



**Paleoenvironmental changes preceding the onset
of the Messinian salinity crisis in the western Mediterranean Sea
(pre-evaporitic Messinian of the Melilla-Nador Basin, NE Morocco)**

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Abstract: In order to contribute to the understanding of the evolution of marine and continental environments, preceding the onset of the Messinian salinity crisis in the western Mediterranean, we conducted an integrated study of the pre-evaporitic Messinian sedimentary series in the Melilla-Nador basin. Three sections have been carried out in the marl-diatomite series and were the subject of a detailed biostratigraphic and palynological study. The study of planktonic foraminifera, pollen, dinocysts, and palynofacies allowed us to characterize the evolution of these environments. From 6.83 to 6.52 Ma, the marine environment was relatively open, calm, probably subject to the action of upwellings and received periodic continental inputs. Starting 6.52 Ma, the abundance and diversity of planktonic foraminifera decreased. Continental inputs gradually dominate, alternating with marine ones, and reflecting a succession between proximal and distal neritic environments. The surface water conditions were warm. After 6.35 Ma, began the degradation of marine conditions. The continental environment shows an open vegetal landscape dominated by herbaceous plants, reflecting a tropical to arid subtropical climate, slightly less dry than that of the South Rifian Corridor. This study confirms the existence of several parameters that contributed to the deposition of the cyclical marl-diatomite series: on the one hand, the hot and dry climate favored the reduction of the plant landscape and therefore erosion (continental inputs); on the other, the tectonics (volcanism and uplift).

Keywords:

- Melilla-Nador basin;
- Morocco;
- Western Mediterranean;
- pre-evaporitic Messinian;
- marine environment;
- continental environment;
- Foraminifera;
- pollen;
- dinocysts

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Résumé : *Changements paléoenvironnementaux précédant le début de la crise de salinité du Messinien dans la mer Méditerranée occidentale (Messinien préévaporitique du bassin de Melilla-Nador, Maroc NE).*- Afin de contribuer à la compréhension de l'évolution des environnements marins et continentaux, précédant le début de la crise de salinité messinienne dans la Méditerranée occidentale, nous avons mené une étude intégrée de la série sédimentaire messinienne préévaporitique dans le bassin de Melilla-Nador. Trois coupes ont été réalisées dans la série marno-diatomique et ont fait l'objet d'une étude biostratigraphique et palynologique détaillée. L'étude des foraminifères planctoniques, du pollen, des dinokystes et du palynofaciès a permis de caractériser l'évolution de ces environnements. De 6,83 à 6,52 Ma, le milieu marin est relativement ouvert, calme, probablement soumis à l'action des upwellings et reçoit périodiquement des apports continentaux. À partir de 6,52 Ma, l'abondance et la diversité des foraminifères planctoniques diminuent. Les apports continentaux, alternant avec des apports marins, deviennent progressivement dominants, l'ensemble reflétant une succession cyclique entre des environnements néritiques proximal et distal. Les conditions de l'eau de surface sont chaudes. Après 6,35 Ma, commence la dégradation des conditions marines. L'environnement continental montre un paysage végétal ouvert dominé par des plantes herbacées, reflétant un climat tropical à subtropical aride, légèrement moins sec que celui du Corridor Sud Rifain.

Cette étude confirme l'existence de plusieurs paramètres qui ont contribué au dépôt de la série cyclique marno-diatomitique avec, d'une part, le climat chaud et sec favorisant l'ouverture du paysage végétal et donc l'érosion (apports continentaux) et, d'autre part, la tectonique (volcanisme et soulèvement).

Mots-clefs :

- bassin de Melilla-Nador ;
- Maroc ;
- Méditerranée occidentale ;
- Messinien préévaporitique ;
- environnement marin ;
- environnement continental ;
- foraminifères ;
- pollen ;
- dinokystes

1. Introduction

The Messinian salinity crisis -MSC- (Hsü *et al.*, 1973, 1977) stands as an exceptional event that profoundly influenced the recent history of the Mediterranean basin. It resulted from the successive closure of the Betic and Rifian corridors (KRIJGSMAN *et al.*, 1999a, 1999b; MARTÍN *et al.*, 2001; ROUCHY *et al.*, 2003; WARNY *et al.*, 2003; CIESM, 2008; BACHE *et al.*, 2015; GORINI *et al.*, 2015a, 2015b; FLECKER *et al.*, 2015; TULBURE *et al.*, 2017; CAPELLA *et al.*, 2018, 2019; TARGHI *et al.*, 2021), which previously served as gateways for water exchange between the Atlantic Ocean and the Mediterranean Sea during the Late Miocene (FLECKER *et al.*, 2015; ACHALHI *et al.*, 2016; CAPELLA *et al.*, 2018, 2019; KRIJGSMAN *et al.*, 2018; SUC *et al.*, 2019).

The progressive isolation of the Mediterranean has caused an important environmental change that has had an impact on the terrestrial and marine ecosystems of the Mediterranean region (SAINT-MARTIN *et al.*, 2003; VASILIEV *et al.*, 2013, 2019; ROVERI *et al.*, 2014; FLECKER *et al.*, 2015; AGIADI *et al.*, 2017; KARAKITSIOS *et al.*, 2017a, 2017b; MOISSETTE *et al.*, 2018; SUC & FRIZON de LAMOTTE, 2019; KONTAKIOTIS *et al.*, 2019, 2020). The pre-evaporitic Messinian series of the peripheral Mediterranean basins are characterized by a typical succession of clays/marls surmounted by a cyclic series of marls and diatomites or sapropels (SIERRO *et al.*, 1993, 1999; SAINT-MARTIN *et al.*, 2003; ASSEN *et al.*, 2006; ACHALHI *et al.*, 2016).

These sediments have registered the changes that preceded the Messinian salinity crisis.

The Melilla-Nador peripheral basin, located in the northeast of Morocco, represents the eastern segment of the southern Rifian corridor. The sedimentary sequence of this basin consists of an Upper Miocene carbonate platform exhibiting reef characteristics, laterally passing to clays and marl-diatomite alternations (SAINT-MARTIN & ROUCHY, 1990; CORNÉE *et al.*, 1996; SAINT-MARTIN *et al.*, 2003).

Extensive research has focused on the Messinian sedimentation in this basin, encompassing stratigraphical, paleontological, and sedimentological investigations (GUILLEMIN et HOUZAY, 1982; ROUCHY, 1982; SAINT-MARTIN & ROUCHY, 1986; SAINT-MARTIN, 1990; SAINT-MARTIN *et al.*, 1991; GAUDANT *et al.*, 1994; CUNNINGHAM *et al.*, 1994; SAINT-MARTIN & CORNÉE, 1996; CORNÉE *et al.*, 1996, 2002, 2006; RACHID *et al.*, 1997; MÜNCH *et al.*, 2001). However, the vegetation and, consequently, the climatic context in the Melilla-Nador basin before the Messinian salinity crisis remains poorly known. The present work is based on the detailed analyses of planktonic foraminifera, spores, pollen, dinocysts, and palynofacies from three selected sections in the study basin. The primary objectives of this study are, on one hand, to provide a better knowledge of the evolution of the marine environments and, on the other hand, to address the information gap regarding the continental environments by reconstructing the vege-



tation and climate of this basin during the pre-evaporitic Messinian.

Building upon a recently developed high-resolution biostratigraphic analysis for the Mediterranean (SIERRO *et al.*, 1993, 2001; LOURENS *et al.*, 2004; ASSEN *et al.*, 2006; CORBÍ & SORIA, 2016; KARAKITSIOS *et al.*, 2017a, 2017b; KONTAKIOTIS *et al.*, 2019; LIRER *et al.*, 2019), a precise biostratigraphic framework has been established for the studied sediments. The study represents a new contribution to the reconstruction of the paleoclimates and the evolution of marine and continental environments during the pre-evaporitic Messinian in the Melilla-Nador basin, within a well-defined chronostratigraphic context. The aim is to enhance our understanding of the impact of the narrowing of the southern Rifian corridor on the climate and environment during a critical period in the history of the Mediterranean.

2. Geographical and geological context of the Melilla-Nador basin

The Melilla-Nador basin, situated in the north-eastern Rif near the Cap des Trois-Fourches (Fig. 1), is bordered to the south by the metamorphic terrains of the Rif foreland. Neogene sediments were deposited unconformably on metamorphic rocks or tectonized Tortonian formations (GUILLEMIN & HOUZAY, 1982). South of the Trois-Fourches cape, this basin is characterized by the development of a carbonate reef platform passing laterally into a basal marl-diatomite sequence, which includes cinerite intercalations (SAINT-MARTIN & CORNÉE, 1996; MÜNCH *et al.*, 2001; SAINT-MARTIN *et al.*, 2003; ASSEN *et al.*, 2006; MÜNCH *et al.*, 2006; CORNÉE *et al.*, 2006). The cyclical succession of marl and diatomite was deposited in shallow marine conditions registering precession cycles (ASSEN *et al.*, 2006). The carbonate platform is initially characterized by conglomeratic to bioclastic retrogradational deposits, followed by bioclastic and reef carbonate prograding deposits (SAINT-MARTIN & CORNÉE, 1996; SAINT-MARTIN *et al.*, 2003; CORNÉE *et al.*, 2006). The initiation of cyclic sedimentation in the Melilla-Nador basin commenced around 6.84 Ma, marking a restriction of paleo-circulation across the basin and the onset of bioclastic platform progradation along the shoreline. The restriction of paleo-circulation is linked to the reduction of the southern Rif corridor (ASSEN *et al.*, 2006). The commencement of diatomite deposition in the Melilla Basin aligned with the tectonic subsidence of the Taza-Guercif Basin and potentially with the initiation of siphoning of intermediate Atlantic waters through the narrowing Rifian corridor (ASSEN *et al.*, 2006). A change in diatom species from boreal to tropical coincided with the appearance of prograding coral reefs along the shelf (ASSEN *et al.*, 2006). This event indicates a decline in the inflow of cold water from the Atlantic (ending the siphoning, according to BENSON *et al.*, 1991). The end of diatomite deposition marks the closure of the open marine envi-

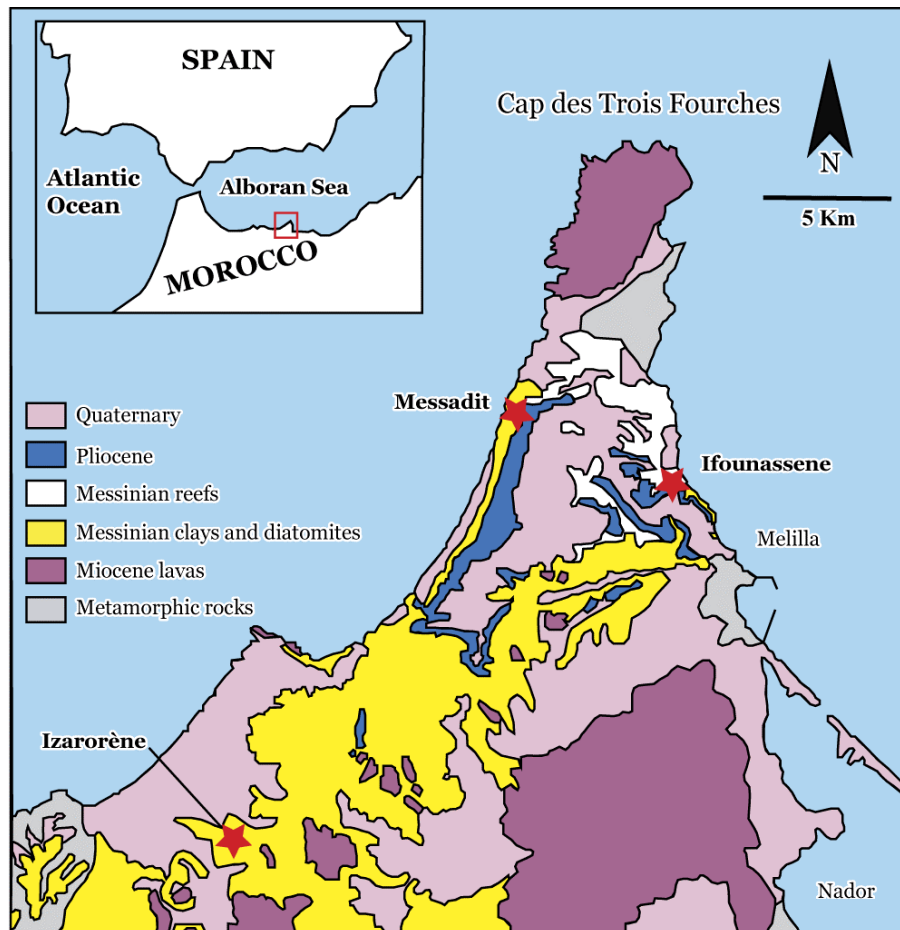
ronment of the Melilla Basin (ASSEN *et al.*, 2006; FLECKER *et al.*, 2015).

Bioclastic limestones and prograding *Porites* fringing reefs characterize the Messinian transgressive system of the studied basin. These sediments transition basinwards to open marine marl, diatomite, and volcano-clastic deposits (CORNÉE *et al.*, 2006). The age of prograding carbonate deposits varies, ranging from around 6.87 ± 0.02 Ma (ROGER *et al.*, 2000) to 5.95–5.99 Ma (CORNÉE *et al.*, 2006). The conclusion of this transgressive cycle (Cycle 1) is marked by the development of *Halimeda* algal beds around 6.08 Ma. This *Halimeda*-rich level serves as a reference point across the entire basin.

