



**Climate and vegetation changes in the southwestern Mediterranean
during the Plio-Pleistocene:
Palynological and climatostratigraphic record
of the Gulf of Hammamet (NE Tunisia)**

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Abstract: Because of the convergence of Africa and Eurasia and the opening of the Atlantic Ocean, the Gulf of Hammamet, which makes up the southwestern portion of the Mediterranean, experienced significant relative sea-level fluctuations and eustatic variations during the late Cenozoic. The sedimentary successions deposited between the Late Miocene and the earliest Pleistocene in the Gulf of Hammamet preserve precious environmental and climatic information. The present paper focuses on the latest Messinian to Gelasian deposits of the Jiriba-1 borehole, which is located off the coast of Tunisia. Here, previous datings obtained through planktonic foraminiferal biostratigraphy are calibrated chronologically on a high-resolution scale. Palynological analysis based on the spores and pollen content of the borehole allows for reconstructing the environmental and vegetational evolution, as well as establishing a precise climatostratigraphic framework for the study area. The latest Messinian to Gelasian palynological record is comprised of abundant continental (pollen and spores) and marine (dinoflagellate cysts) inputs. Distality markers (halophytes, D/S, *Pinus*, and dinoflagellate cysts) indicate that the Gulf of Hammamet was an epicontinental setting that evolved from a proximal to a distal neritic environment.

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The *Lygeum*, *Artemisia*, and S/T ratio curves enable climatostratigraphic correlations with northwestern Europe, the northwestern Mediterranean, and the Black Sea. Furthermore, the climatic evolution depicted by the steppe elements (*Artemisia* and *Ephedra*) from the Jiriba-1 borehole shows parallelisms with the $\delta^{18}\text{O}$ isotope curve.

The vegetation cover was open, dominated by herbaceous plants that inhabited the lower altitudes, and developed into mixed forest-plant formations at mid-altitudes. Between these two formations, a group of trees made up of Mediterranean species was present.

Repetitive changes in vegetation as well as relative sea-level fluctuations in the Gulf of Hammamet suggest that these cyclical variations resulted from the influence of astronomical forcing.

Keywords:

- climate;
- vegetation;
- climatostratigraphy;
- southwestern Mediterranean;
- Gulf of Hammamet;
- Tunisia

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Résumé : Changements climatiques et de la végétation dans le sud-ouest de la Méditerranée au cours du Plio-Pléistocène : Enregistrements palynologiques et climatostratigraphiques dans le golfe de Hammamet (NE Tunisie).- En raison de la convergence entre les plaques africaine et eurasiennne ainsi que de l'ouverture de l'océan Atlantique, le golfe de Hammamet, qui constitue la partie sud-ouest du bassin méditerranéen, a connu d'importantes fluctuations du niveau relatif de la mer ainsi que des variations eustatiques au cours du Cénozoïque supérieur.

Les successions sédimentaires déposées entre le Miocène supérieur et le Pléistocène inférieur dans le golfe de Hammamet renferment de précieuses informations environnementales et climatiques. Notre étude se concentre sur les dépôts du Messinien terminal au Gélasiens reconnus dans le forage Jiriba-1 situé au large des côtes tunisiennes. Dans ce cadre, les datations antérieures basées sur la biostratigraphie des foraminifères planctoniques sont ici recalibrées sur une échelle chronostratigraphique à haute résolution.

L'analyse palynologique, basée sur le contenu en spores et pollen du forage, permet de reconstituer l'évolution de l'environnement et de la végétation, mais aussi d'établir un cadre climatostratigraphique précis pour la zone d'étude. L'enregistrement palynologique s'étendant du Messinien terminal au Gélasiens est marqué par des apports abondants d'origine continentale (pollen et spores) et marine (kystes de dinoflagellés). Les marqueurs de distalité (halophytes, D/S, *Pinus* et kystes de dinoflagellés) indiquent que le golfe de Hammamet constituait un environnement épicontinental ayant évolué depuis un milieu néritique proximal vers un milieu néritique distal.

Les courbes de *Lygeum*, d'*Artémisia* et du rapport S/T permettent d'établir des corrélations climatostratigraphiques avec le nord-ouest de l'Europe, la Méditerranée nord-occidentale et la Mer Noire. Par ailleurs, l'évolution climatique illustrée par les éléments steppiques (*Artémisia* et *Ephedra*) issus du forage Jiriba-1 présente des parallélismes avec la courbe isotopique $\delta^{18}\text{O}$.

La couverture végétale était ouverte, dominée par des plantes herbacées occupant les basses altitudes et évoluant vers des formations forestières mixtes aux altitudes moyennes. Entre ces deux formations, un groupement arboré composé d'espèces méditerranéennes a été présent.

