et al.,

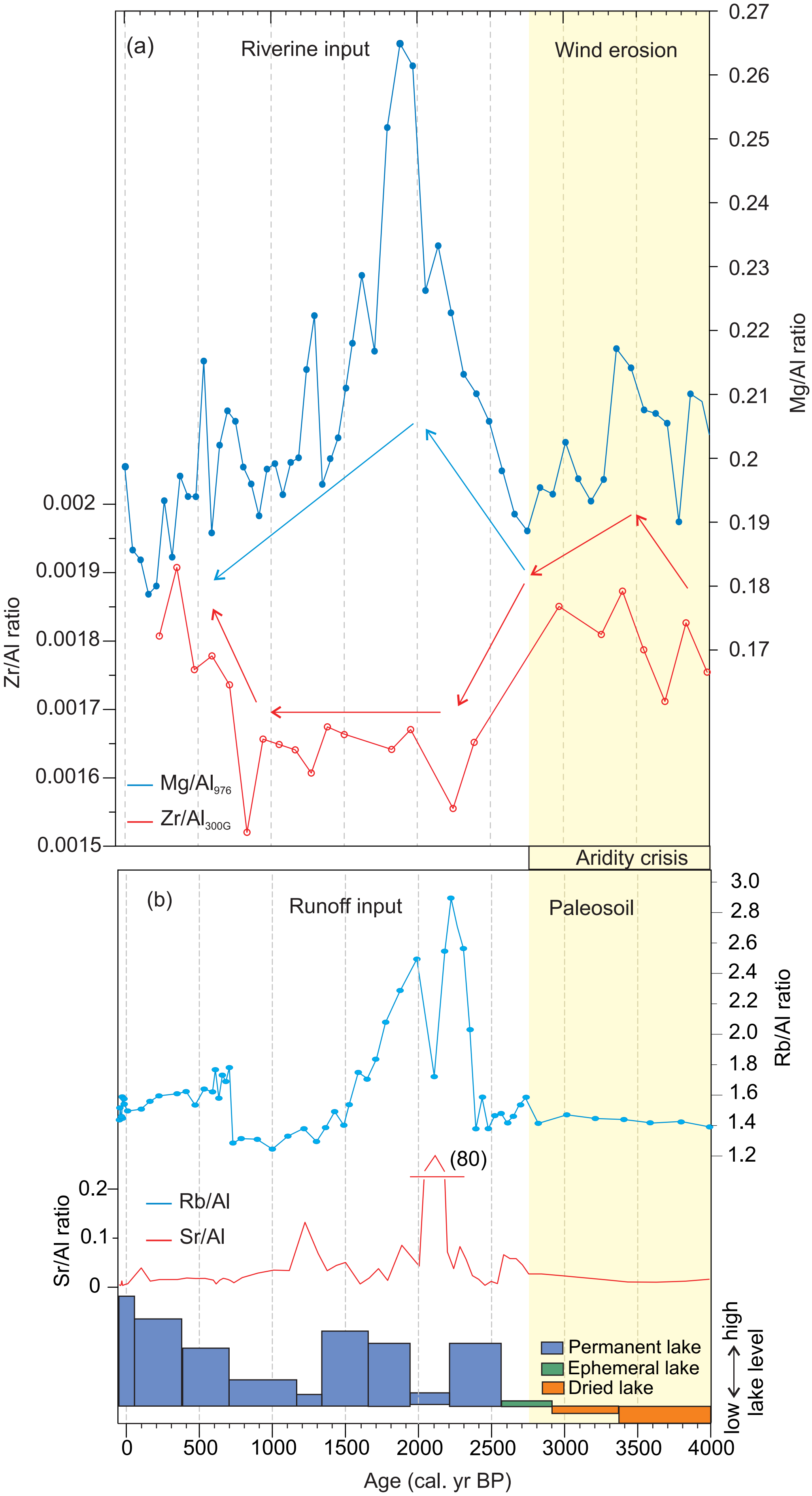
2009); and lake level reconstruction from multiproxy analyses published in Martín-Puertas et al. (2008).

