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Astronomical forcing of Northwest African climate and glacial history during the late Messinian (6.5–5.5 Ma)

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ABSTRACT

High-resolution physical, chemical and biological-based climate proxies from the Ain el Beida (AEB) section in Atlantic Morocco reveal the imprint of the three main orbital parameters precession (19–23 kyr), obliquity (41 kyr) and eccentricity (95–125 and 400 kyr) between 6.5 and 5.5 million years before present (Ma). The precession-related variations are most prominently reflected in the color reflectance and chemical composition of the sediment, showing that precession minimum configurations lead to more humid climate conditions in Northwest Africa probably related to the Atlantic system, while more arid climate conditions prevailed during precession maxima. In addition, precession-bound changes in planktonic foraminifera and calcareous nannofossil assemblages indicate that sea surface temperature (SST) increased during the humid phases, while productivity conditions increased during the dry periods. The clear imprint of the short and long-term eccentricity cycles is explained by a non-linear climatic response to the precession forcing with overall more humid climate conditions during eccentricity maxima. The obliquity-controlled variations in SST and aridity conditions concur with glacial–interglacial variability that is conspicuously recorded in both planktonic and benthic $\delta^{18}O$ records of AEB. The observed warm and wet climates during interglacial periods most likely reflect the direct ice driven thermal response to the reduced ice sheets and more active Atlantic depressions. Similar as during the Pliocene and Pleistocene, obliquity-controlled variations in the planktonic and benthic carbon isotope ($\delta^{13}C$) records of AEB are inversely related to the oxygen isotope records with more depleted values during glacial stages, although with a small lag. The close correspondence between the $\delta^{13}C$ records of AEB and other open ocean sites (i.e., Sites 982 and 926) may therefore point to large-scale glacial-controlled variations in the deep-sea carbon reservoir. Superimposed on the orbital variations, the imprint of the – onset of the – Messinian Salinity Crisis can be traced by a marked ~1.0‰ negative excursion in planktonic $\delta^{13}C$ at 6.0 Ma, followed by a prominent peak in Ti/Al at ~5.97 Ma.

1. Introduction

The region of Northwest Africa, including the Sahelian, Saharan and Mediterranean belts, is characterized by a strong interplay between low-latitude and high-latitude climate oscillations. Today, the region is mainly influenced by the monsoon system in the south and the Atlantic system in the north. From the late Pliocene to the recent, dust flux records indicate that the precipitation regime in Northwest Africa was strongly influenced by dominantly obliquity-controlled glacial cycles as well as a strong 100-kyr cycle during the last 800 ka (Bloemendal and deMenocal, 1989; Ruddiman et al., 1989a, b; Tiedemann et al., 1994; deMenocal, 1995), which occurred superimposed on precession induced regional changes in climate. Although less significant, this imprint of precession has also been found in the terrestrial element composition of deep-sea (piston) cores off Northwest Africa (30°N) for the last 250 ka (Moreno et al., 2001). Evidently, maximum values in the precession-related components of the dust indicators Al and Fe/Al occur during precession minimum configurations, and lead thereby ice volume changes by ~5.5 kyr.

Prior to the onset of major Northern Hemisphere glaciations around 2.8 Ma, long paleoclimatic records off West Africa at ~20°N express a distinct precession signature with a relatively minor contribution of obliquity (Ruddiman et al., 1989a, b; Tiedemann et al., 1994). This cyclicity has been attributed to a direct response of the African monsoon to low-latitude insolation forcing. In contrast to the late Pleistocene, the off-shore West African sediments reveal an increased dust flux (i.e., carbonate depletions) during precession maxima (and obliquity minima). It has been argued that the increased dust flux during these periods is caused by more arid climate conditions at times that the monsoon circulation was reduced, whereas periods of enhanced (monsoon)

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rainfall during precession minima (and obliquity maxima) lead to an increased vegetation cover and a reduced dust flux (i.e., carbonate enriched sediments).

Sonic and gamma-ray cycles reflected in boreholes from the Gulf of Cadiz (Sierro et al., 2000) and sedimentary (e.g. sapropels) successions in the Mediterranean (Hilgen, 1991) showed that, during the early Pliocene warm period, the precession cycle also dominated the regions immediately north of Northwest Africa. Similar to the West African region, it has been inferred that periods of maximum rainfall and runoff in southern Spain and the Mediterranean occur at times of precession minima (Van Os et al., 1994; Schenau et al., 1999; Foucault and Melières, 2000; Sierro et al., 2000). It was argued, however, that the sedimentary cycles in the Gulf of Cadiz are related to variations in annual precipitation coupled to the Atlantic system, and not to the monsoon. Enhanced winter precipitation in the northern borderlands of the eastern Mediterranean may also have set the stage for sapropel formation (Rohling and Hilgen, 1991), but still the most widely accepted theory is that increased African monsoon intensities reduced the Mediterranean anti-estuarine circulation and caused sapropel formation due to an increased Nile outflow (Rossignol-Strick, 1987).