Les changements répétitifs de la végétation ainsi que les fluctuations relatives du niveau marin dans le golfe de Hammamet suggèrent que ces cycles résultent de l'influence de forçages astronomiques.

Mots-clefs :

- climat ;
- végétation ;
- climatostratigraphie ;
- sud-ouest de la Méditerranée ;
- golfe de Hammamet ;
- Tunisie

1. Introduction

The Mediterranean Sea is an intercontinental basin linked to the Atlantic Ocean through the 14-km-wide Strait of Gibraltar to the west. Because of its peculiar position at the confluence between the humid temperate Central European climate and the arid North African climate with North Atlantic and tropical influences (MEHTA & YANG, 2008), the western Mediterranean has undergone geological, climatic, and environmental upheavals, especially during the Neogene, a period characterized by significant geodynamic and palaeogeographic

changes in this area. Processes involving subduction, continental collision, and the opening of sizable basins in a back-arc context shaped this semi-enclosed sea (DO COUTO, 2014). The complicated history of the Mediterranean and the evolution of water exchange was the ultimate result of tectonic forcing combined with eustatic and climatic factors (FLECKER *et al.*, 2015).

At the beginning of the Oligocene (33.9 Ma), the NS-oriented convergence of Africa and Eurasia reduced the oceanic space between these continents along various subduction zones (JOLIVET & FACCENNA, 2000; BERNATCHEZ *et al.*, 2008; DO COU-



to, 2014). The Lower Miocene marked the opening of the western Mediterranean (REHAULT *et al.*, 1984; ROBERTSON & GRASSO, 1995) and the birth of the northern Betic and southern Rifian corridors (MARTÍN MARTÍN *et al.*, 2014; FLECKER *et al.*, 2015; CAPELLA *et al.*, 2018; KRIJGSMAN *et al.*, 2018). This resulted from the westward displacement of the Alboran domain and the continued convergence of the African and Iberian plates (JOLIVET & FACCENNA, 2000; FACCENNA *et al.*, 2004; DO COUTO, 2014). These two corridors enabled the exchange of water between the North Atlantic and the Mediterranean Sea during the Late Miocene (BACHIRI TAOUFIQ, 2000; BARHOUN & BACHIRI TAOUFIQ, 2008; FLECKER *et al.*, 2015; KRIJGSMAN *et al.*, 2018) and the opening of the Aegean Sea during the Tortonian (STEININGER *et al.*, 1988). During the subsequent Messinian, significant tectonic activity occurred because of a N-S-oriented compressional regime (SERPELLONI *et al.*, 2007; BERNATCHEZ *et al.*, 2008; DO COUTO, 2014). This tectonic instability, combined with geodynamic processes and eustatic fluctuations, led to the successive closure of the Betic (7.2 Ma) and Rifian corridors (7.35-7.25 Ma in the north, 7.1-6.9 Ma in the south), and eventually to the constriction of the proto-Strait of Gibraltar (DO COUTO, 2014; MARTÍN MARTÍN *et al.*, 2014; FLECKER *et al.*, 2015; CAPELLA *et al.*, 2018; KRIJGSMAN *et al.*, 2018; SPAKMAN *et al.*, 2018; TARGHI *et al.*, 2021). As a consequence of this, the latter became the only open gateway to the Atlantic during the Messinian, and probably delivered salty water to the Mediterranean during all successive stages of the Messinian Salinity Crisis (5.97-5.333 Ma) (HSÜ *et al.*, 1973; KRIJGSMAN *et al.*, 1999; JOLIVET *et al.*, 2006; CLAUZON *et al.*, 2015; SUC & FRIZON de LAMOTTE, 2019; SUC *et al.*, 2020). This phenomenon constitutes the most fascinating oceanographic event recorded in recent Mediterranean history (CORNÉE *et al.*, 2016) - one that led the Mediterranean to experience major salinity fluctuations and hypersaline conditions (HSÜ *et al.*, 1973; KRIJGSMAN *et al.*, 1999; ROVERI *et al.*, 2014; DIJK *et al.*, 2023) as testified by the deposition of massive evaporitic successions in the peripheral and central Mediterranean basins over a very short time span (ROUCHY, 1982; ROUCHY & CARUSO, 2006; KRIJGSMAN & MEIJER, 2008; ROVERI *et al.*, 2014).