The second carbonate complex, known as the Terminal Carbonate Complex (TCC) or Cycle 2, is of Messinian age. It exhibits a flat aggrading-retrograding geometry (CORNÉE *et al.*, 2002, 2006; MÜNCH *et al.*, 2006) and comprises reefs, giant microbial accumulations, and a combination of siliciclastic-oolitic coastal deposits associated with stromatolites. Two major unconformities border this complex (MÜNCH *et al.*, 2006). The $^{40}\text{Ar}/^{39}\text{Ar}$ dating places the base of the TCC (Terminal Carbonate Complex), coinciding with the onset of the Messinian salinity crisis (MÜNCH *et al.*, 2006), at an average of 5.95 to 5.99 Ma. Previous interpretations suggested that Cycle 2 deposits could be partially identified as continental Lago Mare-type deposits (ROUCHY *et al.*, 2003). However, taking into account that the Melilla-Nador basin emerged after the deposition of Upper Messinian sediments from marine Cycle 2 (CORNÉE *et al.*, 2006), MÜNCH *et al.* (2006) demonstrated that these continental deposits evolved laterally into marine deposits, emphasizing the link between the emersion of the Melilla platform and tectono-magmatic activity.

The second major unconformity, corresponding to the major surface of the Upper Messinian, caps the CCT deposits in the Melilla basin. This erosion surface is associated to the primary Messinian drawdown in the Mediterranean. The duration of the hiatus does not exceed 450 kyr (MÜNCH *et al.*, 2006). The TCC can be considered as the marginal equivalent of the Messinian Salinity Crisis evaporites (ASSEN *et al.*, 2006). Re-flooding deposits (Cycle 3) have primarily developed only in the southwestern part of the basin (CORNÉE *et al.*, 2006). They consist of yellowish marine sandstones and *Isognomon* limestones lying on the Messinian erosional surface. They constitute the second index level in the series. The sediments of Cycle 3 have been attributed to the Pliocene (CHOUBERT *et al.*, 1966; GUILLEMIN & HOUZAY, 1982; MÜNCH *et al.*, 2001, 2006; CORNÉE *et al.*, 2002, 2006).





◀ **Figure 1:** Simplified geological map of the Melilla-Nador basin (CHOUBERT *et al.*, 1966) and the location of the studied sections.

3. Material and methods

3-1. MATERIAL

The material studied is derived from three strategically located sections in the Melilla-Nador basin, namely the Messadit, Izarorène, and Ifounassene sections (Fig. 1). These sections were meticulously sampled, resulting in the collection of more than 139 samples. However, only 103 samples exhibiting well-preserved microfauna and suitable for micropaleontological and biostratigraphical study are represented on the stratigraphic columns (Figs. 2-4). The sampling interval ranges between 0.5 and 1.5 m. We aimed for dense sampling to effectively capture variations in microfaunal associations and to account for lithological changes.

3-1-1. Situation and lithological description of the Messadit section

The Messadit section is situated in the western part of the peninsula, in the south of the village of Messadit (Fig. 1). The section has a thickness of 70 m and is characterized by marl-diatomite alternations containing several cinerite levels. This section is the most comprehensive, encompassing the key events of the Late Messinian in Morocco (GAUDANT *et al.*, 1994; SAINT-MARTIN & CORNÉE, 1996; RACHID *et al.*, 1997; SAINT-MARTIN *et al.*, 2003; ASSEN *et al.*, 2006) (Fig. 2). At the base of the section, there is a volcano-sedimentary level that unconformably lies on glauconitic sands.

Some authors (GAUDANT *et al.*, 1994; RACHID *et al.*, 1997) have described this level as a glauconitic conglomerate level with Messinian age overlying sedimentary Tortonian units. The marl/diatomite alternations contain both planktonic and benthic foraminifera, ostracods, bivalves, bryozoans, sponge spicules, diatoms, and fish remains (GAUDANT *et al.*, 1994; RACHID *et al.*, 1997; SAINT-MARTIN *et al.*, 2003). Indurated silicified laminites are intercalated in some places within this sedimentary series. Toward the upper part of the section, two oyster beds (*Pycnodonte*) were observed. ASSEN *et al.* (2006) conducted a cyclostratigraphic study revealing 35 sedimentary cycles well calibrated on the astronomical time scale. Some cinerite layers have been dated using the isotope method (ROGER *et al.*, 2000; ASSEN *et al.*, 2006), providing precise dating for the carbonate sequences of the Melilla-Nador basin. *Hali-medea* algae limestone banks, which represents the lateral equivalent of the last prograding coral reefs (ROGER *et al.*, 2000; SAINT-MARTIN *et al.*, 2003; CORNÉE *et al.*, 2006), cap the section. A total of thirty-six samples (Fig. 2) were palynologically and biostratigraphically analyzed with planktonic foraminifera.



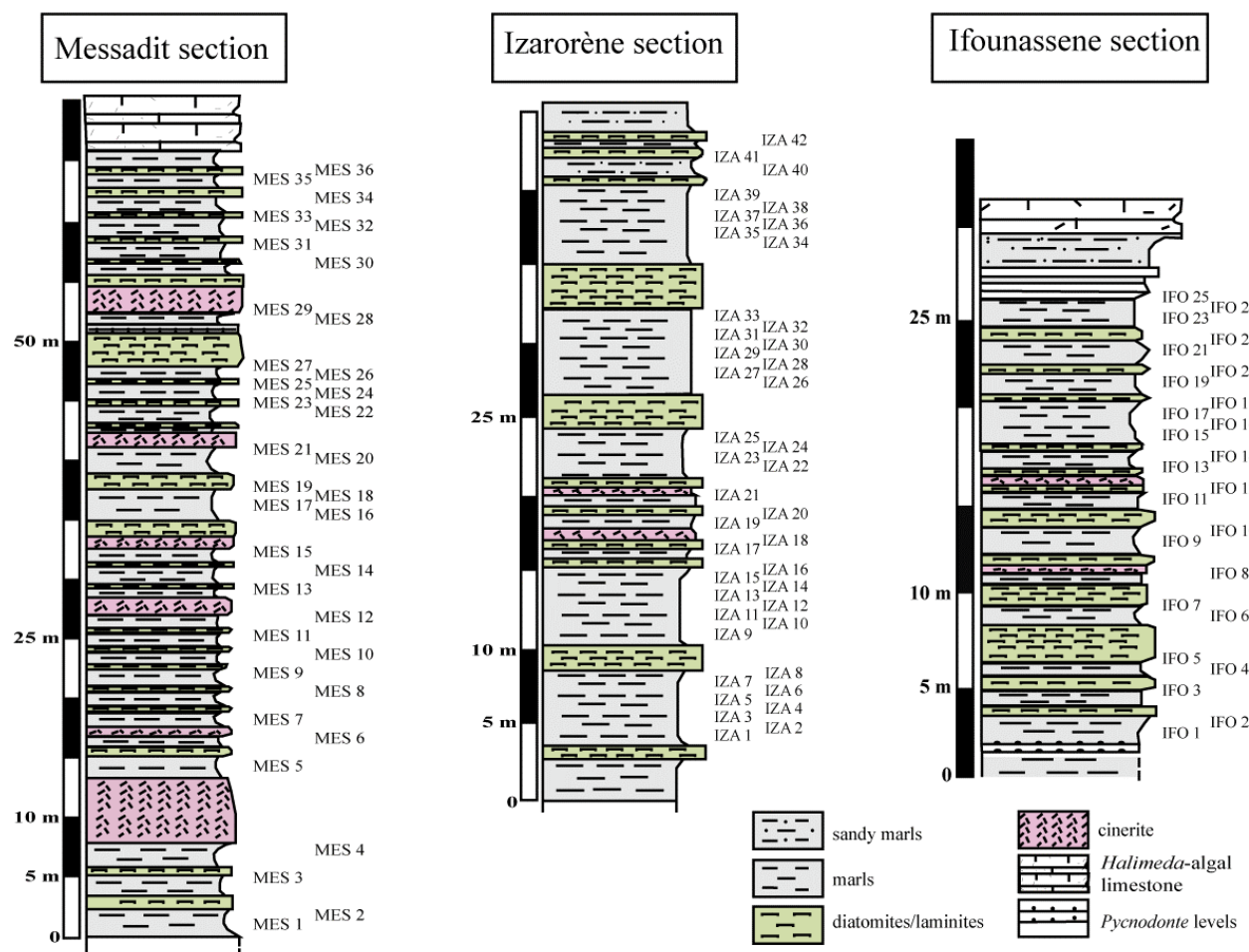


Figure 2: Lithostratigraphy of the studied sections (MES : Messadit section, IZA : Izarorène section, IFO : Ifounassene section).

3-1-2. Situation and lithological description of the Ifounassene section

The Ifounassene section is situated in the eastern part of the peninsula (Fig. 1) and corresponds to the lower part of the Rostrogordo section (SAINT-MARTIN & ROUCHY, 1986; CUNNINGHAM *et al.*, 1994; GAUDANT *et al.*, 1994; RACHID *et al.*, 1997). The visible Messinian series is characterized by marl-diatomite alternations incorporating volcano-sedimentary (cinerites) and bioclastic levels (Fig. 2). The section is 30 m thick and overlaid by *Halimeda* limestone, representing the lateral equivalent of the prograding coral constructions of Unit 3 (ROGER *et al.*, 2000; SAINT-MARTIN *et al.*, 2003; CORNÉE *et al.*, 2006; CUNNINGHAM *et al.*, 1994). The section commences with homogeneous gray marls containing a Neopycnodont (*Neopycnodonte navicularis*) accumulation level (RACHID *et al.*, 1997) and resting on a volcano-sedimentary base level. ASSEN *et al.* (2006) identified seventeen sedimentary cycles in this section, comprising alternating diatomite levels and homogeneous, partly silty marls containing bryozoans, bivalves, and echinoderms. Benthic foraminifera, planktonic foraminifera, and ostracods constitute the primary microfauna in the

sediments. The upper part of the section is composed of homogeneous sandy marls and two silicified and laminated levels with fish remains (GAUDANT *et al.*, 1994). Twenty-five samples (Fig. 2) were analyzed palynologically and biostratigraphically (with planktonic foraminifera).

3-1-3. Situation and lithological description of the Izarorène section

It is located in the east of the village of Izarorène, about 5 km to the ESE of the confluence of the oued Kert with the Mediterranean (Fig. 1). This is a thick series of marls where laminated diatomite levels are intercalated in the upper part of the section (BARHOUN *et al.*, 1999). The section begins with homogeneous blue to gray clayey marl, poorly stratified, overlying a level of white cinerite (Fig. 2). In this section, ASSEN *et al.* (2006) identified six cycles consisting of alternating diatomites and homogeneous marls. Above the third diatomite level, two cinerite levels are intercalated in the homogeneous marls. The section was densely sampled from the top of the first diatomite level. Forty-two samples (Fig. 2) were analyzed palynologically and biostratigraphically (with planktonic foraminifera).



3-2. METHODS

3-2-1. Micropaleontology (planktonic foraminifera)

The samples underwent washing and sieving using the standard method (BARHOUN, 2000). Qualitative and quantitative analyses of planktonic foraminiferal associations were conducted on residues containing a minimum of 300 individuals of the 150 µm fraction. To gain insights into paleoenvironments, two ecological indices were calculated:

1) the Planktonic-Benthic Ratio (P/P+B). This ratio, expressed as $P/(P+B) \times 100$ (the percentage of planktonic foraminifera to the total foraminifera population), is commonly used to reconstruct paleobathymetry (GIBSON, 1989). It also provides information about upwelling phenomena that favor high productivity (MATHIEU, 1986, 1988; BELLIER *et al.*, 2010);

2) the Diversity Index. The species diversity in planktonic foraminiferal assemblages is based on the SHANNON-WEAVER function (SHANNON & WEAVER, 1949). It is calculated from the number of individuals of each species and the number of species for each sample. The estimation of the diversity index considers the proportion of each species in the total population. The SHANNON index considers both the abundance and the uniformity of the species present (DAGET, 1979; MURRAY, 1991).

$$I_{sc} = - \sum (q_i / Q \times \ln q_i / Q)$$

q_i = the number of individuals counted for each species

Q = the total number of individuals for each level

The distribution of planktonic foraminifera is presented in tables. The number of specimens corresponding to abundant, common, and present is: Abundant > 20%; Common = 5-20%, and Present = 1-5%.

3-2-2. Palynology

The standard palynological method, commonly employed for sediment treatment, was utilized for sample preparation following the procedure outlined by BACHIRI TAOUFIQ (2000). It involved HCl and HF treatments, followed by sieving of the residues between 10 and 180 µm, and an organic matter enrichment procedure using $ZnCl_2$. Samples from Izarorène and Messadit sections are poor in pollen and dinocysts. Only 13 samples from the Ifounassene section yielded sufficient pollen grains and dinocysts (at least 160 pollen grains without Pinaceae and 100 dinocysts were counted). Based on the ecology of their representatives, the pollen taxa were grouped in a synthetic diagram (Suc *et al.*, 2018; Fig. 7), with the frequencies of each taxon represented in a detailed diagram.