Figure 3: Pb/Al ratios from a) Alboran (core ODP976) and b) Zoñar Lake. ^{14}C data and ^{137}Cs signal for AD 1963 are included. Gray bars indicate the lead pollution peaks.

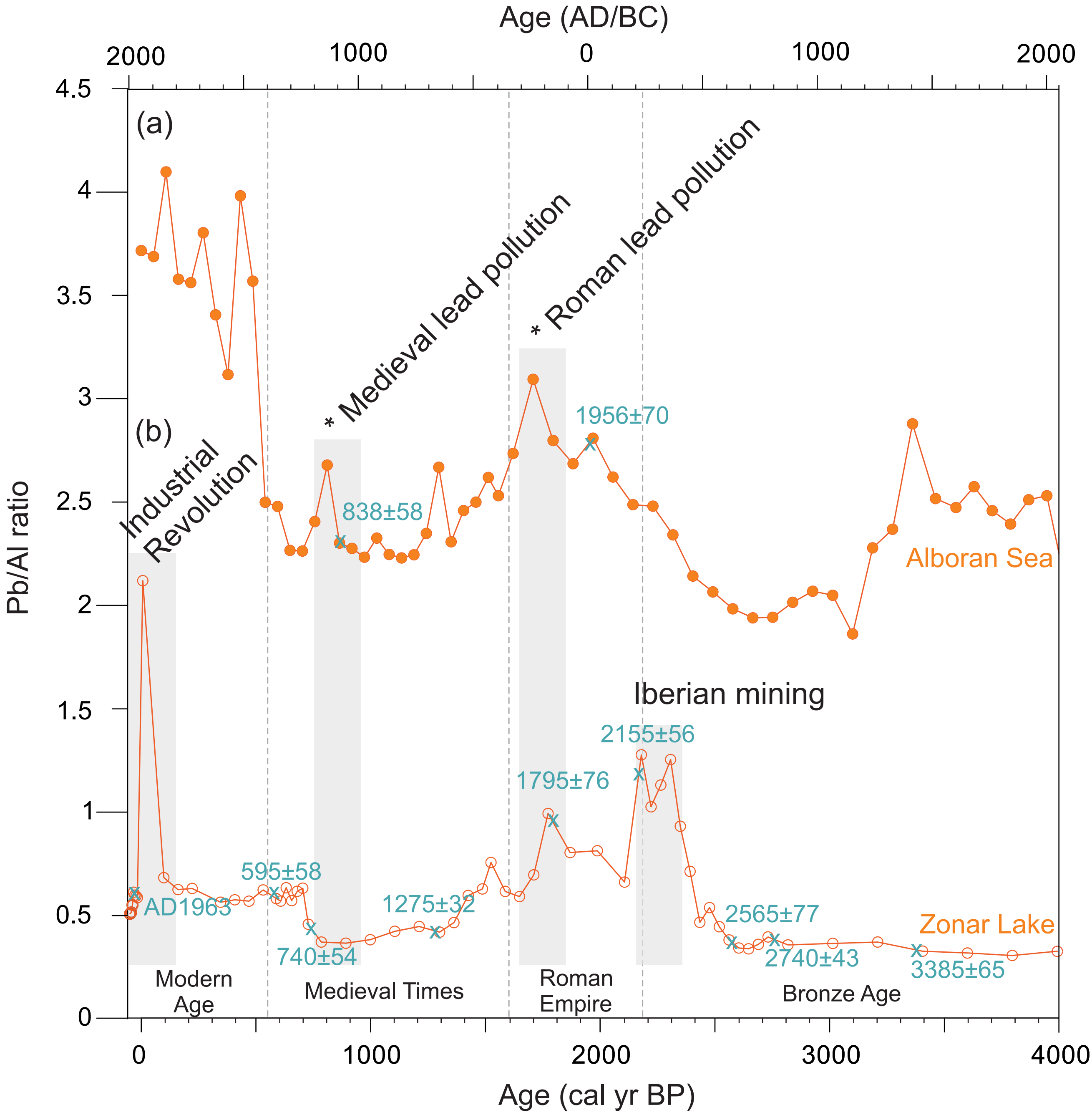
Figure 4: Marine and continental approach based on geochemical proxies for the climate variability: Rb/Al ratio from Zoñar Lake sediments and Mg/Al ratio from Alboran Sea sediments represent precipitation; Zr/Al ratio indicates Saharan winds; $\delta^{18}O$ as indicator of Sea Surface Temperature (SST). Climatic events defined for western Mediterranean region are included for comparison: Alboran Sea pollen events from core ODP 976 (APC1 and APC3) (Combourieu-Nebout et al., 2009), aridification phases in the western Mediterranean (J4 and J6) (Jalut et al., 2000), polar cooling (Mawyesky et al., 2004) and central Mediterranean cold pulses (M0 to 3) (Frigola et al., 2007) during Late Holocene.