The reflooding of the Mediterranean basin through the reopening of the Strait of Gibraltar has been estimated to have begun around 5.46 Ma, before the onset of the Zanclean. It resulted in the restoration of fully marine conditions in most of the depressions bordering the Alboran Sea, as well as in a sudden, generalized rise of the Mediterranean sea-level (STEININGER & RÖGL, 1984; BLANC, 2002; LOGET & DRIESSCHE, 2006; GARCÍA-CASTELLANOS *et al.*, 2009; ESTRADA *et al.*, 2011; BACHE *et al.*, 2012; SUC & FRIZON de LAMOTTE, 2019; SUC *et al.*, 2020).

Situated between Africa and Eurasia, the Mediterranean region was colonized by vegetation combining tropical, northern, and native flora (FEDDI *et al.*, 2011). The rich fossil pollen record

from this area provides a detailed history of plant ecosystems, and indicates tropical to subtropical climatic conditions from the early Neogene (23.04 Ma) to the latest Pliocene (2.6 Ma) (SUC, 1984, 1989; BESSEDIK, 1985; SUC & POPESCU, 2005; JIMÉNEZ-MORENO *et al.*, 2009, 2013, 2015; SUC *et al.*, 2018b; BERTINI & COMBOURIEU-NEBOUT, 2023; BERTINI *et al.*, 2025). In the northern Mediterranean, over the past 23 million years, thermophilous and hygrophilous taxa declined, which was accompanied by a transition from dense forests to open landscapes. *Avicennia* mangroves first migrated southward before disappearing and being replaced by swamps that also vanished subsequently. Subtropical evergreen forests were successively replaced by sclerophyllous Mediterranean vegetation and then by *Artemisia* steppes, alternating with mesophilous forests during glacial-interglacial cycles. In the southern Mediterranean, open subdesertic associations prevailed, with *Avicennia* persisting until the Early Pliocene. Mediterranean sclerophyllous plants, which first appeared in the Early Miocene, expanded during the Neogene in response to climatic changes, with subsequent variations being influenced by temperature and seasonal instability (SUC *et al.*, 2018b).

Pollen analysis shows that the Mediterranean changing climate can be subdivided into three main phases covering the past 23 million years (SUC *et al.*, 2018b). After a phase of relatively stable, warm conditions with limited thermal seasonality, ranging from the Miocene to the early Late Pliocene (23 - 3.37 Ma), the 3.37-2.6 Ma time span represents a transitional phase during which a Mediterranean-type seasonal rhythm was established. Around 2.6 Ma, floristic diversity declined, and plant communities underwent major transformations as a consequence of the intensification of Northern Hemisphere glaciation (INHG), which was initiated around 2.7 Ma (MUDELSEE & RAYMO, 2005; KABOTH-BAHR *et al.*, 2021; MCCLYMONT *et al.*, 2023; BERTINI *et al.*, 2025). This led to widespread xericity and cold temperatures, with highly contrasting seasons, while interglacial periods were warmer and wetter (POPESCU, 2001; SUC *et al.*, 2018b). In addition to these long-term changes, ZACHARIASSE *et al.* (1989), HILGEN (1990, 1991), LANGEREIS and HILGEN (1991), and LAAN *et al.* (2006) have demonstrated that, in Sicily and Morocco, the variability of orbital parameters strongly controlled marine sedimentation during the Early Pliocene. In the Mediterranean region, cyclical changes in vegetation during the Pliocene were mainly due to precession (POPESCU, 2001; POPESCU *et al.*, 2010; JIMÉNEZ-MORENO *et al.*, 2013).

The Gulf of Hammamet has been the focus of intense oil exploration activity in recent years. It is part of the Southeast Mediterranean region and comprises a sizable sedimentary reservoir with precious geological and climatic archives. It is home to several basins, which mostly accommodated deposition during the Pliocene and Quaternary (BEN BRAHIM *et al.*, 2013). The sedimentary fill of these basins represents a valuable paleoenvironmental archive for characterizing and under-



standing the last few million years of climate change in the Mediterranean Basin.

Data on vegetation, climate, and their evolution between the latest Messinian to the Gelasian are scarce in Tunisia and the surrounding countries (Algeria and Morocco). The only available studies are those of SUC *et al.* (1995) and FAUQUETTE *et al.* (1999) on Oued et Tellil in Tunisia and Habibas-1 in Algeria, as well as those of FEDDI *et al.* (2011) and WARNY (1999) concerning Nador-1 and Bou Regreg in Morocco. To fill this gap, we conducted a palynological study based on pollen and spore analysis of the Jiriba-1 borehole, located on the eastern coast of Tunisia.

The goal of the present work is threefold. Firstly, it aims at reconstructing the evolution of vegetation and climate in the Gulf of Hammamet between the latest Messinian and Gelasian within a precise chronostratigraphic framework. Secondly, it focuses on reconstructing the continental and marine environments, and placing them in the overall context of climate change in the Mediterranean region. Thirdly, it aims at investigating how vegetation along the southwestern Mediterranean coast reacted to the forcing of orbital parameters.

