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Reconstructing 2000-Year, Oceanic Temperature Changes off Southwest Morocco Using G. bulloides Foraminifera Mg/Ca Ratios

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Abstract: This study was conducted on the GeoB8601-3 core, collected off the southwest coast of Morocco, to reconstruct the variations in oceanic temperatures over the past 2000 years. Geochemical analyses of planktonic foraminifera G. bulloides in the core provided Mg/Ca ratios, as well as stable carbon (δ13C) and oxygen (δ18O) isotopes. The distribution of Mg/Ca ratios with respect to core depth exhibited significant variations, with the lowest values recorded at a depth of 90-91.5 cm and the highest values observed at depths of 110-111.5 cm and 135-136.5 cm. Through specific calibrations, Mg/Ca values were converted to temperatures, allowing for the reconstruction of oceanic temperatures off southwest Morocco over the 2000-year period. The results indicated a significant temperature increase during certain periods, particularly between ±2112 and ±1681 years BP, as well as between ±1191 and 233 years BP. Relatively cooler temperatures were observed from approximately 165 years BP to the present, with a notable cooling event around 1351 years BP. Comparative analysis of the records obtained, through the two calibration methods, revealed a general trend of decreasing sea surface temperatures over the past 2000 years. It is important to note that these findings are based on the specific study of the GeoB8601-3 core and G. bulloides foraminifera. Further research and additional data are necessary to confirm these observations and gain a better understanding of oceanic temperature variations in this region during the studied period.

Keywords: Southwest Morocco, Oceanic Temperatures, Mg/Ca Ratios, G. bulloides Foraminifera, Reconstruction, Last 2000 Years

1. Introduction

Paleoceanography research aims to quantify the climate and chemical variability of the oceans at different timescales, evaluate their sensitivity to internal and external forcings, and determine their role in regulating atmospheric CO2 pressure. To better understand the role of the oceans in climate variability, it is essential to accurately describe the physical properties of the oceans, such as temperature and salinity, at the surface and in depth, as well as quantify the activity of marine ecosystems.

This work focuses on the importance of reading oceanic archives and using Mg/Ca thermometry of foraminifera to reconstruct past oceanic temperatures. Foraminifera, marine organisms commonly used in paleoclimatic studies, are present in oceans worldwide and preserve well in sediment records. The Mg/Ca ratio of foraminiferal tests has become a promising proxy for estimating surface and subsurface ocean water temperatures.

Over the years, advancements in the analysis of foraminiferal Mg/Ca ratios have improved our understanding of the relationship between this ratio and seawater temperature during organism calcification. Studies have shown that the shells of planktonic foraminifera contain varying amounts of magnesium depending on the water temperature at the time of their formation. Thus, by analyzing the Mg/Ca ratio of foraminifera, it is possible to reconstruct past oceanic temperatures at different depths based on the habitat preferences of foraminiferal species.

Recent progress in microanalytical techniques, such as inductively coupled plasma atomic emission spectrometry (ICP-AES), allows for high-resolution analysis of

foraminiferal tests. This provides the opportunity to obtain high-resolution records of past oceanic temperatures over timescales ranging from several years to several thousand years.

In brief, this research employs Mg/Ca ratio-based calibrations to estimate temperatures from planktonic foraminifera. The calibrations established [15, 9] collect applied to planktonic foraminifera samples (G. bulloides) within the study region. These findings facilitate the reconstruction of temperature variations in both surface and subsurface waters off the coast of southwest Morocco spanning the past two millennia.

2. Study Area

The Moroccan Atlantic coast is located in the South-west of Morocco, between 30°-31°N and 10°-11°W. It is considered one of the richest regions in exploitable biological resources, classified according to their bioecological characteristics and their socio-economic importance. This richness is also manifested at the level of small pelagics, it is also characterized by the resurgence of deep waters, which ensures a supply of mineral elements, favoring photosynthesis in surface waters and, consequently, the production of the entire food web (National Institute of Fisheries Research, 2014). In addition, this coast plays a very important role in the Moroccan climate and is an important climatic factor.

The marine sampling was carried out during the oceanographic campaign "METEOR" Cruise M45 /5, Cruise M37/1 and Cruise M58/2. The marine sites studied during this thesis are located on the Atlantic coast of southwestern Morocco. Nine marine sedimentary records, two of which have been retained, to discuss the Holocene paleo-environmental evolution and to discuss the last 2000 years in the South of Morocco.