Figure 5. Precipitation proxies (Rb/Al and Mg/Al ratios) compared with lake level reconstruction for central Europe (Magny, 2004 in blue and red; Magny et al., 2007 in green), $\delta^{18}O$ composition from Lake Bosumtwi (Mulitza et al., 2010) and South East Mediterranean Sea (Schilman et al., 2001) as indicators of humid conditions in North-central Africa and eastern Mediterranean, respectively.

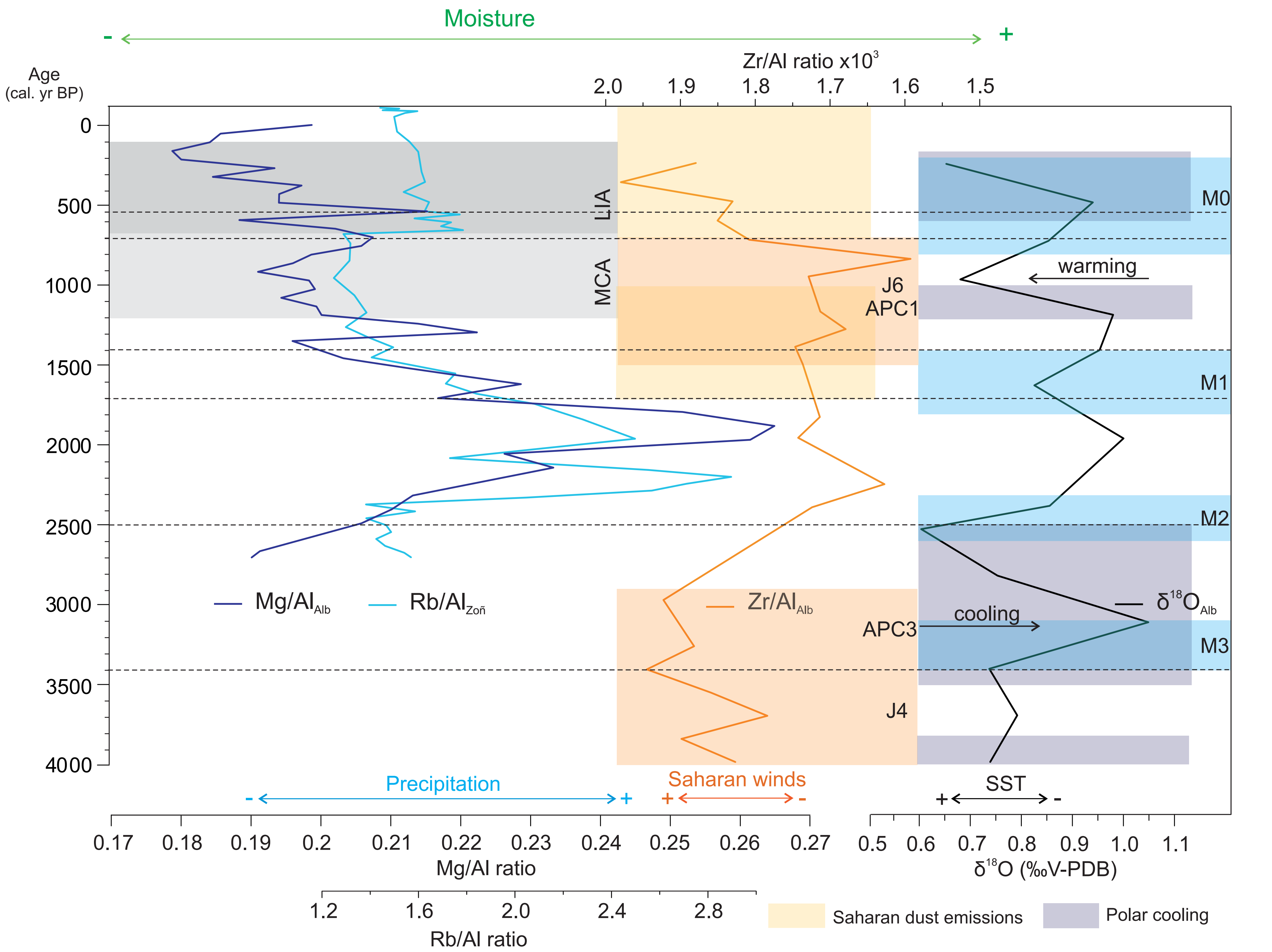

9º W
8º W
7º W
6º W
5º W
4 W
3º W