2. Geographical and geological setting

Northern Tunisia is bordered by the Mediterranean Sea, and its coastline is deeply indented by numerous embayments, most notably the gulfs of Tunis, Hammamet, and Gabes (TAYECH, 1984) (Fig. 1).

Our study area, the Gulf of Hammamet, is located in the offshore zone of northeastern Tunisia, between two major geological domains: the Atlas domain to the west and the Pelagian domain to the east (BEN BRAHIM *et al.*, 2013). It is bounded by the Cap Bon Peninsula to the north, the Sicily Channel to the northeast, the Sahel province to the west, and the Mahdia-Kerkennah uplift to the south (BOCCALETTI *et al.*, 1987; GARDINER *et al.*, 1995; TORELLI *et al.*, 1995; CATALANO *et al.*, 1996; TAVARNELLI *et al.*, 2004; BEN BRAHIM *et al.*, 2013). Its surface area covers approximately 20,000 km² (BEN BRAHIM *et al.*, 2013) (Fig. 1).

The northeastern region of Tunisia is characterized by a significant accumulation of Neogene deposits resulting from continuous subsidence during the Oligocene-Miocene to the Pliocene (BENZAKOUR, 1992; DLALA, 1994, 1995; KACEM, 2004; MEJRI, 2012). Resulting from the erosion of the surrounding reliefs, these deposits filled the subsiding basins, which are segmented by horsts and grabens (MEJRI, 2012). The Miocene successions in the Gulf of Hammamet can reach up to 2,500 m in thickness and are mainly composed of clayey, sandstone units, along with gypsum (MEJRI, 2012). Phytogenic deposits interbedded within these mostly siliciclastic successions indicate a paralic setting (BEN MOKTAR & MANNAÏ-TAYECH, 2012).

The Messinian deposits of northeastern Tunisia - including the Kechabta, Oued Belkhedim, and Oued Et Tebala formations - are unconformably

overlain by the Lower Pliocene Raf-Raf Formation, which is mainly composed of marls and clays. This unit is further overlain by the Upper Pliocene Porto Farina Formation, which is dominated by sandstone deposits. The succession formed by the Raf-Raf and Porto Farina formations contains terrestrial mammal fossils assigned to the Early Villafranchian (LAFFITTE & DUMON, 1948; BIZON *et al.*, 1980; BESÈME & LAJMI, 1981; MEJRI, 2012).

Overall, the Mio-Pliocene deposits constitute a regressive megasequence bounded at its base by a discontinuity marking the Tortonian-Messinian transition, and at the top by a second discontinuity associated with the Pliocene transgression (BESÈME & KAMOUN, 1988; GAALLOUL & RAZGALLAH, 2008; FRIGUI *et al.*, 2016).

The sedimentary settings of northeastern Tunisia evolved from a shallow marine carbonate platform characterized by a diverse fauna to a lagoonal setting marked by evaporitic sedimentation, and eventually to a shallow-water, restricted environment. This palaeoenvironmental succession extends in a nearly continuous fashion between the Messinian and the Quaternary (TEMANI & GAALLOUL, 2007; GAALLOUL & RAZGALLAH, 2008).

The tectonic framework of the Gulf of Hammamet reflects the dynamic convergence between the African and Eurasian plates, as well as the opening of the Atlantic Ocean (CHIH & PHILIP, 1999; MANNAÏ-TAYECH, 2006; BEN BRAHIM *et al.*, 2013). At different times, these processes have induced both compressive and extensive tectonic regimes, leading to a variety of structures and tectonic inversions of sedimentary basins (BEN AYED *et al.*, 1983; BUROLLET, 1991; BÉDIR *et al.*, 1992; BENSALAM, 1992; PIQUET *et al.*, 2002; BEN BRAHIM *et al.*, 2013; ABIDI *et al.*, 2015; SAINT-MARTIN *et al.*, 2023).

The study area is marked by a major north-south-oriented structure, crossing the entire Atlas domain of central Tunisia (BOUAZIZ *et al.*, 2002; BEN BRAHIM *et al.*, 2013) (Fig. 1). To the east of this north-south axis, the Pelagian domain is subdivided into two distinct zones: on the one hand, the continental Sahel domain, where upper Cenozoic sediments are buried beneath a folded zone affected by major NW-SE- and E-W-trending normal faults; on the other hand, the offshore Pelagian Sea, which is characterized by a set of shallow platforms and intermediate basins controlled by a complex fault network (HALLER, 1983; BÉDIR, 1995; ARGNANI & TORELLI, 2001; BEN BRAHIM *et al.*, 2013).