To deduce global climate parameters, several methods were applied. The mean annual temperature (Tann) was estimated using current ecological conditions for plant groupings (NIX, 1982): megathermal elements (24°C), megamesothermal elements (20-24°C), mesothermal elements

(14-24°C), and microthermal elements (10-14°C). For humidity assessment, the ratio Poaceae/Asteraceae (COUR & DUZER, 1978) was used. According to COUR and DUZER (1978), a Poaceae/Asteraceae ratio > 20 indicates a relatively humid climate, with precipitation exceeding 500 mm/year; conversely, a Poaceae/Asteraceae ratio < 20 indicates an arid climate with annual precipitation not exceeding 500 mm/year. Dry conditions favor the development of Asteraceae, whereas wet conditions favor Poaceae.

To reconstruct the marine environment, we applied indices previously used in the Neogene of Morocco by WARNY (1999), BACHIRI TAOUFIQ (2000), and TARGHI *et al.* (2021, 2023). These indices are derived from the environmental preferences of dinocysts as recognized in the literature (VERNAL *et al.*, 1994, 1998, 2001; VERNAL & MARRET, 2007; MARRET *et al.*, 2001; ZONNEVELD, 1995, 1996; ZONNEVELD *et al.*, 2013; LONDEIX *et al.*, 2007). The curve resulting from the D/S ratio (D: Dinocysts and S: Spores + Pollen) is used to appreciate the marine influence versus the continental influence (MORZADÉC-KERFOURN, 1976; TYSON, 1993; WARNY, 1999). The curve resulting from the G/P ratio (TYSON, 1993; WARNY, 1999) is used to detect the in-shore-offshore direction (G: Gonyaulacoid family, P: Peridinioid family). The IN/ON distality index is the ratio of inner platform neritic assemblages to outer platform neritic assemblages (VERSTEEGH, 1994; WARNY, 1999). The temperature index of surface waters is evaluated by the ratio of warm surface water dinocysts (W) to cool surface water dinocysts (C) (WARNY, 1999). For the analysis of palynofacies, four standard groups have been identified in this work (POUMOT & SUC, 1994; COMBAZ, 1991): woody organic matter (WOM), cellular organic matter (COM), black organic matter (BOM), and amorphous organic matter (AOM).

4. Biostratigraphic results (Foraminifera)

4-1. INTRODUCTION

In light of recent work carried out on the Upper Neogene in the Mediterranean (CORBÍ & SORIA, 2016; KARAKITSIOS *et al.*, 2017a, 2017b; KONTAKIOTIS *et al.*, 2019; LIRER *et al.*, 2019), we conducted a detailed analysis of planktonic foraminiferal associations to revise the biostratigraphic framework of the studied sections. Three carefully chosen sections in the Melilla-Nador basin, where the Messinian deposits are thick and well represented, have been investigated (Messadit, Ifounassene, and Izarorène sections). Each section underwent intensive sampling to identify all the biostratigraphic and paleoenvironmental events characteristic of the Messinian. The analysis and detailed study of 103 samples collected from the three sections allowed the identification of 28 species of planktonic foraminifera, classified into 12 genera. To highlight biostratigraphic events, a complete count was performed on a portion containing

**Table 1:** Main bioevents of planktonic foraminifera characterizing the Messinian in the Mediterranean area.

Planktonic foraminifera bioevents	Chronostratigraphy (Ma)	References
Last Influx <i>Turborotalita multiloba</i>	6.07	SIERRO <i>et al.</i> (2001); BLANC-VALLERON <i>et al.</i> (2002); LOURENS <i>et al.</i> (2004)
II Influx sinistral <i>Neogloboquadrina acostaensis</i> (40%)	6.08	SIERRO <i>et al.</i> (2001); LOURENS <i>et al.</i> (2004)
I Influx sinistral <i>Neogloboquadrina acostaensis</i> (90%)	6.12	SIERRO <i>et al.</i> (2001); LOURENS <i>et al.</i> (2004)
II Influx <i>Turborotalita multiloba</i>	6.23	SIERRO <i>et al.</i> (2001); LOURENS <i>et al.</i> (2004)
Influx dextral <i>Globorotalia scitula</i>	6.29	SIERRO <i>et al.</i> (2001); LOURENS <i>et al.</i> (2004)
S/D <i>Neogloboquadrina acostaensis</i>	6.35-6.37	SIERRO <i>et al.</i> (2001); LOURENS <i>et al.</i> (2004); HÜSING <i>et al.</i> (2009)
FCO <i>Turborotalita multiloba</i>	6.42	SIERRO <i>et al.</i> (2001); LOURENS <i>et al.</i> (2004)
LO <i>Globorotalia miotumida</i> gr.	6.52	SIERRO <i>et al.</i> (2001); LOURENS <i>et al.</i> (2004)
LO <i>Globorotalia nicolae</i>	6.72	SIERRO <i>et al.</i> (2001); BLANC-VALLERON <i>et al.</i> (2002); LOURENS <i>et al.</i> (2004)
FO <i>Globorotalia nicolae</i>	6.83	BLANC-VALLERON <i>et al.</i> (2002); LOURENS <i>et al.</i> (2004)
Top dominant sinistral (<i>Globorotalia</i>) <i>scitula</i> gr.	7.08	LOURENS <i>et al.</i> (2004)
influx conical <i>Globorotalia miotumida</i>	7.18-7.22	LOURENS <i>et al.</i> (2004)
LCO <i>Globorotalia menardii</i>	7.23	HILGEN <i>et al.</i> (2000a, 2000b); LOURENS <i>et al.</i> (2004); LIRER <i>et al.</i> (2019)
FCO <i>Globorotalia miotumida</i> gr.	7.24	HILGEN <i>et al.</i> (2000a, 2000b); LOURENS <i>et al.</i> (2004); LIRER <i>et al.</i> (2019)

about 300 individuals from the 150 µm fraction. In this work, we adopted high-resolution biostratigraphy, astronomically calibrated, recently utilized in the Mediterranean area, favoring precise dating and correlation (HILGEN *et al.*, 1995; KRIJGSMAN *et al.*, 1994, 1995, 1999a, 1999b; SIERRO *et al.*, 1993, 2001; LOURENS *et al.*, 2004; CORBI *et al.*, 2016; KARAKITSIOS *et al.*, 2017a, 2017b; KONTAKIOTIS *et al.*, 2019; LIRER *et al.*, 2019). The main biostratigraphic events characterizing the Messinian in the Mediterranean area are indicated in Table 1.

4-2. MESSADIT SECTION

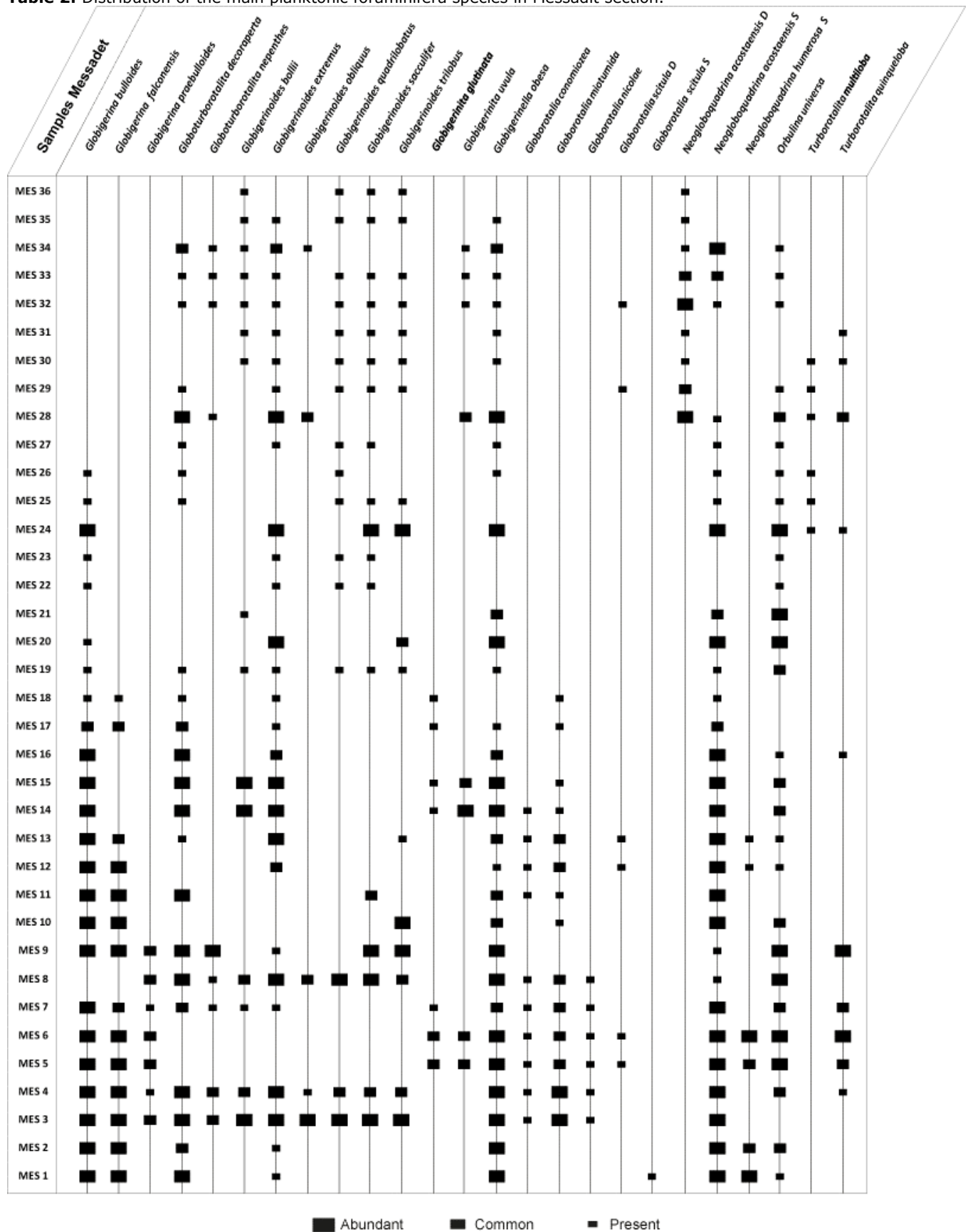
The micropaleontological study of sediments from the Messadit section reveals a remarkable richness in species and individuals of planktonic foraminifera, mainly in its lower part (Table 2). The abundance of planktonic assemblages diminishes from moderate to low towards the upper part of the section. This study identified 28 species and 10 genera. The microfauna also includes benthic foraminifera, some ostracods, fragments of bivalve shells, sponge spicules, and urchin radicles. In the marl and marl-diatomite levels, the planktonic microfauna is well-preserved, enabling a qualitative and quantitative biostratigraphic study, whereas planktonic foraminifera are deformed and poorly preserved in some diatomite levels, making their identification challenging. The evolution of planktonic foraminiferal associations, diversity, and the plankton-benthic ratio in the Messadit section allow us to distinguish two intervals (Fig. 3):

- **The lower part of the section from MES 1 to MES 18** is characterized by high diversity with a SHANNON Diversity Index between 1.9 and 2.28. The Planktonic/Benthic ratio varies between 60 and 90%. Planktonic foraminifera assemblages are dominated by globular forms such as *Globigerinoides*, *Globigerina*, *Globoturborotalita*, *Neogloboquadrina*, *etc.*, compared to the keeled forms of *Globorotalia*, represented by *Globor. miotumida* and *Globor. conomiozea*. These deposits are characterized by a notable abundance of *Globigerina bulloides* and *Globig. falconensis* in some levels (MES 2-MES 6 and MES 9-MES 15).
- **The upper part of the section from MES 19 to MES 36:** The microfauna in these sediments is characterized by average diversity, with a SHANNON Diversity Index between 1.5 and 1.9. The Planktonic/Benthic ratio is average to low, fluctuating between 10 and 60%. Benthic foraminifera are globally abundant and well represented compared to planktonic foraminifera.





Table 2: Distribution of the main planktonic foraminifera species in Messadit section.