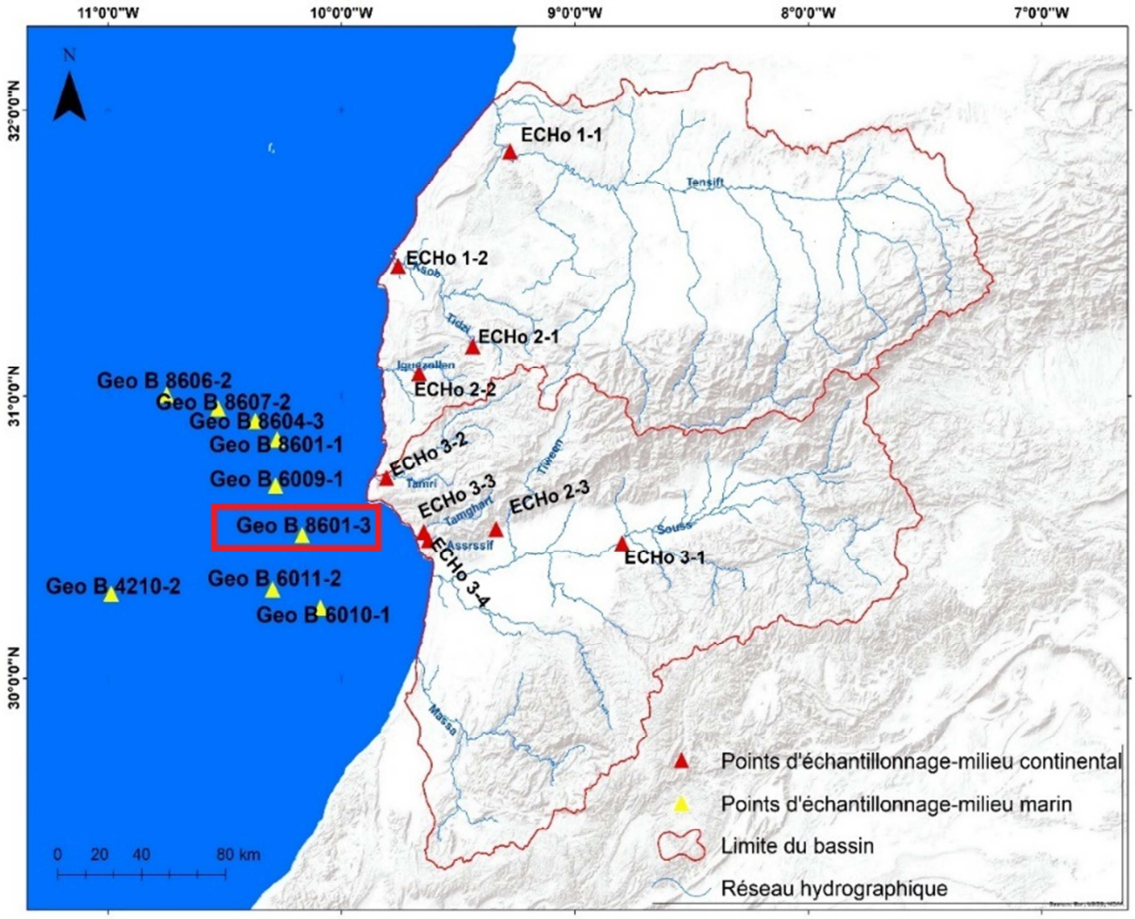

Figure 1. *Geographical location of the Geo8601-3 core sample.*

3. Materials and Methods

3.1. Materials

To go back in time, we focused on the analysis of the core GeoB8601-3 (30 ° 50.9 ° N, 10 ° 16.1 °W), recovered southwest of Cape Ghir, off the coast of southern Morocco during the cruise "METEOR" M 58/2 [5]. This core was taken from the upper northwest continental slope of Africa (South of Morocco), to recover high resolution sediment sequences over the last 2000 years. The site was selected on the edge of the Agadir canyon and a second canyon west of Cape Ghir.

The sediments of the core "GeoB8601-3" consist of nannofossils, or fine-grained olive-brown to dark

greenish-gray nannofossil mud with a small amount of foraminiferal shells and quartz grains. The presence of basalt fragments the size of sand and silty volcanic glass is attributed to the activity of the neighboring volcanoes of the Canary Islands. Small layers of turbidity do not disturb the almost homogeneous sequences of these nuclei [5].