During the Middle Miocene (Langhian), the Hammamet Basin underwent a very strong subsidence with a subsidence rate reaching 150 m/Ma (PATRIAT *et al.*, 2003; BEN BRAHIM *et al.*, 2013). This conspicuous subsidence was synchronous with the emplacement of thrust sheets in the Tellian domain (ROUVIER, 1977). During the Late Miocene, the northeastern region of Tunisia experienced a tectonic peak marked by the combined activity of Atlas and Alpine phases. This geodynamic evolution led to the formation of the Alpine chains, such as the Kroumirie in the north and northwest, and the antiform of Jebel Abder-



rahmane in the northeast. It also contributed to the structuring of the Tunisian Ridge and the individualization of several microbasins, which were filled with molassic and fluviodeltaic siliciclastic deposits organized into sedimentary sequences (MANNAÏ-TAYECH, 2006; BEN MOKTAR & MANNAÏ-TAYECH, 2012).

In Pliocene and Pleistocene times, the Gulf of Hammamet and the nearby Kuriate Islands were affected by significant subsidence associated with extensional tectonics linked to the active Siculo-Tunisian rift, which resulted in the development of horst and graben structures since the Oligocene and Miocene (HALLER, 1983; BUROLLET, 1991; BENZAKOUR, 1992; BÉDIR, 1995; BÉDIR *et al.*, 1996; BEN BRAHIM *et al.*, 2013). Subsequently, the post-Villafranchian compressive phase triggered the formation of the Jiriba trough by reactivating pre-existing normal faults as reverse faults (BEN BRAHIM *et al.*, 2013).

This subsiding basin is home to significant Cretaceous and Miocene-Pliocene reservoirs, which provide favorable conditions for hydrocarbon accumulation due to their structural geometries (ABIDI *et al.*, 2015).

3. Material and method

3.1. Sampling

The Jiriba-1 borehole, located in the Gulf of Hammamet (Fig. 1) approximately 18 km offshore from the eastern Tunisian coast (36°12'N, 10°40'E), was drilled to a total depth of 2885 m. Samples were collected in 1982 by Elf-Aquitaine Tunisie and Shell as part of an exploration program targeting Upper Miocene (Messinian) to Quaternary deposits (BISMUTH & BENZARTI, 1982; LONDEIX *et al.*, 1999).



3.2. Lithological description of the Jiriba-1 borehole

Palynological slides from the Jiriba-1 borehole are stored at the Laboratory of Geosciences, Geomatics, and Environment, Geology Department, Faculty of Sciences Ben M'Sick, Hassan II University of Casablanca (Morocco). The borehole spans between the Messinian and the base of the Gelasian and features a reasonably continuous Pliocene succession (Fig. 2). The deposits were thoroughly described by BISMUTH and BENZARTI (1982), BENZAKOUR (1992), and LONDEIX *et al.* (1999), who distinguished two main formations (Fig. 2):

- The Oued Et Tebala Formation (2994 m to 2411 m) is primarily composed, from base to top, of evaporites, coarse to fine sands, and clay layers.
- The Raf Raf Formation (2411 m to 300 m) generally includes, upward from the base, brown clays rich in pelagic microfauna, yellow sands, light grey micritic clayey marls and limestones, pyritic clays very rich in fossils, beige dolomicrites with sandy interbeds, and clayey sands.

Sampling for palynology was carried out every 20 m between depths of 2994 m and 300 m. The samples analyzed in this study are located between depths of 2480 and 500 m.

3.3. Biostratigraphy of the Jiriba-1 borehole

BISMUTH and BENZARTI (1982) conducted the first micropalaeontological study of the Jiriba-1 borehole. It focused on benthic and planktonic foraminifera as well as on ostracods. Based on the vertical distribution of planktonic foraminiferal marker species, BENZAKOUR (1992) and LONDEIX *et al.* (1999) proposed a stratigraphic subdivision of the succession. The bioevents considered in this study correspond to the first and last appearances of the following taxa: *Sphaeroidinellopsis*, *Globorotalia margaritae*, *Globorotalia puncticulata*, *Globorotalia crassaformis*, and *Globorotalia inflata*. These events are presented sequentially, from top to bottom (Table 1).

Table 1: Main Planktonic Foraminiferal Bioevents in the Jiriba-1 Borehole.