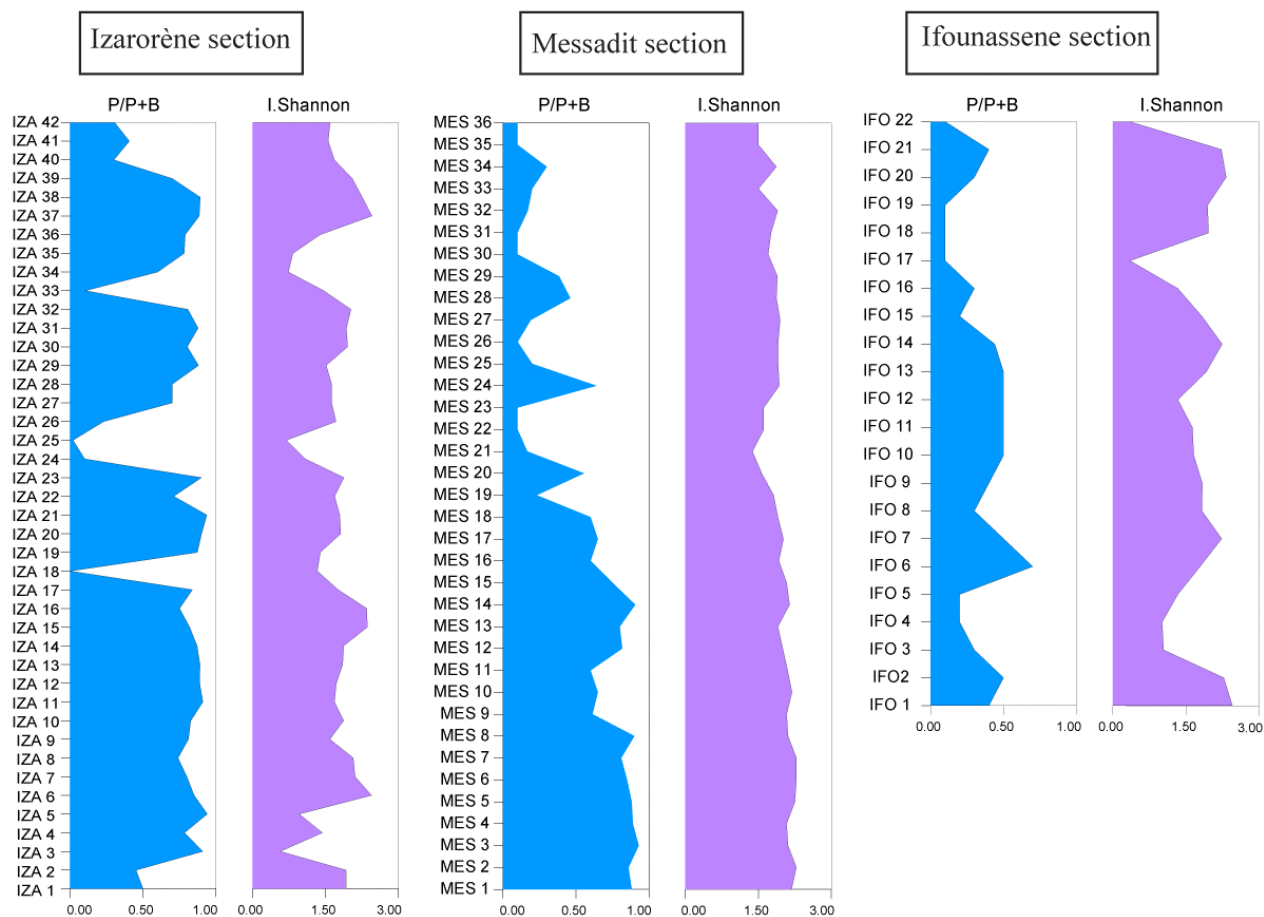


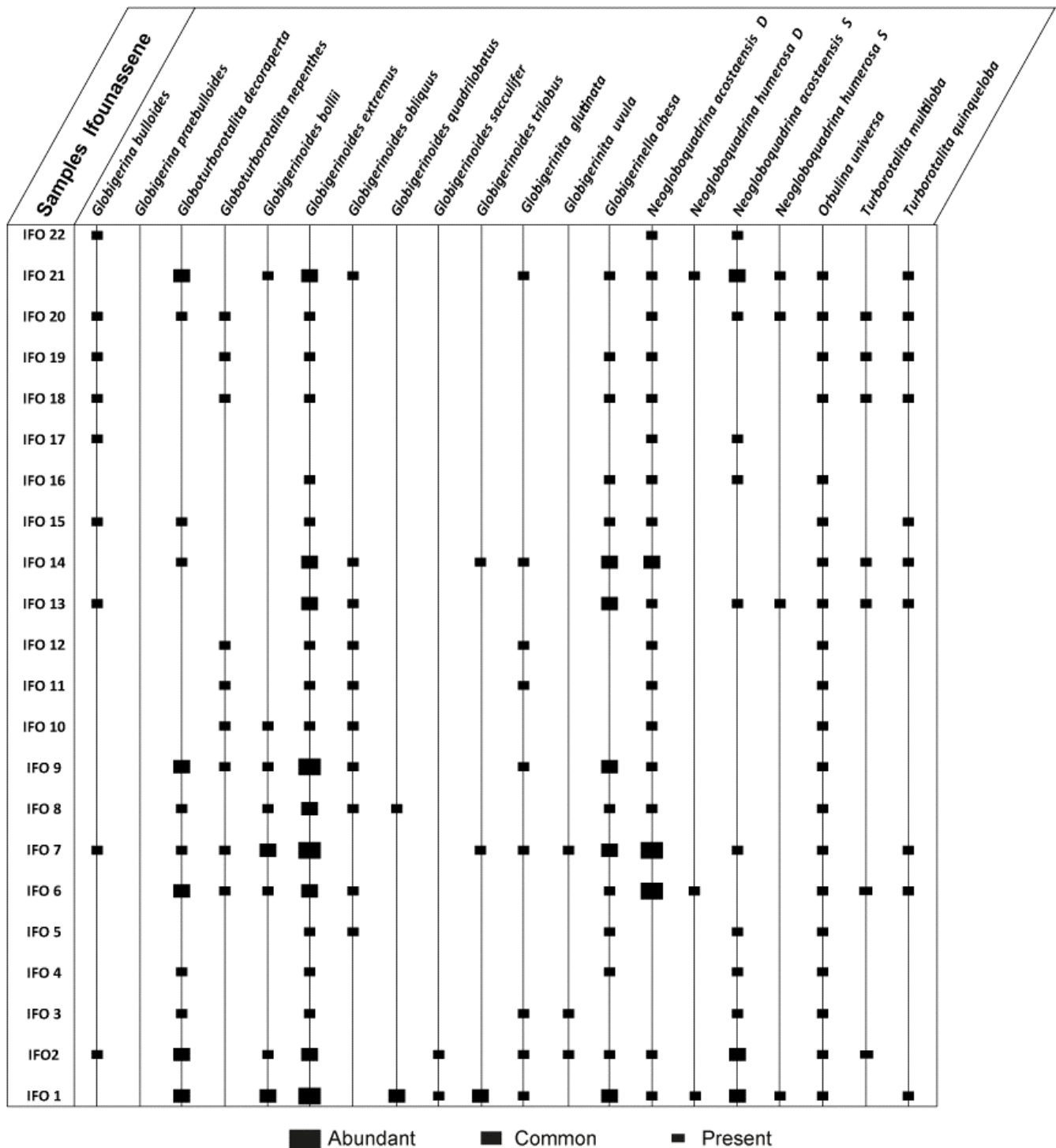
Figure 3: Planktonic/Benthic ratio and Diversity Index of the studied sections.

Biostratigraphic analysis and dating: The stratigraphic distribution and quantitative analysis of planktonic foraminifera species, especially markers (*Globorotalia nicolae*, *Globor. miotumida* group, *Turborotalita multiloba*, and *Neogloboquadrina acostaensis*), along the series allows us to highlight the succession of the following events:

- Event 1: It corresponds to the first presence of *Globorotalia nicolae* (FO *Globorotalia nicolae*). It was observed at the bottom of the section, precisely in the sample MES 3. Its astronomical age is 6.83 Ma (SIERRO *et al.*, 2001; BLANC-VALLERON *et al.*, 2002; LOURENS *et al.*, 2004; LIRER *et al.*, 2019);
- Event 2: The disappearance of *Globorotalia nicolae* (LO *Globorotalia nicolae*) is identified in sample MES 8. This event, dated at 6.712 Ma, has been documented by SIERRO *et al.* (2001), BLANC-VALLERON *et al.* (2002), LOURENS *et al.* (2004), and LIRER *et al.* (2019);
- Event 3: The *Globorotalia miotumida* group is present and sometimes abundant from the base of the section. The event 3 is defined by its last occurrence (LO *Globorotalia miotumida* gr.), located in sample MES 18. The astronomical age of LO *Globorotalia miotumida* gr. is 6.52 Ma (SIERRO *et al.*, 2001; LOURENS *et al.*, 2004);

- Event 4: The first presence of *Turborotalita multiloba* (FCO *T. multiloba*) is observed in the MES 24 sample. SIERRO *et al.* (2001), LOURENS *et al.* (2004), and LIRER *et al.* (2019) have reported this event, with an astronomical age of 6.42 Ma;
- Event 5: It is characterized by the sinister to dextral coiling change of *Neogloboquadrina acostaensis* (S/D *N. acostaensis*). It was identified in sample MES 28. This event, astronomically dated at 6.358 Ma, has been observed in many pre-evaporitic Messinian sedimentary series in the Mediterranean (KRIJGSMAN *et al.*, 1999a, 1999b; HILGEN & KRIJGSMAN, 1999; SIERRO *et al.*, 2001; LOURENS *et al.*, 2004; DRINIA *et al.*, 2007; HÜSING *et al.*, 2009; CORBÍ & SORIA, 2016; LIRER *et al.*, 2019);
- Event 6: The last identified is marked by the first significant reappearance of the sinisterly coiled *Neogloboquadrina acostaensis* ("sinistral *Neogloboquadrina acostaensis* influx"). This event was located in sample MES 34, and its astronomical age is 6.12 Ma (SIERRO *et al.*, 2001; LOURENS *et al.*, 2004).



**Table 3:** Distribution of planktonic foraminifera in the Ifounassene section.

From the succession of these biostratigraphic bioevents, we could date this section to the pre-evaporitic Messinian with an estimated age of 7.08 to 6.08 Ma. The age of 6.08 Ma corresponds to the base of the *Halimeda* Limestone (ASSEN *et al.*, 2006). This biostratigraphic analysis identified new biostratigraphic events and confirmed the results of previous work (MÜNCH *et al.*, 2001; ASSEN *et al.*, 2006).

4-3. IFOUNASSENE SECTION

Microfaunal analysis from the Ifounassene section reveals an average to low abundance and diversity of planktonic foraminifera. Nineteen species and eight genera were identified. The washed residues are composed of planktonic and benthic foraminifera, some ostracods, mollusc fragments, sponge spicules, and urchin radioles. Towards the top of the section the microfauna becomes rare to absent (from IFO 22 to IFO 25). The vertical distribution of foraminiferal species is illustrated in



Table 4: Distribution of planktonic foraminifera in the Izarorène section.

Samples Izarorène	<i>Globobulimina bulimoides</i>	<i>Globobulimina yolkensis</i>	<i>Globobulimina prebulimoides</i>	<i>Globobulimina apertura</i>	<i>Globobulimina discolorata</i>	<i>Globobulimina superba</i>	<i>Globobulimina buli</i>	<i>Globobulimina bulimoides</i>	<i>Globobulimina extrusum</i>	<i>Globobulimina obliquum</i>	<i>Globobulimina quadrilobum</i>	<i>Globobulimina vuculifer</i>	<i>Globobulimina vuculus</i>	<i>Globobulimina glabella</i>	<i>Globobulimina vucula</i>	<i>Globobulimina dactyl</i>	<i>Globobulimina constricta</i>	<i>Globobulimina multilobata</i>	<i>Globobulimina nichol</i>	<i>Globobulimina rotula D</i>	<i>Globobulimina rotula S</i>	<i>Neoglobobulimina sphaerulata</i>	<i>Neoglobobulimina acuminata D</i>	<i>Neoglobobulimina acuminata S</i>	<i>Olivulina unguis</i>	<i>Sphaerobulimina unguis</i>	<i>Turbostrimina unguis</i>
IZA 42	■																										
IZA 41	■																										
IZA 40	■	■																									
IZA 39	■	■																									
IZA 38	■	■																									
IZA 37	■	■																									
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■ Abundant ■ Common ■ Present

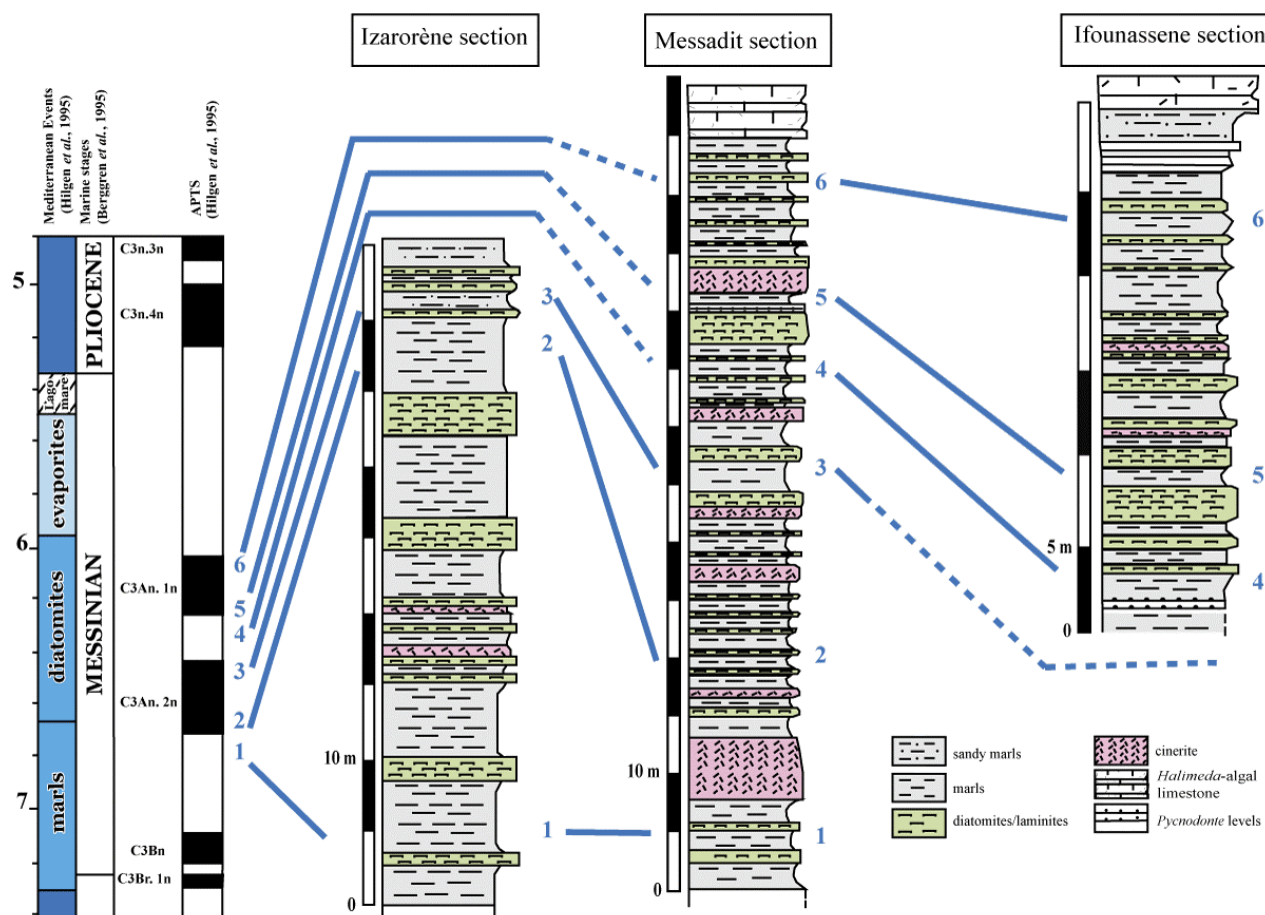


Figure 4: Correlations of the studied sections.