3.2. Methods

Foraminifera are planktonic or benthic organisms, some of which form a calcite test. They have been used for many years, for paleoceanographic studies, because their tests are found in abundance in marine sedimentary cores [10]. Among the planktonic species, the most used (Globigerinoides ruber, for warm regions and Globigerina Bulloides, for temperate or cold regions) live on the surface of the oceans. There is another category of planktonic foraminifera: so-called deep planktonic species. Several studies had already shown that deep planktonic foraminifera could record the conditions at the level of the thermocline. The growth depths of deep planktonic foraminifera, deduced from these different studies, appeared contradictory with respect to each other [11]. For this reason, we were interested in the species of benthic foraminifera of the type: Globigerina Bulloides.

Each selected sample for analysis contained between 16 and 30 planktonic foraminifera (G. bulloides). The sample preparation methods adhered to the procedures established by Lea and Boyle [14], with modifications based on the cleaning protocol introduced by Barker et al. [2], as further adapted by Professor Groeneveld J. from the University of Bremen. A comprehensive description of these cleaning procedures is provided in Chapter 2 of the study.

Measurements of the Mg/Ca ratio were conducted using inductively coupled plasma atomic emission spectrometry (ICP-AES). This technique allows for high-precision measurements with an accuracy of approximately 70.5% [16]. All cleaning and measurement steps were carried out at the MARUM Center of the University of Bremen in Germany, following a specific method described in Chapter 2 of the study.

The samples of planktonic foraminifera (G. bulloides) were cleaned according to a specific procedure, and the Mg/Ca ratio was measured using ICP-AES at the MARUM Center of the University of Bremen. These analyses allowed for the reconstruction of ocean surface temperature changes during the studied period.

In this context, several calibrations were used to estimate temperatures from the Mg/Ca ratios of planktonic foraminifera. Calibrations are available for a limited number of species, including G. sacculifer, O. universa, G. bulloides, and N. pachyderma. Available experiments suggest a temperature sensitivity of approximately 9.7 ± 0.9% variation in the Mg/Ca ratio per degree Celsius. These experiments provide the strongest evidence of temperature control on the Mg/Ca ratio of planktonic foraminifera, confirming thermodynamic expectations based on inorganic experiments.

In this study, the calibration proposed by [15, 9] was utilized to estimate temperatures based on the measured Mg/Ca ratios in planktonic foraminifera (G. bulloides). This calibration was applied to the data from the GeoB8601-3 core collected in the same geographical region of the study. The results of the Mg/Ca ratio measurements on surface planktonic foraminifera and the reconstruction of past temperatures at different depths over the past 2000 years are discussed in the subsequent sections of the study.

4. Results and Discussion

4.1. Mg/Ca Ratio of Planktonic Foraminifera as a "Proxy" Indicator of Paleo-Ocean Temperature in the South-West of Morocco

The Atlantic Ocean communicates in the extreme north with the Mediterranean through the Strait of Gibraltar. In Morocco, the Atlantic coast develops linearly towards the Southwest over 2934 km from Cape Spartel to Lagouira. This latitudinal extension (from 35°N to 16 °N) means that the oceanic influences are even modulated by the effect of latitude, reflecting the transition between the temperate domain and the tropical domain. As a result, the Atlantic Ocean plays a role in transporting disturbances from the Arctic [3].

Thus, Morocco receives, especially in winter, the margins of disturbances arriving on its Atlantic coast, when the Azores anticyclonic system is shifted to the south. Due to their course over the ocean, the Polar Mobile Anticyclones (MPas), which reach Morocco by its Atlantic coast are generally less powerful and are characterized by milder temperatures than the MPas which approach it from the East. As well, the Atlantic Ocean is the main source of moisture for Morocco [12].

The decisive influence of the ocean on the climate of the bordering regions, even if its precise assessment still arouses debates, has already been the subject of numerous works including the synthesis of Bryan [7]. The ocean, in immediate contact with the atmosphere on 71% of the Earth's surface, maintains a constant relationship of energy, water and wind dynamics exchanges with the troposphere. As a result, it plays an essential role in climate variability, at all time scales. By its high storage capacity (1200 times that of the atmosphere), it modulates the climate on a secular scale, through the energy stored in its deepest layers. In contrast, surface currents play a role in regulating short-term climatic changes, including daily, seasonal, or annual fluctuations in the climate.

In the opposite direction, the atmosphere animates the surface dynamics of the oceans, through wind activity. The conjugation of the wind force with the Coriolis force is at the origin of the horizontal displacements of the surface layers of the oceans. This is a process that only triggers other mechanisms, giving rise to local or even regional oceano-atmospheric phenomena such as coastal upwelling which strongly characterizes the climate of the Moroccan coastal fringe [8].