Stage	Planktonic foraminifera bioevents	Depth (m)	Age (Ma)
Gelasian	First Occurrence (FO) of <i>Globorotalia inflata</i>	620 m	2.09 Ma
	Last Regular Occurrence (LRO) of <i>Globorotalia crassaformis</i>	880 m	2.13 Ma
Piacenzian	Last Occurrence (LO) of <i>Sphaeroidinellopsis</i>	1280 m	3.19 Ma
	Last Occurrence (LO) of <i>Globorotalia puncticulata</i>	1420 m	3.57 Ma
Zanclean	Last Common Occurrence (LCO) of <i>Globorotalia margaritae</i>	1620 m	3.98 Ma
	First Occurrence (FO) of <i>Globorotalia puncticulata</i>	1960 m	4.52 Ma
	First Common Occurrence (FCO) of <i>Globorotalia margaritae</i>	2320 m	5.08 Ma
Zanclean Base	Acme Base (AB) of <i>Sphaeroidinellopsis</i>	2400 m	5.30 Ma

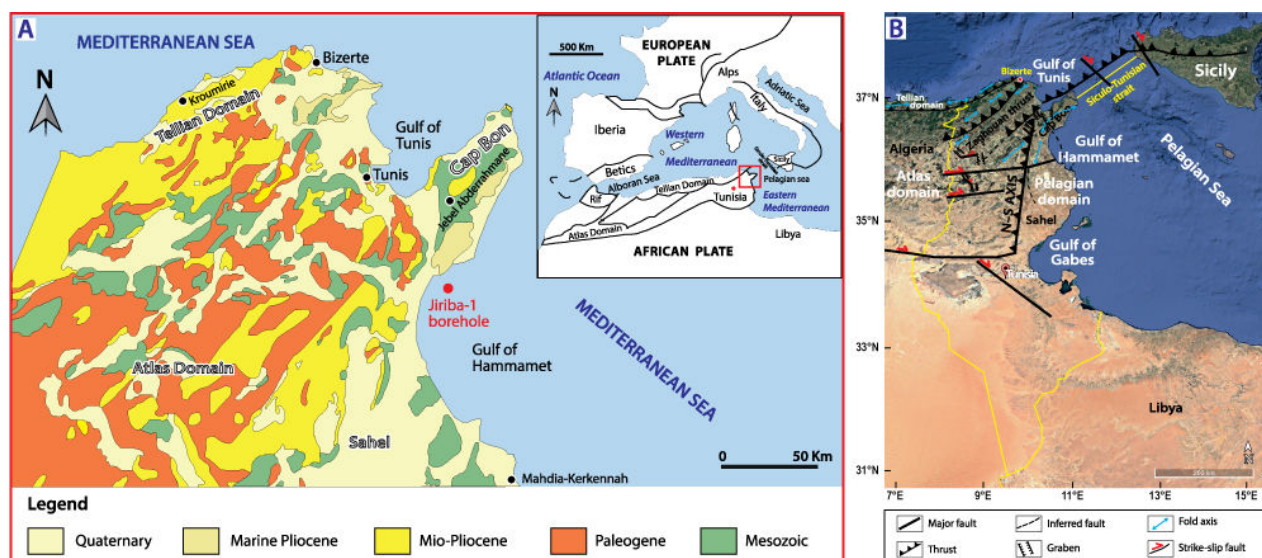


Figure 1: A) Simplified geological map of northeastern Tunisia (BENZAKOUR, 1992); **B)** Location map of the studied region showing the main structural elements.

In the present work, these bioevents were calibrated with the Mediterranean stratigraphic scale (LOURENS *et al.*, 2004; IACCARINO *et al.*, 2007; LIRER *et al.*, 2019), which allowed us to recognize the uppermost Messinian, the Pliocene (Zanclean and Piacenzian), and the Gelasian (Fig. 2). According to the most recent version of the International Commission on Stratigraphy (ICS), the Gelasian stage is regarded herein as part of the Lower Pleistocene.

The uppermost Messinian (5.5 Ma to 5.333 Ma) corresponds to depths between 2480 and 2400 m, directly below the AB *Sphaeroidinellopsis* (*Sphaeroidinellopsis* Acme Base) bioevent, corresponding to 5.333 Ma (LOURENS *et al.*, 2004), which marks the restoration of open-marine conditions in the Mediterranean Basin following the Messinian Salinity Crisis (Fig. 2).

The Zanclean (Lower Pliocene) (5.333 Ma to 3.600 Ma) extends from 2400 to 1420 m in depth, according to previously cited studies. Palynologically, the 2400-2000 m interval is barren, whereas only the samples between 2000 and 1420 m are rich in terrestrial and marine palynomorphs. This interval corresponds to the upper part of the Zanclean, specifically to the MPL3 zone and MPL4a subzone (Fig. 2).