Table 3. Planktonic foraminifera assemblages in the Ifounassene section are characterized by average to low diversity, with a SHANNON Diversity Index of approximately 1.6 (Fig. 3). Some samples showed a high diversity in the order of 2.3. The Planktonic/Benthic ratio oscillates between 10 and 60%. The planktonic foraminifera association is mainly composed of globular forms such as *Globigerinoides*, *Neogloboquadrina*, and *Turborotalita*.

Biostratigraphic analysis and dating: Based on the vertical evolution of the marker species and the qualitative and quantitative analyses, the first presence of *Turborotalita multiloba* was observed from IFO 2, always associated with *Turborotalita quinqueloba*. Therefore, the FCO *T. multiloba* event is recorded at the IFO 2 sample. Furthermore, the vertical evolution of the percentage of *Neogloboquadrina acostaensis* sinistral and dextral forms of the studied samples expresses that the biostratigraphic event "coiling change of *Neogloboquadrina acostaensis* sin/dex (S/D *N. acostaensis*)" is located in sample IFO 6. The first significant reappearance of the sinistral coiling of *Neogloboquadrina acostaensis* (sinistral influx *Neogloboquadrina acostaensis*) was observed in sample IFO 21. From these biostratigraphic results, the Ifounassene section is dated to the pre-evaporitic Messinian with an estimated age of 6.52 to 6.08 Ma. This dating confirms the results of ASSEN *et al.* (2006).

4-4. IZARORÈNE SECTION

The detailed analysis of the planktonic foraminiferal assemblages in the Izarorène section reveals significant richness in both species and individuals. A total of 30 species from 10 genera were identified. The microfauna consists of planktonic and benthic foraminifera, along with some ostracods, fragments of bivalves, and urchin radioles. Planktonic foraminiferal assemblages in the Izarorène section are characterized by moderate to high diversity, with SHANNON Diversity Index varying between 1.4 and 2.4. The Planktonic/Benthic ratio is generally high, varying between 70 and 90% (Fig. 3). *Globigerina bulloides*, often associated with *Globig. falconensis*, is well represented in most samples, with significant abundances in some levels. However, periods of high abundance of *Globig. bulloides* alternate with periods where this species is poorly documented. This information will be utilized in the discussion. The vertical distribution of foraminiferal species is illustrated in Table 4.

Biostratigraphic analysis and dating: The stratigraphic distribution and quantitative analyses of planktonic foraminiferal species, particularly the markers, reveals the presence of *Globorotalia nicolae*, the *Globor. miotumida* group, and *Neogloboquadrina acostaensis*. The examination highlights the succession of three significant bio-

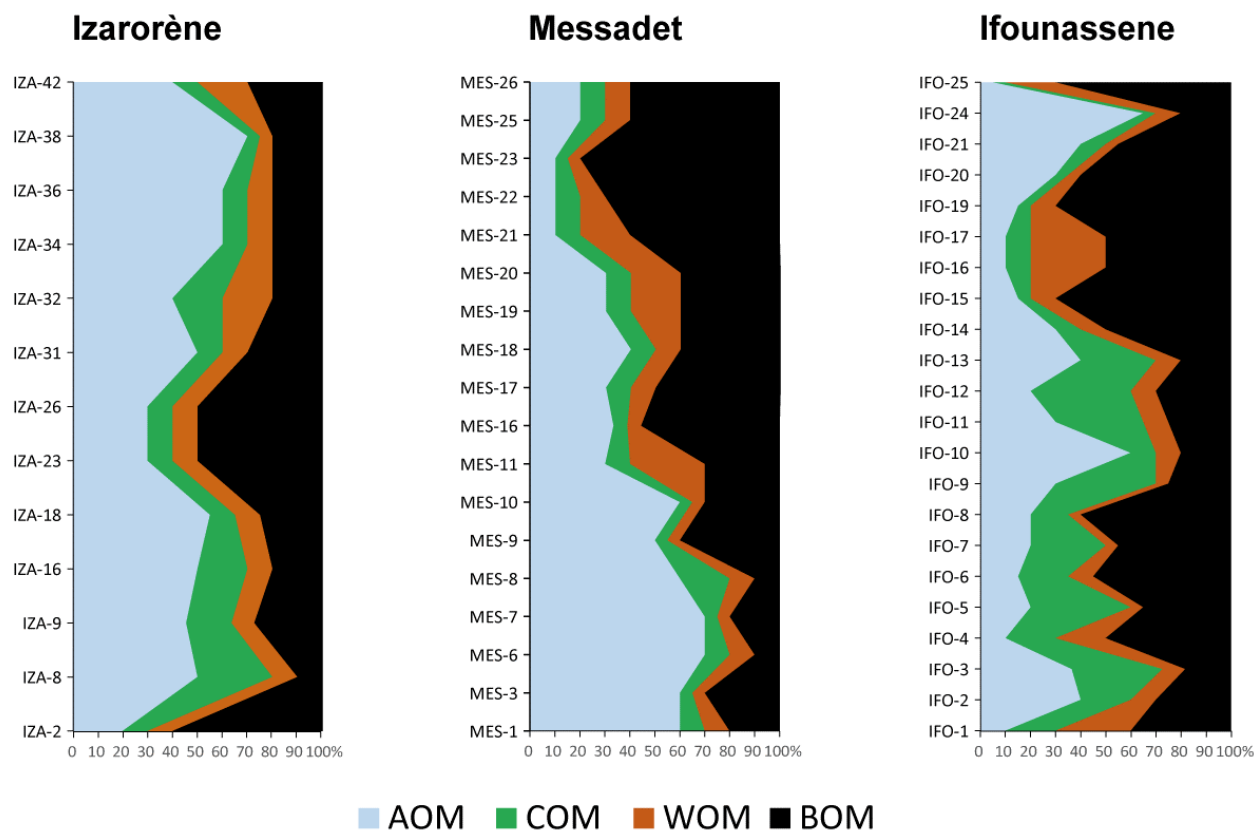


Figure 5: Palynofacies of the studied sections.

stratigraphic events. In the lower part of the Izarorène section, the first occurrence (FO) of *Globorotalia nicolae* was situated in sample IZA 3, whereas its last common occurrence (LO *Globor. nicolae*) is above the last massive diatomite (sample IZA 38). *Globor. miotumida* group is present from the base of the section, with its last occurrence (LO *Globor. miotumida* gr.) recorded in sample IZA 40. The succession of these bioevents allows us to attribute the Izarorène section to the pre-evaporitic Messinian with an estimated age of 7.24 to 6.35 Ma. These biostratigraphic findings refine and enhance previous dating efforts (BARHOUN *et al.*, 1999; ASSEN *et al.*, 2006).

4-5. BIOSTRATIGRAPHIC CORRELATIONS

The correlation of the studied sections shows minor variations in thickness and the progressive installation of the degradation in environmental conditions, as evidenced by the decrease in the abundance and diversity of planktonic species and sometimes the microfauna is rare to absent. These unfavorable conditions for the proliferation of planktonic microfauna are related to the Messinian salinity crisis (Fig. 4). Within the interval 6.83-6.52 Ma, the thickness is 36 m in the Izarorène section and about 30 m in Messadit. The environmental conditions indicate a relatively open marine environment probably subjected to the action of upwellings as shown by the P/P+B ratio and the diversity index as well as the abundance

of *Globigerina bulloides* and *Globigerina falconensis*. Indeed, *Globigerina bulloides* is a species that proliferates in cold, rich nutrient waters and is often used as an indicator of upwellings (THIEDE, 1983; PRELL, 1984). Conversely, from 6.52 Ma to 6.12 Ma, the thickness is around 20 m in the Messadit section. The P/P+B ratio is average to low, planktonic foraminifera are low in abundance and diversity, particularly after 6.35 Ma, indicating a shallower marine environment (GIBSON, 1989). From 6.12 Ma the planktonic microfauna is rare to absent because of deteriorating marine conditions caused by reduced water inflow from the Atlantic Ocean to the Mediterranean Sea resulting in widespread salt precipitation and a decrease in Mediterranean Sea-level due to evaporation. Furthermore, the end of the diatom bloom was reported around 6.11 Ma by ASSEN *et al.* (2006), followed by the installation of the algal level of *Halimeda*. These events indicate the closure of the open marine environment in the Melilla-Nador basin and the degradation of environmental conditions in relation to the Messinian salinity crisis.

5. Palynological results

On all the samples processed, 13 from the Ifounassene section contained sufficient pollen, spores, and dinocysts for analysis. The samples from the Izarorène and Messadet sections, however, exhibited a low abundance of palynomorphs and were studied in terms of palynofacies.

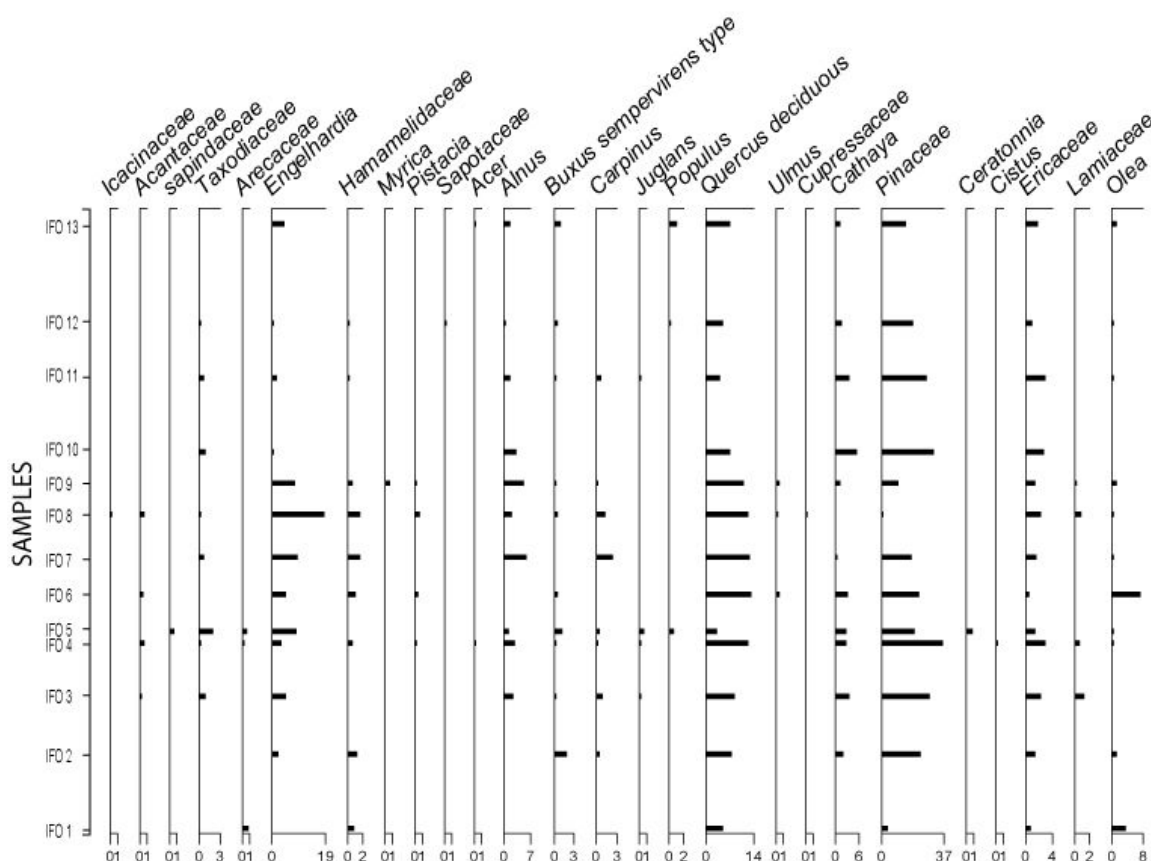


Figure 6: Detailed pollen diagram of the Ifounassene section.