4.2. Contribution to the Characterization of Marine Surface Temperatures in the South-West of Morocco

The values of d18O measured on G. bulloides of surface

sediments and their corresponding calcification temperatures using the atomic emission spectrometry method (ICP-AES), are summarized in the table below. The results for the Mg/Ca measured on G.bulloides are also presented in Table n°23. The Mg/Ca values of G.bulloides obtained were converted into temperatures (SSTMg/Ca) using the equation of Mashiotta et al, 1999 and the equation of Eldderfield and Ganssen [9], for the planktonic foraminifer of the G. bulloides type.

The Mg/Ca values of G. bulloides were transformed into temperatures (SSTMg/Ca) through the equations provided by [1, 2] for planktonic foraminifera of the G. bulloides type.

Table 1. *Geochemical characteristics of surface marine sediments obtained. Core name depth (cm) lat. long. G. bulloides t (°C) (mashiotta cal.) t (°C) (elderfield and ganssen cal.) mg/ca (mmol/mol) d13c d18o.*

Nom carotte	Prof. (cm)	Lat.	Long.	G. bulloides			T (°C)	T (°C) (Cal.Elderfield
				Mg/Ca (mmol/mol)	d13C	d18O	(Cal.Mashiotta)	et Ganssen)
GeoB8614-2	2-3	27,535	-13,850	3,06	-0,95	-0,14	17,4	18
GeoB8613-7	2-3	27,535	-13,737	3,98	-1,12	-0,08	19,9	20
GeoB4239-2	B3	28,495	-13,180	3,36	-1,07	-0,40	18,3	19
GeoB8612-2	2-3	28,802	-12,860	3,54	-1,07	-0,28	18,8	19
GeoB8611-3	2-3	28,795	-12,682	4,85	-1,42	-0,43	21,7	22
GeoB8610-2	2-3	28,782	-12,577	7,22	-1,24	-0,15	25,5	26
GeoB4229-1	B3	29,185	-12,650	3,16	-0,71	-0,05	17,7	18
Muc4223-4	2-3	29,018	-12,467	4,22	-1,09	-0,13	20,4	21
GeoB4226-3	B3	29,318	-11,833	5,42	-0,28	0,11	22,8	23
GeoB4228-2	B3	29,470	-12,993	4,25	-0,58	0,13	20,5	21
GeoB4218-1	A3	29,955	-12,912	3,73	-0,35	0,38	19,3	20
GeoB4210-1	B3	30,300	-10,980	3,27	-0,96	-0,07	18,0	18
GeoB4217-1	2-3	30,435	-12,895	4,29	-0,27	0,33	20,6	21
GeoB4216-2	2-3	30,632	-12,397	3,28	-0,31	0,41	18,1	18
GeoB8604-3	2-3	30,957	-10,522	3,74	-1,38	-0,10	19,3	20
GeoB8607-2	2-3	30,912	-10,362	11,89	-1,06	0,14	30,1	31
GeoB6011-2	2-3	30,315	-10,288	4,49	-1,08	-0,05	21,0	22
GeoB6009-1	2-3	30,682	-10,275	3,09	-1,16	-0,10	17,5	18
GeoB8601-1	2-3	30,848	-10,268	3,82	-1,39	0,09	19,5	20
GeoB6010-1	2-3	30,250	-10,083	10,82	-1,05	-0,13	29,2	30
GeoB8606-2	2-3	31,003	-10,742	2,62	-1,16	-0,11	16,0	16
GeoB5560-1	B3	32,610	-13,117	3,81	-1,01	1,55	19,5	20
GeoB5561-1	2-3	32,703	-12,935	4,25	-0,64	0,36	20,5	21
GeoB4201-2	B3	32,702	-13,545	3,77	-0,07	0,66	19,4	20

According to the results in the table, the Mg/Ca ratio of the foraminifera G. bulloides shows significant variability. However, there appears to be little dependence on temperature in the study area. Generally, the Mg/Ca ratios of the foraminifera have been used as indicators of past ocean temperatures in tropical and subtropical regions of the ocean.

The results show a wide range of variability among the studied samples. Based on the Mg/Ca measurements, sea surface temperatures (SST) in the Atlantic region southwest of Morocco vary between 16°C (Mg/Ca = 2.62 mmol/mol) and 30.1°C (Mg/Ca = 11.89 mmol/mol) according to the Mashiotta calibration, or between 16°C and 31°C according to the Elderfield and Ganssen calibration [9].