The MPL3 Zone (2000 to 1700 m) corresponds to the interval between the FO of *Globorotalia puncticulata* and the LCO of *Globorotalia margaritae*, from 4.52 Ma to 3.98 Ma (LOURENS *et al.*, 2004). The interval between the LCO of *Globorotalia margaritae* and the LO of *Globorotalia puncticulata*, from 3.98 Ma to 3.57 Ma, coincides with subzone MPL4a (1700 to 1420 m) (LOURENS *et al.*, 2004) (Fig. 2).

The Zanclean-Piacenzian boundary (3.600 Ma) is located at a depth of 1420 m and coincides with the LO of *Globorotalia puncticulata* (LOURENS *et al.*, 2004; LIRER *et al.*, 2019) (Fig. 2).

The Piacenzian (Upper Pliocene) (3.600 Ma to 2.58 Ma) extends between depths of 1420 m and 960 m (Fig. 2).

The Piacenzian-Gelasian boundary (2.58 Ma; LOURENS *et al.*, 2004) is marked by the LCO of *Globorotalia bononiensis* (LOURENS *et al.*, 2004). However, according to previous studies, this species was not recorded in the Jiriba-1 borehole. In turn, the LRO of *Globorotalia crassaformis*, dated at 2.134 Ma, was identified at a depth of approximately 880 m. Therefore, the base of the Gelasian would be slightly deeper, between 1060 m and 880 m, most likely around 960 m, based on the attempted correlation of this borehole with the reference Rossello section (Fig. 2).

The Gelasian (lowermost Pleistocene) (2.58-1.80 Ma) is characterized by two events, namely, the FCO of *Neogloboquadrina pachyderma* with sinistral coiling and the influx of *Globorotalia crassaformis* (LOURENS *et al.*, 2004). In the studied borehole, only one bioevent was observed at around 620 m, corresponding to the FO *Globorotalia inflata*, while the appearance of *Globorotalia truncatulinoides* was not recorded. Therefore, the sediments between 960 m and 500 m are of Gelasian age, probably corresponding to subzone MPL6a. The latter spans between the FO of *Globorotalia inflata* and the FO of *Globorotalia truncatulinoides* (LOURENS *et al.*, 2004; IACCARINO *et al.*, 2007) (Fig. 2).

Remarks: The biostratigraphic subdivisions adopted herein for the Jiriba-1 Borehole generally correlate with the major climatic phases thereof (see Discussion below). Indeed, the MPL3 zone corresponds to the Pollen sub-zone P Ib of Suc and the Brunssumian B of ZAGWIJN (from 4.75 Ma to 4.0 Ma; 2000 to 1700 m), while the MPL4a zone coincides with the pollen sub-zone P Ic of Suc and the Brunssumian C of ZAGWIJN (from 4.0 Ma to 3.600 Ma; 1700 to 1420 m). The Piacenzian (3.600 Ma to 2.58 Ma) is consistent with the P II zone of Suc and the Reuverian of ZAGWIJN (1420 to 960 m). The Gelasian (2.58 Ma to 1.80 Ma; 960 to 500 m) matches the P III zone of Suc and the Praetiglian of ZAGWIJN (ZAGWIJN, 1960; SUC & ZAGWIJN, 1983; SUC, 1984; SUC *et al.*, 1995).