At present, not much is known about the climate response to orbital forcing of Northwest Africa during the latest Miocene time period (i.e., Messinian) when vast amounts of evaporites were deposited in the Mediterranean during the so-called Messinian Salinity Crisis (MSC) (Hsü et al., 1973; Ryan et al., 1973). At that time, the connection between the Mediterranean and the Atlantic Ocean was restricted and probably even interrupted at times, resulting in a significant lowering of sea level in the Mediterranean due to evaporitic drawdown. It can thus be questioned whether the early Pliocene orbital phase relations remained stable or underwent significant changes as a consequence of the changing boundary conditions (see Clemens et al., 1996). In addition, this time period is marked by punctuated obliquity-controlled glacial cycles (Hodell et al., 1994; 2001; Shackleton et al., 1995; Vidal et al., 2002, among others), which are clearly reflected in the oxygen isotope records of the marine successions in the Ain el Beida and Loulja sections located in the Bou Regreg area on the Atlantic side of Morocco (Van der Laan et al., 2005, 2006). By contrast, the sedimentary color alternations of these successions are dominated by the precession cycle; most likely indicating aridity variations, as found for time equivalent successions in the eastern Mediterranean (Santarelli et al., 1998). Here, we will elaborate on the astronomical phase behavior of Northwest African climates during the latest Miocene by applying a multi-proxy approach, including physical, chemical and biological parameters, to the Ain el Beida section. The main goal of this study is to discriminate between the role of regional climate changes versus glacial variability and the impact of the MSC. For this purpose we will apply cross-spectral analysis to determine phase relations with the orbital parameters.

2. Section and setting

The Ain el Beida (AEB) section is located in the Bou Regreg area in Northwest Morocco, in a brick-quarry a few km southeast of Rabat-Salé (Fig. 1). The section contains relatively deep marine sediments that belong to the Blue Marl formation (Cita and Ryan, 1978). These homogeneous marly sediments have a gray–blue color when freshly excavated, which gives the formation its informal name. Deposition of the Blue Marl in the Bou Regreg area started in the late Tortonian. The marls were deposited in the Gharb basin, representing the westward extension – and opening to the Atlantic – of the Rifian Corridor. This corridor acted as an extensional foredeep during the late Miocene to early Pliocene, separating the active Rif Orogen and nappe complex in the north from the Central Moroccan Meseta to the south (Benson and Rakic-El Bied, 1996); it formed one of the two Atlantic–Mediterranean connections during the late Miocene. While the marine gateway was closed in the course of the Messinian, deposition of the Blue Marl in the Gharb Basin continued well into the Pliocene (e.g., Benson and Rakic-El Bied, 1996).

The Blue Marl exposed at AEB belongs to the middle part of the formation. The weathered outcrops are characterized by a regular alternation of yellow-beige and reddish layers (color cycles). The AEB section contains in total 45 of these dominantly precession controlled color cycles with varying thickness and distinctness, the reddish layers being softer and the beige layers more indurated (Fig. 2). The stratigraphic height of the section is about 75 m.

3. Material and methods

3.1. Sampling

A total of 297 samples were collected from 44 color cycles. After removing the weathered surface, 6 to 8 samples were taken from each color cycle using a water-cooled hand-drill. Unfortunately it was not possible to sample the uppermost steep part of the section. All samples were processed and subjected to physical, chemical and biological analyses to generate various proxy records for paleoclimatic reconstruction.

3.2. Physical properties

Initially a visual distinction in the intensity of the color of the reddish layers was made in the field. Quantitative color measurements were subsequently performed on dry samples in the laboratory, using a Minolta CM-508I spectrophotometer. Measurements are automatically converted into reflectance (%) values for 10 nm intervals between 400 and 700 nm. The resultant red-green component (a^* values) is used in the present study because it reflects the cyclicity as observed in the field best.

Magnetic susceptibility is a measure of the strength of the magnetic signal in a sample after it has been subjected to a (weak) magnetic field. It was measured in the laboratory at room temperature on a KLY-2 Kappabridge (Hrouda, 1994).

3.3. Calcareous plankton

For calcareous nannofossil counts, all samples were processed using the settling method reported in De Kaenel and Villa (1996). This technique provides a uniform dispersion of calcareous nannofossils on each slide that is necessary for quantitative counting. On average, nannofossils were counted on 3 long traverses on a slide and at 630× magnification (612 fields of view). This was necessary to obtain a reproducible counting for each slide. The abundance in number of specimens is expressed relative to unit area of the slide (specimens per mm^2). This methodology has the advantage to express the absolute abundance of species and to take rare species into account; some rare species have a more significant ecological signal than more abundant species (see also Appendix 1).

Counting of planktonic foraminifera was performed on the species level, whereby at least 200 individuals were picked from each sample and mounted on Chapman slides. In this study we focused on the abundance variations in the *Globigerinoides* group, sinistrally-coiled *Neogloboquadrina* (*N.* sin) and *Globorotalia margaritae* (*G. margaritae primitiva* and *G. margaritae margaritae*). The habitat characteristics of these species are listed in Appendix 2. Finally, we will use the number of foraminifera per gram sediment as a measure for dilution by terrigenous material.

3.4. Stable isotopes

Stable isotope measurements were performed on the calcitic tests of the planktonic foraminiferal species *Globigerinoides obliquus* and the benthic foraminiferal species *Planulina ariminensis* and are