The distribution of sea surface temperatures (SST) varies depending on the geographical position of the samples. The GeoB8607-2 sample has the highest temperature of approximately 31°C, while the GeoB8606-2 sample records the lowest temperature of approximately 16°C. There is also a temperature gradient along the Moroccan Atlantic coast, near the Cap Ghir region. In general, temperature values in this study region vary between 17°C and 30°C.

It is important to note that these temperature values are estimated based on the Mg/Ca measurements of G. bulloides foraminifera and the calibration equations of Mashiotta [15] and Elderfield [9]. These estimations are based on empirical relationships and may have uncertainties. Therefore, it is necessary to consider these limitations when interpreting the results.

Reconstruct deep-water temperatures in the south-west of Morocco during the last 2000 years, using the Mg/Ca ratio of foraminifera (G.buloides).

The study conducted on the GeoB8601-3 core, taken from the Atlantic margin off the southwest of Morocco, aims to reconstruct deep-water temperatures over the past 2000 years using the Mg/Ca ratio of the planktonic foraminifera G. bulloides.

To achieve this, the Mg/Ca ratios of the planktonic foraminifera were measured in the sediments of the GeoB8601-3 core. Carbon-14 dating was also performed to establish age models and associate precise core depths with absolute calendar ages.

The measured Mg/Ca data were converted into temperatures using calibrations specific to the G. bulloides species. To verify the consistency of the results, they were compared to existing calibrations in the literature for this species, such as those presented by Mashiotta [15] and Elderfield [9].

It is important to note that the data were obtained using the same cleaning method, and an adjustment coefficient of approximately 0.09 mmol/mol was systematically added to the data obtained from the Boyle and Keigwin (1985)

reductive method. This coefficient was determined from inter-calibration measurements conducted by different laboratories in recent years to ensure result consistency.

The objective of this study is to better define the variations in surface ocean temperatures (SST) over the past 2000 years in the studied region, based on the reconstructed temperatures derived from the Mg/Ca ratio of the planktonic foraminifera G. bulloides in the GeoB8601-3 core.

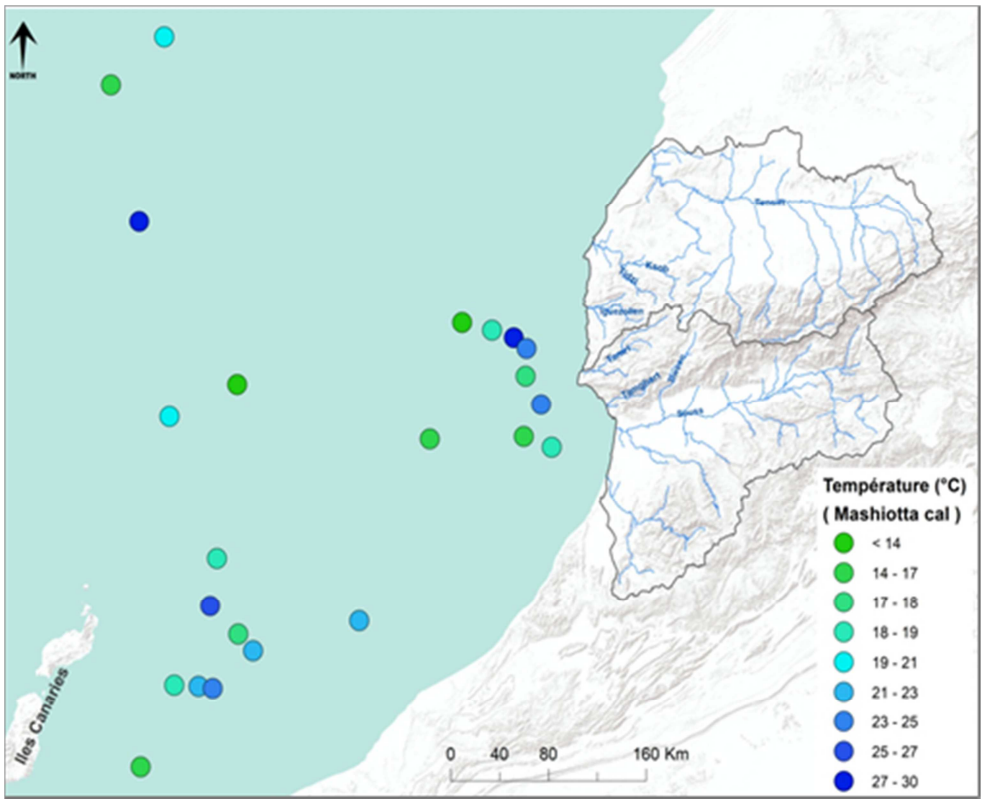

Figure 2. *Estimated marine surface temperatures from the Mg/Ca ratio of planktonic foraminifera (G.buloides) according to the Mashiotta method, 1999.*