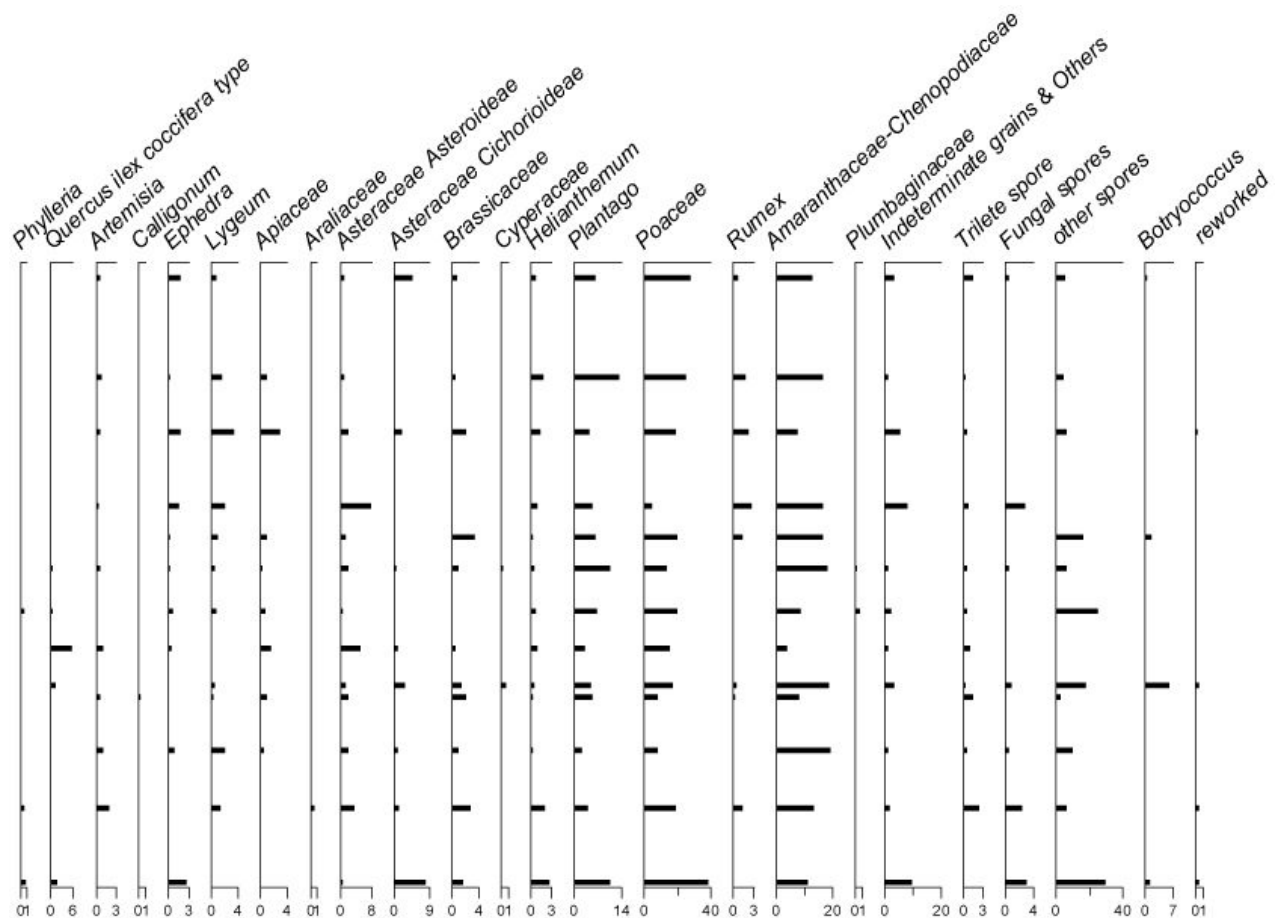
5-1. IZARORÈNE AND MESSADIT SECTIONS

The palynofacies study of 13 levels from the Izarorène section reveals a richness in AOM, reaching up to 70%, except for levels IZA 2, 23, and 26, where the BOM exceeds 45% (Fig. 5). Samples from the Messadit section were found to be poor in palynomorphs. The palynofacies study indicates abundant AOM in the lower part of the section, reaching 70%, gradually decreasing towards the upper part, reaching 10% (Fig. 5). Conversely, BOM follows the opposite trend. In the Messadit section, starting from MES 9, there is an alternation between the abundance of continental (BOM, WOM, and COM) and marine (AOM) inputs. The content of woody debris (WOM) and cellular organic matter is low, varying between 5 and 20%.

5-2. IFOUNASSENE SECTION

Pollen grains and spores: Out of 23 samples collected, only 13 yielded palynomorphs. The pollen flora comprises 45 taxa (Figs. 6-7). The floristic image reflected by the pollen spectra is predominantly homogeneous (Figs. 6-7). The synthetic diagram indicates richness in herbaceous plants, *Pinus*, mesotherms, and mega-mesotherms with sporadic presence of megatherms (Fig. 7). *Pinus* constitutes 37% of the total, exhibiting a

decrease in the IFO 1 and IFO 8 samples (Fig. 7). *Cathaya* pollen is consistently present (0 to 6%) whereas *Cupressaceae* pollen is rare. High-altitude conifer pollen (*Picea*, *Tsuga*, *Abies*) was not detected. Megatherm elements, including *Acanthaceae*, *Icacinaceae*, and *Sapindaceae*, are sporadic, not exceeding 1%. In contrast, *Engelhardia* dominates (0 to 19%) over the other mega-mesothermal elements (e.g., *Taxodium*, *Araliaceae*, *Hamamelidaceae*, *Myrica*, *Arecaceae*, *Sapotaceae*), which are represented by a lower percentage. Mesothermal elements are characterized by the prevalence of *Quercus* (3 to 13%), alongside the presence of *Ericaceae*, *Alnus*, *Buxus*, *Populus*, *Carya*, *Ulmus*, *Acer*, and *Juglans*. Mediterranean xerophytes, including *Pistacia*, *Cistus*, *Phillyrea*, and *Ceratonia*, are present with prevailing pollen grains of *Quercus coccifera* and *Olea*. Poaceae (5 to 40%) and Amaranthaceae-Chenopodiaceae (4 to 19.5%) dominate the pollen spectra. Other herbs (*Asteraceae* Asteroideae, *Asteraceae* Cichoroideae, *Apiaceae*, *Lamiaceae*, *Rumex*, *Brassicaceae*, *Helianthemum*, and *Cyperaceae*) are represented with low frequencies, except for the *Plantago* genus, reaching 13%. *Lygeum*, *Calligonum*, *Artemisia*, and *Ephedra* are found in almost all samples without exceeding 4%.



Pteridophyte spores vary between 0 and 30%. *Botryococcus* is present discontinuously.

Dinocysts: The D/S curve shows consistently low values, indicative of a continental influence, except in samples IFO 2, IFO 6, and IFO 11, where the ratio exceeds 0.5, suggesting a marine influence (Fig. 9). The G/P curve shows ratios ranging between 0.92 and 1.00 in all samples (Fig. 9). The prevalence of Gonyaulocaceae indicates an open marine environment. Dinocyst assemblages consist mainly of neritic taxa, including *Spiniferites* (13-52%), *Pixydinopsis psilata* (6-56%), *Operculodinium israelianum* (0-3.22%), *Selenopemphix nephroides* (0-6%), *Lingulodinium machaerophorum* (1-49%), and *Polysphaeridium zoharyi* (0-8.6%) (Fig. 8). Oceanic taxa are sparsely represented. These neritic dinocyst associations have been documented during the Early Messinian in Morocco at the Rifian corridor, reflecting a neritic environment (WARNY, 1999; WARNY et al., 2003, BACHIRI TAOUFIQ, 2000; TARGHI et al., 2021, 2023). These dinocyst associations collectively suggest the existence of a neritic marine environment.

Distality index: The abundance of continental inputs indicates that the depositional environment of the Ifounassene section was epicontinental. The D/S curve consistently shows low values, reflecting a continental influence, except in samples IFO 2, IFO 6, and IFO 11, where the ratio exceeds

0.5, suggesting a marine influence (Fig. 9). The IN/ON distality index (Fig. 9) varies between 0.1 and 0.8; indicating an external platform environment, except in levels 3, 7, 4.5, 8, and 12, where the ratio increases, suggesting a shift towards a proximal neritic environment. This trend aligns well with the Planktonic/Benthic ratio (Fig. 3).

Temperature index: The temperature index varies between 0.8 and 1 (Fig. 9), indicating a predominance of warm water taxa and warm thermal conditions at the water surface. In samples 2, 11, and particularly 6, a slight decrease in the W/C ratio is observed due to the appearance of cold taxa such as *Operculodinium centrocarpum* and *Nematospheropsis labyrinthea*.

Ifounassene Palynofacies: The palynofacies of Ifounassene section exhibits a recurring shift between the prevalence of amorphous organic matter and the abundance of black organic matter (BOM) and cellular debris (COM) (Fig. 5). The richness of this organic matter indicates a strong continental influence, supporting the dinocyst data suggesting a continental-influenced neritic environment. Presumably, when conditions become less turbulent, they favor the development of AOM.



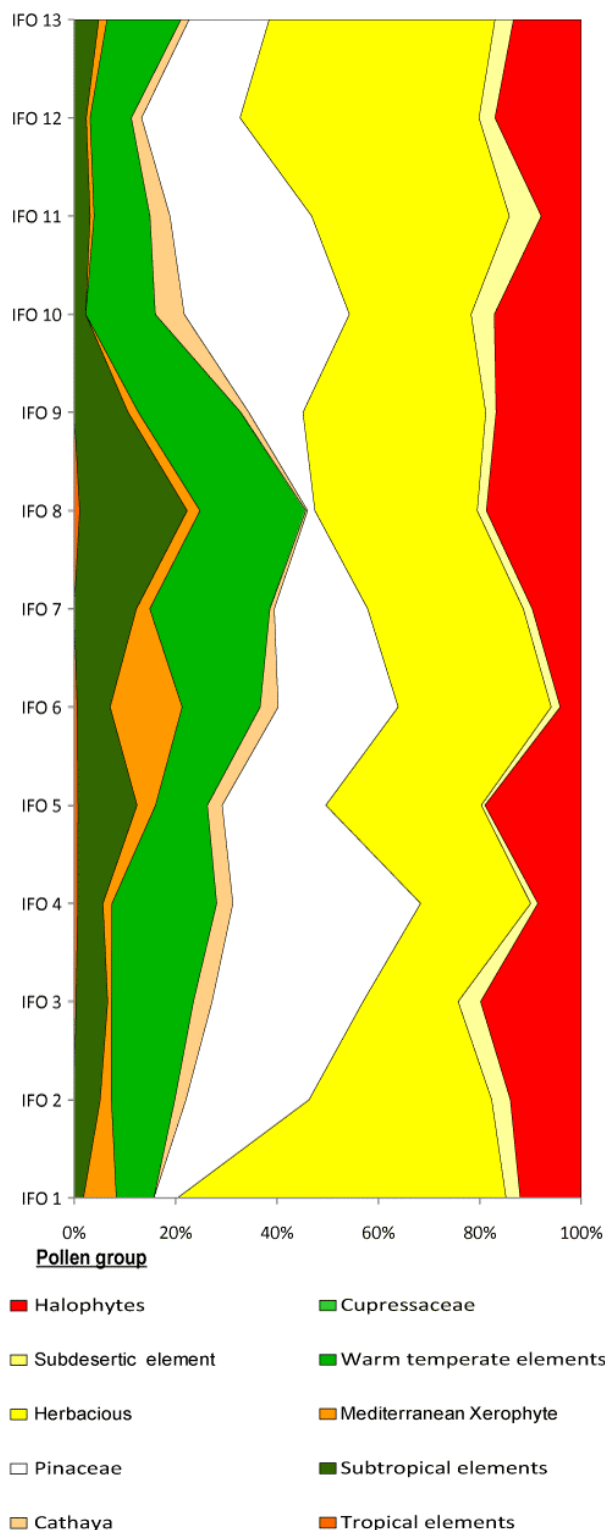


Figure 7: Synthetic diagram of the Ifounassene section.

6. Discussion

6-1. MARINE ENVIRONMENT

The evolution of the marine environment in the Melilla-Nador basin during the pre-evaporitic Messinian is proposed in three stages based on the qualitative and quantitative analyses of planktonic foraminifera, spores, pollen grains, dinocysts, and palynofacies.

Stage 1, from 6.83 to 6.52 Ma: This interval is characterized by three biostratigraphic events: First Occurrence (FO) of *Globorotalia nicolae*, Last Occurrence (LO) of *Globor. nicolae*, and Last Occurrence (LO) of *Globor. miotumida* group. It spans from the onset of cyclic marine sedimentation in the Melilla-Nador basin to the initial changes in diatom associations (ASSEN *et al.*, 2006). The P/P+B ratio is often high, and the diversity is normal, occasionally marked by an abundance of *Globigerina bulloides* and *Globig. falconensis*, indicating a relatively open marine environment likely affected by upwellings. Benthic foraminifera also register episodes of upwellings, characterized by the prevalence of bolivinids and buliminids (RACHID *et al.*, 1997). During this interval (6.83-6.52 Ma), sediment thickness varies between 30 and 36 m. The environmental conditions suggest a relatively open marine setting, as evidenced by the consistently high P/P+B ratio. The presence of *Globigerina bulloides* and *Globig. falconensis* implies the impact of upwelling, with *Globog. bulloides* often considered an indicator of cold, nutrient-rich waters and used as an upwelling indicator (THIEDE, 1983; PRELL, 1984). The examination of diatom assemblages and benthic foraminifera provides additional insights into the dynamics of Messinian upwellings in this basin (RACHID *et al.*, 1997; SAINT-MARTIN *et al.*, 2003). The palynofacies is characterized by an overall abundance of amorphous organic matter, indicating a distal and calm environment. However, exceptions are noted in levels IZA 2, IZA 23, and IZA 26, where continental inputs (MOX, MOV, and MOB) dominate, reflecting an agitated and proximal environment at these levels. Additionally, the lower part of the Messadit section exhibits calm and distal conditions conducive to the development of amorphous organic matter. These findings align with the diatom data, which feature oceanic and oceanic-neritic species, along with silicoflagellates, confirming the existence of a distinct marine environment connected to the oceanic domain (SAINT-MARTIN *et al.*, 2003). Similar wet and warm conditions with oceanic environments and an external neritic trend have been observed in Salé (NW Morocco) between 7.3 and 6.5 Ma (WARNY *et al.*, 2003), the Guadalquivir Basin in Spain between 6.8 and 6.5 Ma (JIMÉNEZ-MORENO *et al.*, 2013), and in the central Mediterranean between 7.6 and 6.5 Ma (BERTINI & MENICETTI, 2015).