2º W
37º N
36º N
N
Zoñar Lake
EUROPE
IBERIAN PENINSULA
500
500
1000
ODP 976
1000
500
300G
3000
2000
1000
Strait of Gibraltar
Alboran Sea
500
100
1000
100
ATLANTIC OCEAN
500
1000
MOROCCO
100
AFRICA



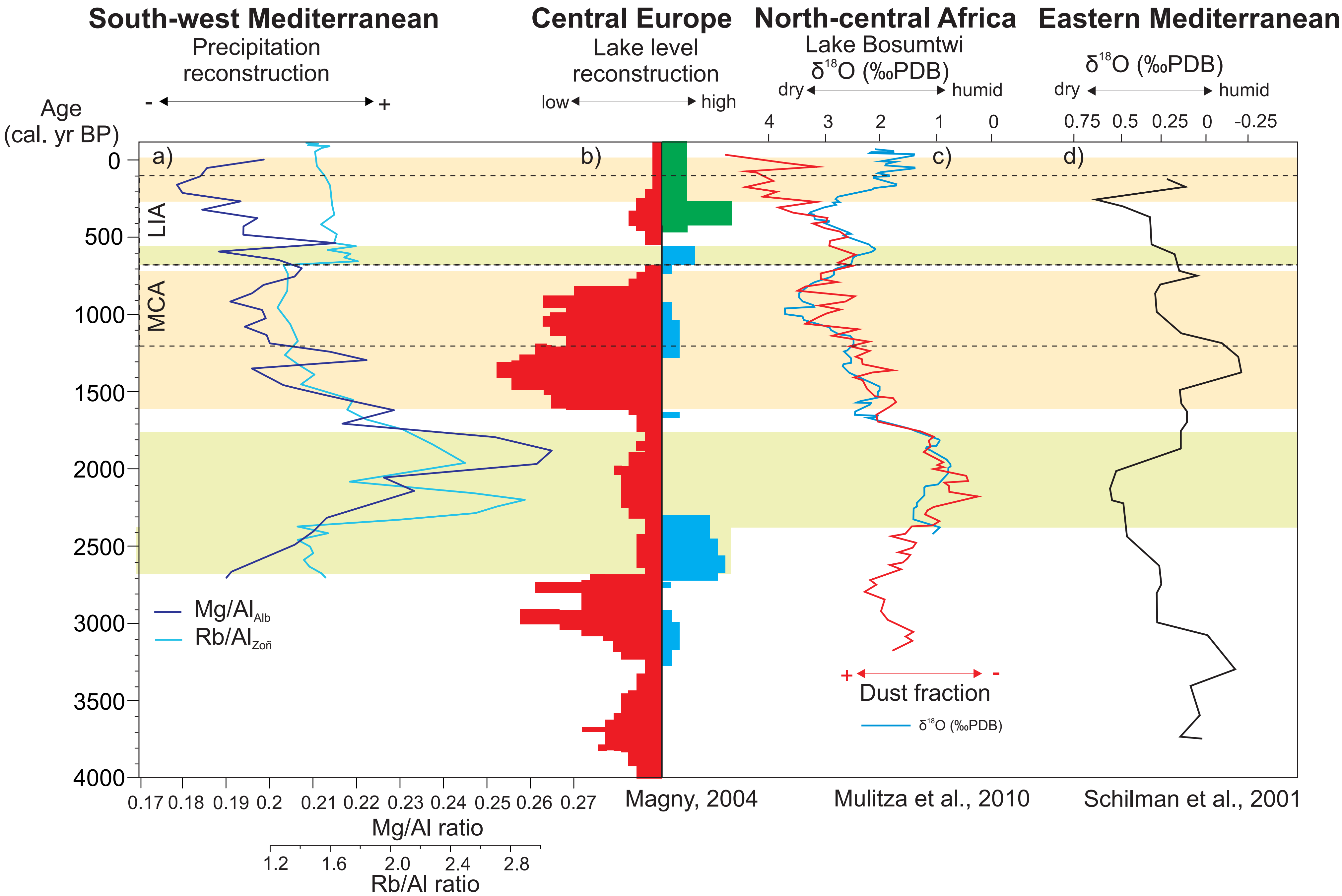
(a)
Riverine input
Wind erosion
Mg/Al ratio
Zr/Al ratio
Mg/Al976
Zr/Al300G
Aridity crisis
(b)
Runoff input
Paleosoil
Rb/Al ratio
Sr/Al ratio
Rb/Al
Sr/Al
(80)
Permanent lake
Ephemeral lake
Dried lake
low ↔ high
lake level
Age (cal. yr BP)