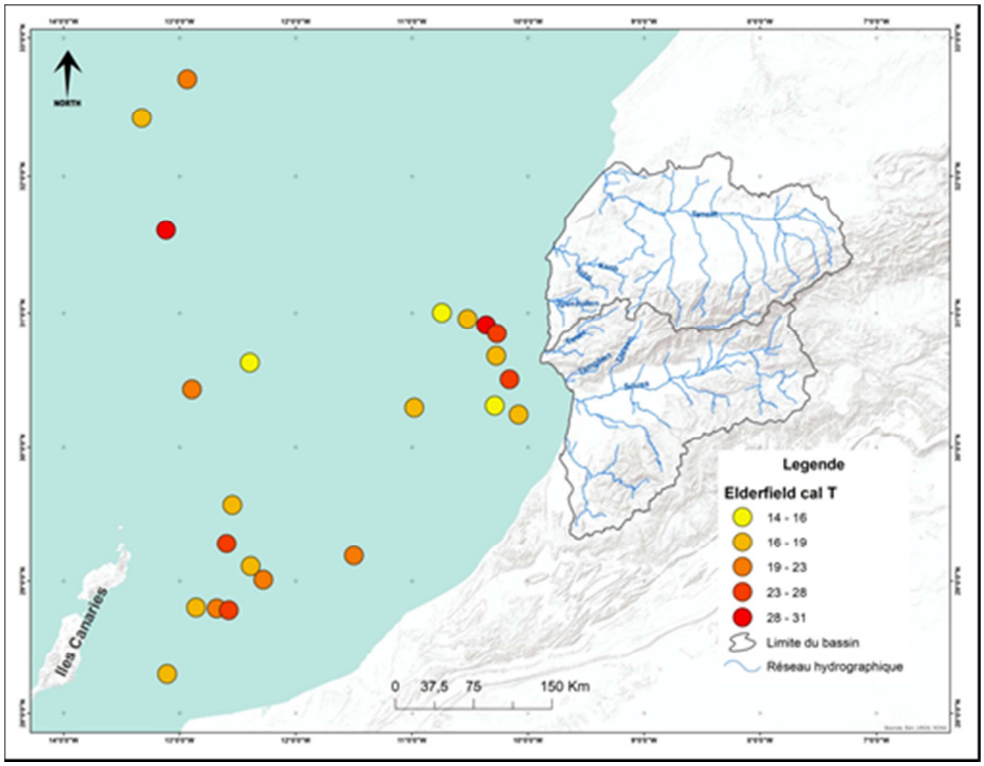

Figure 3. *Estimated marine surface temperatures from the Mg/Ca ratio of planktonic foraminifera (G.buloides) according to the method of Eldderfield et al, 2000.*

Table 2. *Geochemical characteristics of the geob8601-3 core obtained on globigerina bulloides.*

Nom carotte	Prof. (cm)	G. bulloides		
		Mg/Ca (mmol/mol)	d13C	d18O
GeoB8601-3	0-1,5	3,03	-0,63	-0,02
GeoB8601-3	5-6,5	2,99	-1,23	-0,01
GeoB8601-3	10-11,5	3,37	-0,69	0,09
GeoB8601-3	15-16,5	3,60	-0,76	0,16
GeoB8601-3	21-22,5	3,24	-1,02	0,13
GeoB8601-3	45-46,6	3,86	-0,86	0,01
GeoB8601-3	70-71,5	3,59	-0,83	0,13
GeoB8601-3	80-81-5	3,43	-1,16	-0,12
GeoB8601-3	85-86,5	3,48	-0,36	0,10
GeoB8601-3	90-91,5	2,30	-0,92	0,07
GeoB8601-3	100-101,5	3,27	-	-
GeoB8601-3	110-111,5	4,44	-0,30	0,43
GeoB8601-3	125-126,5	4,11	-0,51	0,37
GeoB8601-3	130-131,5	3,91	-1,54	-0,16
GeoB8601-3	135-136,5	4,44	-0,89	-0,12
GeoB8601-3	145-146,5	2,91	-0,21	0,28

In the provided table, the geochemical characteristics of the GeoB8601-3 core for the samples of Globigerina bulloides are shown, including the values of Mg/Ca, δ13C, and δ18O. However, there are no direct data on deep-water temperatures in this table.