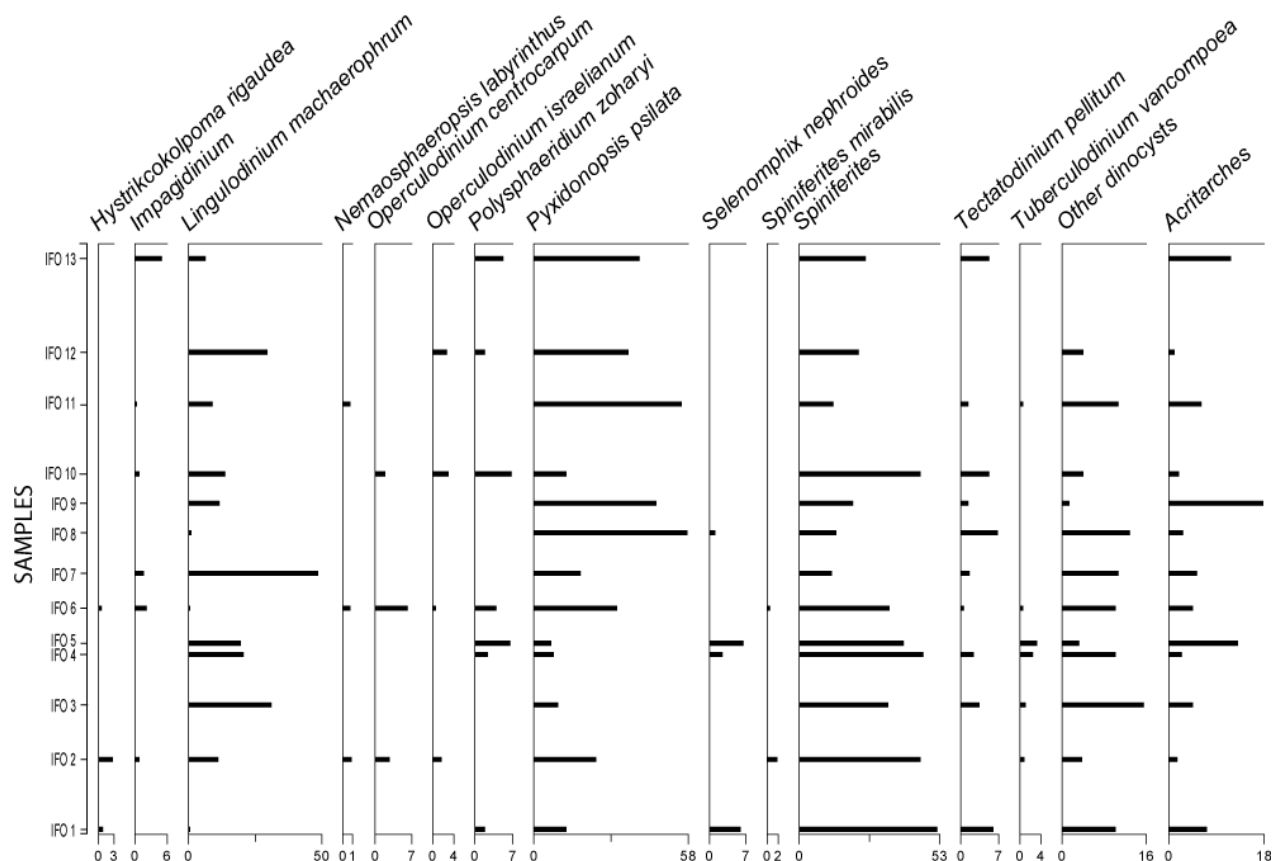


Figure 8: Detailed dinocyst diagram of the Ifounassene section.

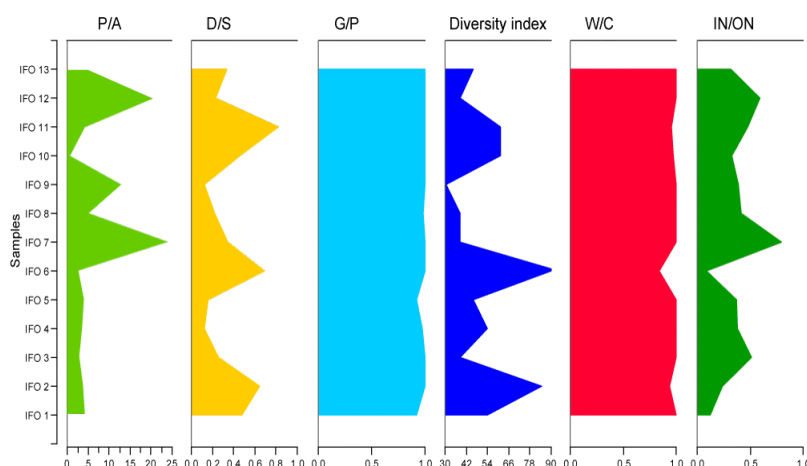
Stage 2, from 6.52 to 6.35 Ma: This stage is characterized by the succession of two biostratigraphic events observed in the Messadit and Ifounassene sections: First Common Occurrence (FCO) of *Turborotalia multiloba* and the coiling change *S/D Neogloboquadrina acostaensis*. From 6.52 Ma onwards, the P/P+B ratio becomes average to low, and planktonic foraminifera are less abundant and diversified, suggesting a shallower environment. Continental inputs, including pollen grains, spores, and plant debris dominate, prevail. They indicate a marine environment very close to the continent with significant fluvial inputs. Dinocyst associations in Ifounassene (IFO 1 to IFO 6 samples) suggest a neritic environment with warm surface waters. Distality indices (D/S, ID, Pinaceae) reveal an alternation between proximal and distal neritic environments. Comparisons with sections in Salé, Briqueterie site (NW Morocco, WARNY *et al.*, 2003), and the Guadalquivir basin (Spain, JIMÉNEZ-MORENO *et al.*, 2013) indicate that the percentage of pine trees in Ifounassene (not exceeding 35%) is very low. This implies that, from 6.52 Ma, the bathymetry in the Messinian marl-diatomite series gradually decreases due to the reduction of Atlantic water inflow and the uplift of the basin.

Stage 3, from 6.35 Ma to 6.12 Ma: From 6.35 Ma, planktonic foraminifera are poorly represented compared to benthic foraminifera. Regarding palynofacies, from IFO 6 to IFO 25, continental inputs continue to dominate compared to Mes-

sadit section. Distality indices (D/S, ID, pins) consistently show an alternation between proximal and distal neritic environments. Despite the closure of the two Rifian Corridors, *i.e.*, the South Rifian Corridor at 7.1-6.9 Ma and the North Rifian Corridor from 7.35 to 7.00 Ma (CAPPELLA *et al.*, 2018, 2019), the basin remains open to the Atlantic and likely receives input through the Strait of Gibraltar (CAPPELLA *et al.*, 2018; KRIJGSMAN *et al.*, 2018). From 6.12 Ma, planktonic microfauna becomes rare to absent due to deteriorating marine conditions. Additionally, ASSEN *et al.* (2006) reported the end of the diatom bloom around 6.11 Ma, followed by the establishment of the *Halimeda* algal level, indicating the closure of the open marine environment in the Melilla-Nador basin and the deterioration of environmental conditions associated with the Messinian salinity crisis.

6-2. Continental environment

Vegetal landscapes: The pollen study of the pre-evaporitic Messinian deposits of the Ifounassene section reveals the presence of plant elements living today in the American and Asian regions (*Cathaya*, *Engelhardia*, Sapotaceae, Arecaceae, and Hamamelidaceae), alongside elements currently living in Europe (*Quercus*, Ericaceae, *Alnus*, *Buxus*, *Populus*, *Carya*, *Ulmus*, *Acer*, and *Juglans*) or the Mediterranean regions (*Olea*, *Quercus* type *ilex-coccifera*, *Cistus*, *Pistacia*, *Phillyrea*, and *Ceratonia*). These same plant taxa have also been recorded in the Moroccan



◀ **Figure 9:** Curves of P/A, D/S, G/P ratios and diversity, W/C (temperature), IN/ON (distality) index of the Ifounassene section.

Messinian at the Rifain corridor (BACHIRI TAOUFIQ, 2000; BACHIRI TAOUFIQ *et al.*, 2008; SUC *et al.*, 2018; TARGHI *et al.*, 2021) and Boudinar basin (ACHALHI *et al.*, 2016). Sub-desert taxa were also identified (*Lygeum*, *Calligonum*, *Artemisia*, and *Ephedra*). Taxa representing open plant formations (Poaceae, Amaranthaceae-Chenopodiaceae, *Plantago*, etc.) constitute a significant percentage. The mangrove element *Avicennia*, encountered in the northwestern Mediterranean from the Early to the Middle Miocene (BESSEDIK, 1984, 1985; BESSEDIK *et al.*, 1984), and in the south and western Mediterranean (Spain, Sicily, Algeria, and Morocco) until the Messinian (SUC & BESSAIS, 1990; CHIKHI, 1992a, 1992b; BACHIRI TAOUFIQ *et al.*, 2001a, 2001b; JIMÉNEZ-MORENO *et al.*, 2013; TARGHI *et al.*, 2021, 2023), has not been recorded in this pre-evaporitic Messinian section. The presence of a mixture of taxa with different thermal and hydric requirements can be explained by a certain staging of the vegetation (BESSEDIK, 1985; SUC, 1986, 1989) and, consequently, a depositional environment relatively near the littoral and the mountain massifs. Detailed analysis of the diagrams (Figs. 6-7) reveals two types of formations that succeeded each other behind the coral formations.

Open littoral lowland formation: The littoral associations comprised xerophilous and/or halophilous herbaceous plants, including Poaceae, Amaranthaceae-Chenopodiaceae *Plantago*, and Asteraceae (Cichorioideae and Asteroideae). The prevalence of these pollen grains indicates the presence of a vast littoral plain. The occurrence of sub-desert plants such as *Lygeum*, *Calligonum*, *Artemisia*, and *Ephedra* confirms the arid nature of the environment. Trees and shrubs such as Arecaceae and Sapotaceae could also coexist in more humid areas. This open vegetation likely transitioned to a formation with Mediterranean elements, including *Olea*, *Quercus* type *ilex-coccifera*, *Cistus*, *Pistacia*, *Phillyrea*, and *Ceratonia*.

Arboreal formation: In areas relatively distant from the littoral, above the Mediterranean grouping and on the first reliefs, more forested associations of *Pinus*, *Quercus*, Ericaceae, *Alnus*, *Buxus*, *Populus*, *Carya*, *Ulmus*, *Acer*, *Juglans*, and

evergreen elements (Sapotaceae, Arecaceae, *Ilex*) were likely present (BACHIRI TAOUFIQ, 2000; SUC *et al.*, 2018; TARGHI *et al.*, 2021). At higher elevations, towards the hinterland, this mixed mesophilic forest probably transitioned to a vegetation dominated by thermophilic elements like *Taxodium*, *Cathaya*, *Engelhardia*, Hamamelidaceae, *Quercus*, and Cupressaceae. The absence of high-altitude trees (*Cedrus*, *Abies*, and *Picea*) suggests a relatively low relief.