Age (AD/BC)
2000
1000
0
1000
2000
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
Pb/Al ratio
(a)
(b)
Industrial Revolution
* Medieval lead pollution
* Roman lead pollution
1956±70
838±58
Alboran Sea
Iberian mining
2155±56
1795±76
595±58
AD1963
1275±32
740±54
2565±77
2740±43
3385±65
Zonar Lake
Modern Age
Medieval Times
Roman Empire
Bronze Age
0
1000
2000
3000
4000
Age (cal yr BP)



Moisture
- +
Age
(cal. yr BP)
Zr/Al ratio x10³
2.0 1.9 1.8 1.7 1.6 1.5
0 500 1000 1500 2000 2500 3000 3500 4000
LIA
MCA
J6
APC1
M0
M1
M2
M3
warming
cooling
APC3
J4
Mg/Al_Alb
Rb/Al_Zoñ
Zr/Al_Alb
δ18O_Alb
Precipitation
Saharan winds
SST
0.17 0.18 0.19 0.2 0.21 0.22 0.23 0.24 0.25 0.26 0.27
Mg/Al ratio
1.2 1.6 2.0 2.4 2.8
Rb/Al ratio
0.5 0.6 0.7 0.8 0.9 1.0 1.1
δ18O (‰V-PDB)
Saharan dust emissions
Polar cooling
Arid phases in Iberian Peninsula
West Mediterranean cool pulses



South-west Mediterranean
Precipitation reconstruction
- +
Age (cal. yr BP)
a)
LIA
MCA
Mg/Al Alb
Rb/Al Zoñ
Mg/Al ratio
Rb/Al ratio
Central Europe
Lake level reconstruction
low high
b)
Magny, 2004
North-central Africa
Lake Bosumtwi
δ18O (‰PDB)
dry humid
c)
+ Dust fraction -
δ18O (‰PDB)
Mulitza et al., 2010
Eastern Mediterranean
δ18O (‰PDB)
dry humid
d)
Schilman et al., 2001