The temperatures of the 8601-3 core over the past 2000 years are indicated to be slightly colder than those of the southernmost core (4223-4), which can be explained by the influence of freshwater influx from continental rivers. These freshwater inputs likely had a significant impact on surface temperatures in the Cape Ghir area, which are influenced by continental waters. Therefore, it is important to consider this local factor when comparing temperature signals between different cores.

It is noted that the Mg/Ca data in the study area vary with depth. The distribution of Mg/Ca shows a minimum value in the depth range of 90-91.5 cm (2.30 mmol/mol), while the maximum values are observed in the depth ranges of 110-111.5 cm and 135-136.5 cm (4.44 mmol/mol). The latter depth range exhibits values higher than the average for this core, raising questions about whether they are related to specific circumstances or data processing.

In conclusion, the provided data do not allow for a direct reconstruction of deep-water temperatures off the southwest of Morocco over the past 2000 years using the Mg/Ca ratio of G. bulloides foraminifera. Further studies and specific data on deep-water temperatures would be necessary to achieve such a reconstruction.

By the calibration tools and the precise chronological framework established using carbon-13 dating, it has been possible to highlight variations in ocean temperatures off the southwest of Morocco over the past 2000 years. The reconstruction of sea surface temperatures (SST) from the GeoB8601-3 core allows for the identification of the major climatic phases during this period.

The results show a significant increase in temperatures during the years between approximately 2112 years BP (Before Present) and 1681 years BP, as well as between approximately 1191 years BP and 233 years BP. Conversely, relatively cold temperatures are observed from approximately 165 years BP until the present, with an interruption marked by a notable cooling around 1351 years BP.

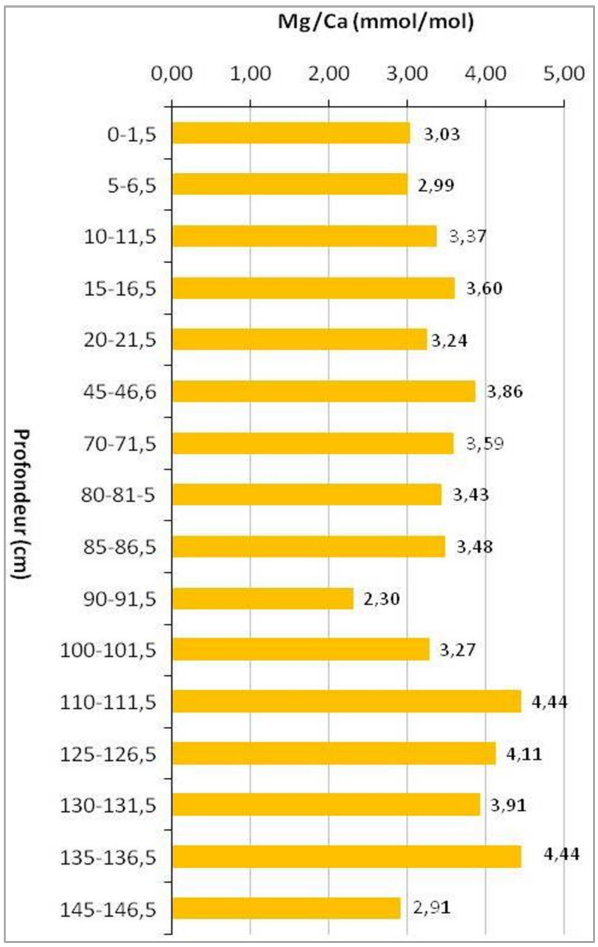

Figure 4. *Mg/Ca (mmol/mol) records of the GeoB8601-3 core obtained on Globigerina bulloides.*

When comparing the records obtained from the two calibration methods, a general trend of decreasing SST throughout this period is observed. This suggests an overall evolution of ocean temperatures off the southwest of Morocco

over the past 2000 years.

It is important to note that these results are based on reconstructions using the Mg/Ca ratio of G. bulloides foraminifera and the specific calibrations used in this study. Further studies and additional data would be necessary to confirm these observations and gain a better understanding of the variations in ocean temperatures in this region during this period.