Climate: The pollen flora identified in Ifounassene section indicates a hot and dry climate, characterized by the presence of thermophilic elements such as *Taxodium*, *Cathaya*, *Engelhardia*, Hamamelidaceae, *Quercus*, and Cupressaceae, along with the abundance of taxa of dry environments such as herbaceous sub-desert elements (*Artemisia*, *Ephedra*, *Lygeum*, and *Calligonum*). Similar climatic conditions were observed in the southwestern Mediterranean in Morocco and Algeria during the Messinian (CHIKHI, 1992a, 1992b; WARNY, 1999; WARNY *et al.*, 2003; BACHIRI TAOUFIQ *et al.*, 2001a, 2001b, 2008; ACHALHI *et al.*, 2016; SUC *et al.*, 2018; TARGHI *et al.*, 2021). In the Ifounassene section, the absence of microthermals and the presence of megathermals, megamesothermals, and mesothermals are notable. This observation leads us to estimate an average temperature ranging from 20 to 24°C, consistent with the presence of guide taxa such as *Lygeum* (FAUQUETTE *et al.*, 1999). At the middle altitude where *Engelhardtia* lived (FAUQUETTE *et al.*, 1999), temperatures consistently remained high (18-21°C), and precipitation levels were higher (600-700 mm per year). These climatic conditions bear similarity to those encountered in the Early Messinian in Algeria (CHIKHI, 1992a, 1992b); Morocco (WARNY, 1999; BACHIRI TAOUFIQ, 2000), Sicily (SUC & BESSAIS, 1990; BERTINI *et al.*, 1998), and Spain (JIMÉNEZ-MORENO *et al.*, 2013). These estimates align with results from transfer function results applied to the Upper Miocene (FAUQUETTE *et al.*, 2007; SUC *et al.*, 2018) and the Lower Pliocene (FAUQUETTE *et al.*, 1999), indicating a mean annual temperature of approximately 23°C and annual precipitation around 450 mm. Precipitation values were estimated the ratio P/A was used. In the Ifounassene



section, the Poaceae/ Asteraceae ratio is generally less than 20, except in levels IFO 7 and IFO 12 samples, where it is greater than or equal to 20 (Fig. 9). In the former case, rainfall is estimated to be less than 500 mm while, in both levels, it exceeds 500 mm/year. A comparison of the Ifou-nassene section ratio with those of the lower Messinian in the southern Rifian corridor (BACHIRI, 2000; BACHIRI *et al.*, 2008; TARGHI *et al.*, 2021, 2023) indicates that climatic conditions in the Melilla-Nador basin were comparatively less dry. Moreover, in the Melilla-Nador basin located in the north, tropical elements such as *Avicennia* (found in the Tortonian and Lower Messinian along the southern Rifian corridor) are rare, and subtropical elements are less diverse. This implies a slight decrease in temperature and an increase in humidity from the south to the north of Morocco. These findings align with quantifications confirming the existence of an increasing latitudinal gradient of temperature and dryness from north to south, similar to the current gradient (JIMÉNEZ-MORENO *et al.*, 2013; BERTINI & MENICHETTI, 2015; SUC *et al.*, 2018).

7. Conclusions

The detailed study of planktonic foraminifera, spores, pollen grains, dinocysts, and palynofacies on three marl-diatomite sedimentary series in the Melilla-Nador Basin enhances our understanding of the evolution of marine and continental environments during the pre-evaporitic Messinian in the Western Mediterranean. During the interval 6.83-6.52 Ma, the marine environment in the basin was relatively deep and open, likely influenced by upwellings, rich in planktonic foraminifera, oceanic and oceanic-meridian diatoms, and MOA. Periodically, continental inputs occurred, suggesting a shift towards a proximal environment. Warm surface water conditions are indicated by the presence of coral reefs.

Starting from 6.52 Ma, the significance and diversity of planktonic foraminifera decreased, boreal diatoms transitioned to tropical diatoms, and carbonate platform reefs prograded. Alternating with amorphous organic matter, continental inputs gradually dominated, indicating a marine environment close to the continent with significant fluvial inputs. Distality indexes suggest alternation between proximal and distal neritic environments. Surface water conditions remained warm and tropical, and the continental environment exhibited an open vegetation landscape dominated by herbaceous plants, reflecting a tropical to subtropical arid climate conducive to erosion.

Post 6.35 Ma, the environment evolved towards the degradation of marine conditions, as evidenced by the rarity of the planktonic microfauna. At 6.08 Ma, the formation of *Halimeda* algal beds commenced, overlying the marl-diatomite cyclic sequence.

In summary, during the pre-evaporitic Messinian, the Melilla-Nador Basin underwent the influence of two main factors contributing to the formation of the marl-diatomite series: 1) tectonic activity causing a decrease in bathymetry and progressive uplift and 2) global parameters including 2a) a warm, arid climate favoring herbaceous plant spread, and 2b) episodic oceanographic phenomena such as upwelling. These findings support and align with previous results reported by PELLIGRINO *et al.* (2018).

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Plates

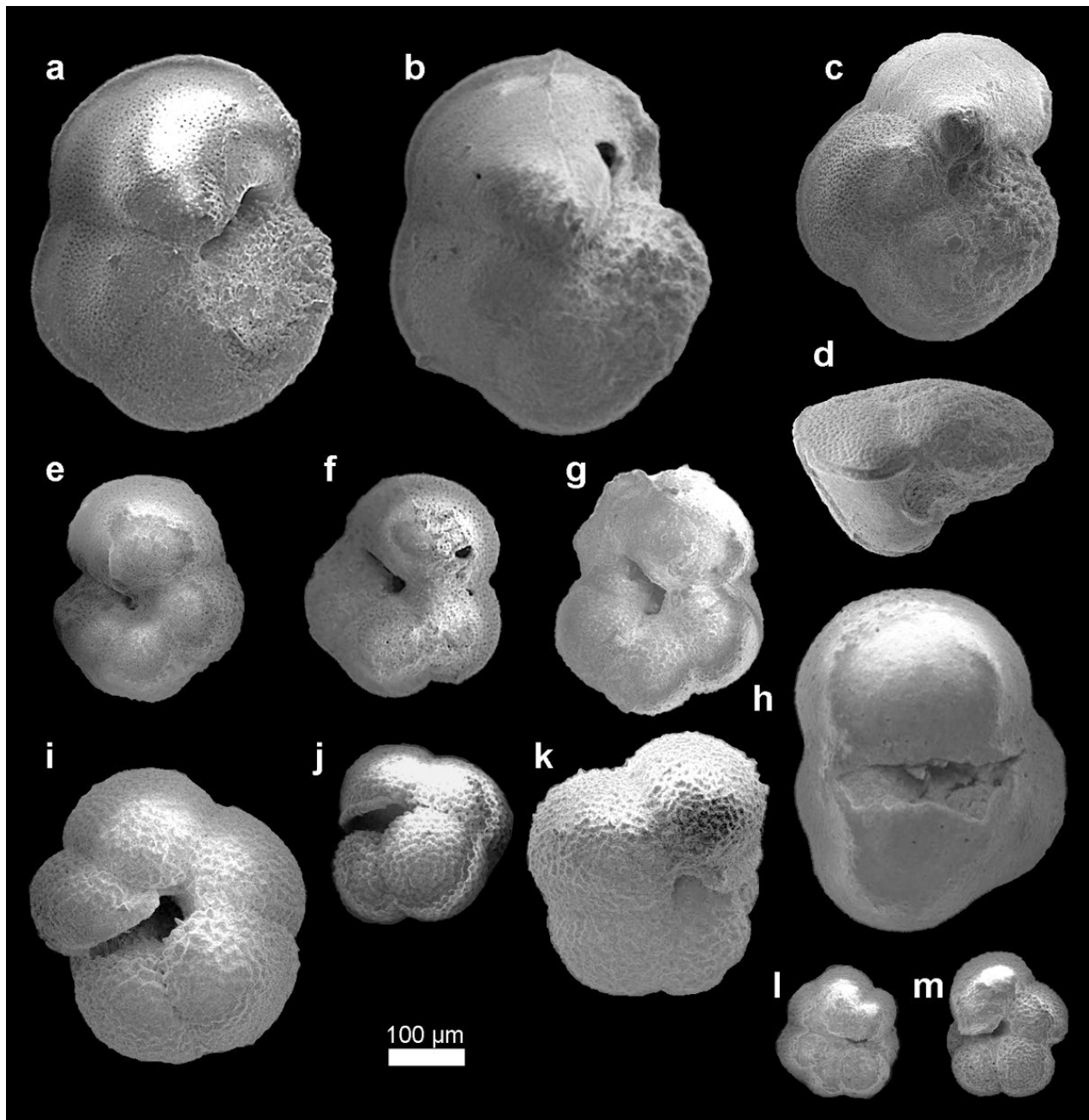


Plate 1: **a-b:** *Globorotalia miotumida* (WALTERS, 1965), SHY-3, Sidi El Haj Youssef section, Boudinar basin; **c-d:** *Globorotalia conomiozea* (KENNETT, 1966), SHY-3, Sidi El Haj Youssef section, Boudinar basin; **e:** *Globorotalia nicolae* CATALANO & SPROVIERI, 1971, IZA 22, Izarorène section, Melilla-Nador basin; **f-g:** *Globorotalia nicolae* CATALANO & SPROVIERI, 1971, IZA 23, Izarorène section, Melilla-Nador basin; **h:** *Sphaeroidinellopsis* sp., IZA 3, Izarorène section, Melilla-Nador basin; **i-j:** *Neogloboquadrina acostaensis* (BLOW, 1959) with dextral coiling, MES 28, Messadit section, Melilla-Nador basin; **k:** *Neogloboquadrina acostaensis* (BLOW, 1959) with sinistral coiling, MES 14, Messadit section, Melilla-Nador basin; **l:** *Turborotalita multiloba* (ROMEO, 1965), IFO 14, Ifounassene section, Melilla-Nador basin; **m:** *Turborotalita quinqualeba* (NATLAND, 1938), SHY-17, Sidi El Haj Youssef section, Boudinar basin. All photomicrographs have the same scale (scale bar = 100 µm).

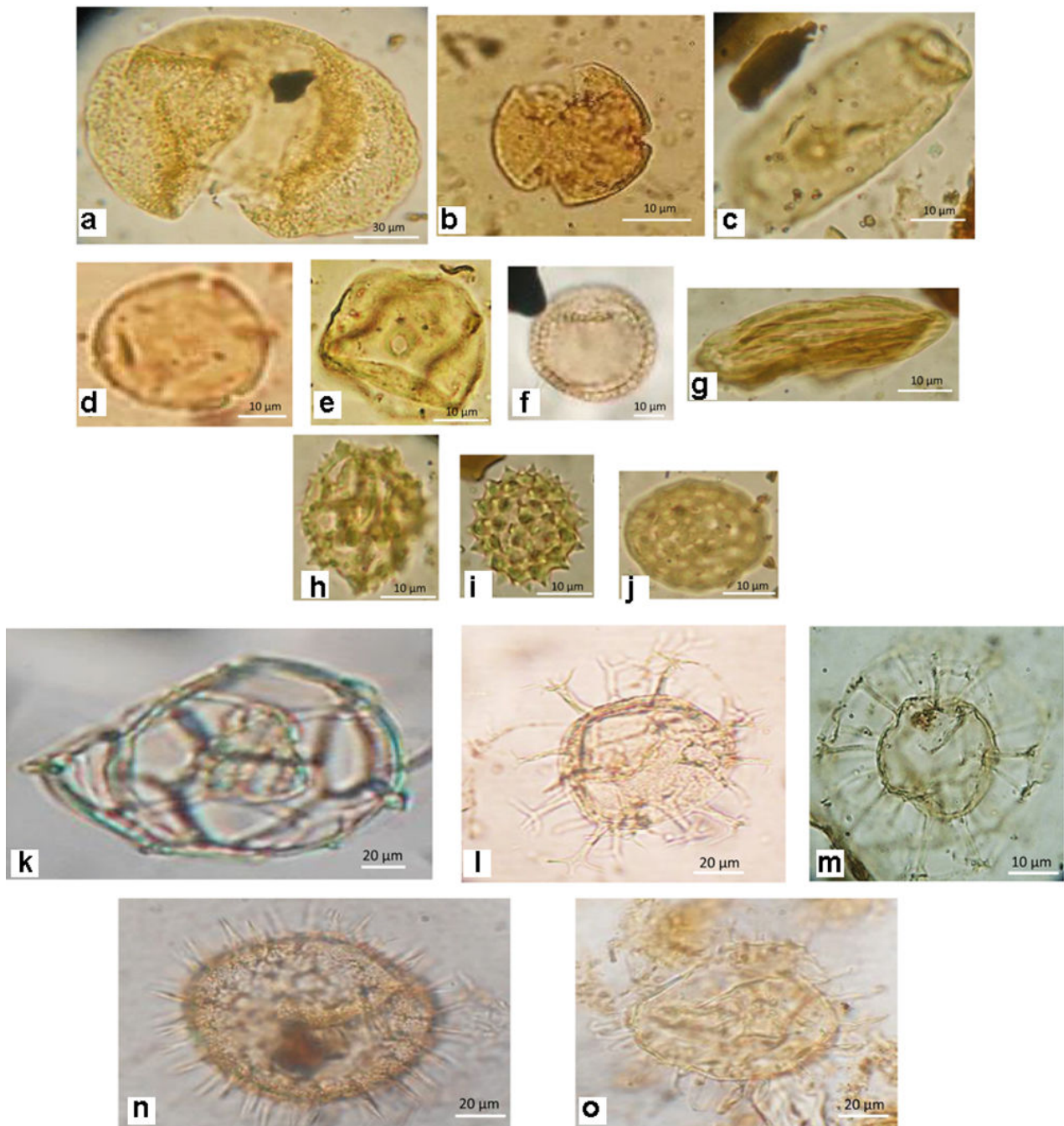


Plate 2: Pollen: **a:** *Cathaya*, IFO 10; **b:** *Lygeum*, IFO 11, subdesertic; **c:** *Quercus*, IFO 6, mesotherm; **d:** *Engelhardtia*, IFO 4, mega-mesotherm; **e:** Poaceae, IFO 1, herb; **f:** *Olea*, IFO 4, Mediterranean xerophyte; **g:** *Ephedra*, IFO 11, subdesertic; **h-i:** Asteraceae, IFO 10, herb; **j:** Amaranthaceae - Chenopodiaceae, IFO 5, halophyte. **Dinocysts:** **k:** *Impagidinium* spp., IFO 13; **l:** *Spiniferites* spp., IFO 4; **m:** *Nematospheropsis labyrinthus* (OSTENFELD, 1903), IFO 2; **n:** *Operculodinium israelianum* (ROSSIGNOL, 1962), IFO 10; **o:** *Lingulodinium machaerophorum* (DEFLANDRE & COOKSON, 1955), IFO 7.