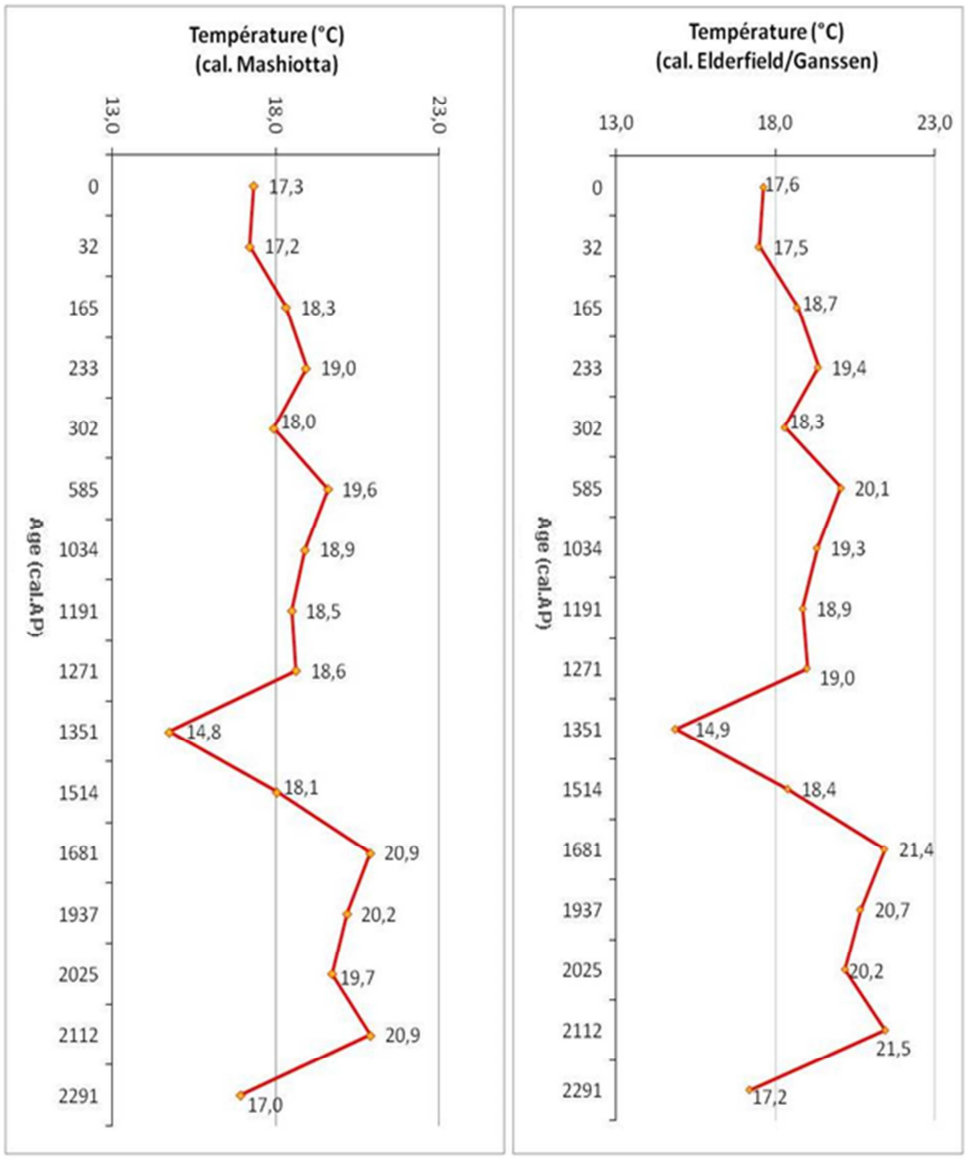

Figure 5. *Surface Paleotemperatures estimated by measuring the Mg/Ca ratio of the planktonic foraminifera G. bulloides (Calibration of Mashiotta, 1999 and Elderfield et al, 2000).*

5. Conclusion

The study of the GeoB8601-3 core off the south-west of Morocco, based on the analysis of planktonic foraminifera G. bulloides, made it possible to reconstruct the variations in ocean temperatures over the last 2000 years. The results indicate significant fluctuations in temperatures during this period.

The sea surface temperatures showed a marked increase during the years between ±2112 and ±1681 years BP, as well as during the years between ±1191 and 233 years BP. However, since about 165 years BP until today, the temperatures seem to have been relatively cold, with a noticeable cooling about 1351 years BP ago.

A comparison between the records of the two calibration methods revealed a general trend of decreasing sea surface temperatures over time. However, it should be noted that these results are specific to the GeoB8601-3 core and the G. bulloides foraminifera studied.

It is important to emphasize that these conclusions are based on specific data and that additional studies are necessary to confirm these observations and obtain a more complete understanding of the variations in ocean temperatures in the south-west region of Morocco over the last 2000 years.

Conflict of Interest

The authors declare that they do not have any conflict of interest related to this research study.

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