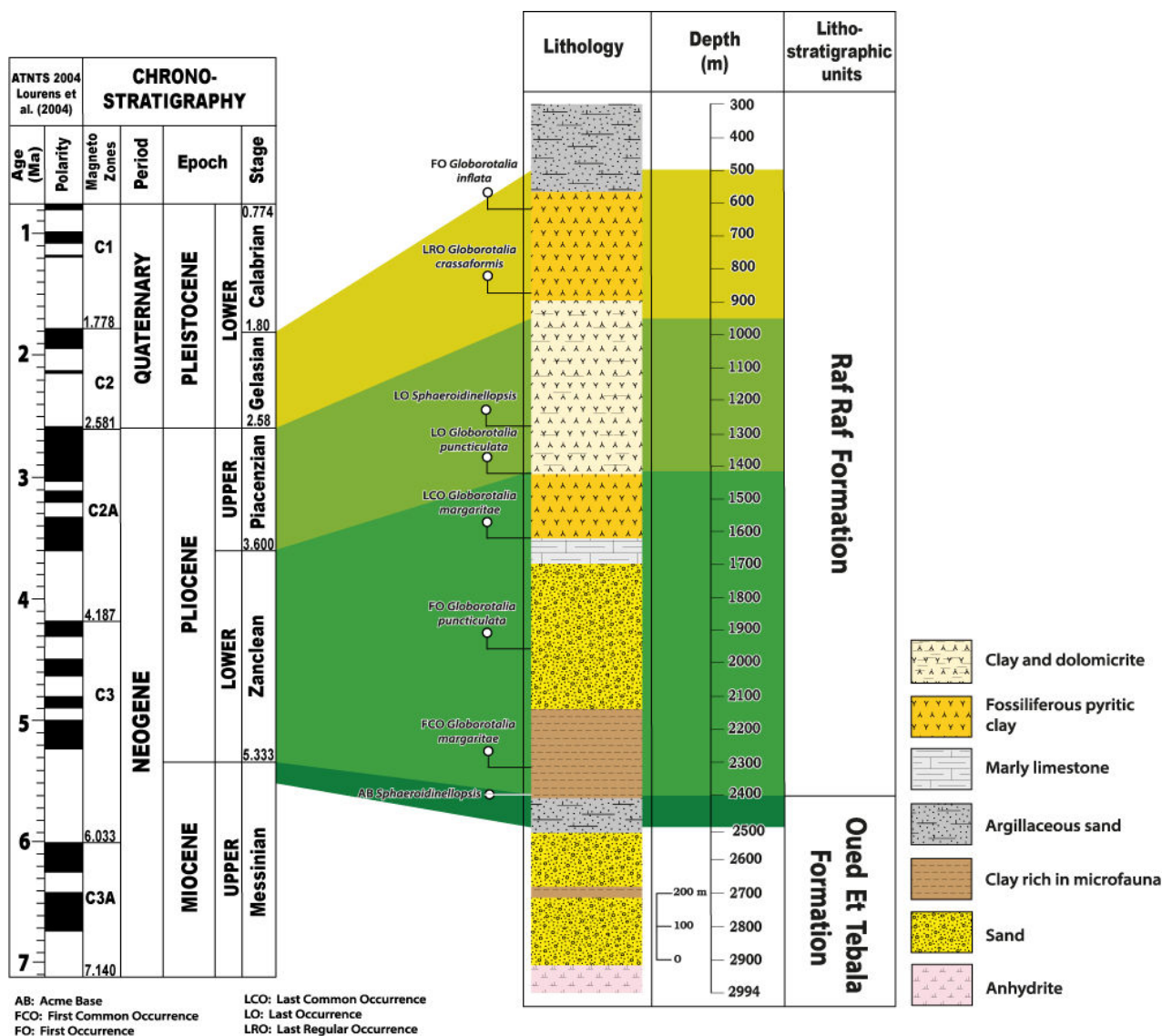


Figure 2: Lithostratigraphy and biostratigraphy of the Jiriba-1 borehole.

3.4. Methods

3.4.1. Palynological technique

This method aims at progressively eliminating all mineral and organic constituents, thereby concentrating the palynomorphs. To achieve this, samples from the Jiriba-1 borehole were prepared using the classical palynological technique adopted by POPESCU (2001), following the steps below:

- Several repeated treatments with hydrochloric acid (HCl 20%) and hydrofluoric acid (HF 40%) were applied to remove the carbonates and silicates, followed by a hot, 37% hydrochloric acid treatment to destroy the fluoro-silicates. Samples were neutralized with distilled water after each acid treatment.
- Separation of organic particles from mineral residues was performed by density separation using a $ZnCl_2$ solution, followed by 10- μm sieving to remove the remaining fine clay and silt particles.

- The resulting organic residues were diluted in glycerin, and mounted between slides and lamellae to allow for the observation and correct identification of the palynomorphs.
- Pollen grains are frequently identified at the family level, often at the genus level, and rarely at the species level. At least 160 grains were counted per sample, excluding Pinaceae, spores, algae, as well as indeterminate and unidentifiable grains.
- The percentages of all identified taxa were calculated relative to the total sum of pollen grains. The frequency of each taxon was presented in a detailed pollen diagram. Pollen taxa were grouped in a synthetic diagram based on their current climatic and/or ecological significance (POPESCU, 2001; Suc *et al.*, 2018b).
- Dinoflagellate cyst assemblages are moderately diverse and include 33 taxa. The relative proportions of each dinocyst taxon have been reported by BENZAKOUR (1992).



3.4.2. Bioclimatic markers of continental environments

The mean annual temperature (MAT) can be inferred from ecological data derived from current plant assemblages (NIX, 1982), including megatherm, mega-mesotherm, mesotherm, and microtherm elements (SUC *et al.*, 2018b). Humidity can be estimated using the Poaceae/Compositae ratio (COUR & DUZER, 1978).

- Megatherm elements

These correspond to the megatherm plants from equatorial and tropical forests (MAT > 24°C). The group includes Euphorbiaceae, Rubiaceae, Hamamelidaceae, and Malvaceae.

- Mega-mesotherm elements

These correspond to plants living in subtropical forests (24°C > MAT > 20°C). This group includes Taxodiaceae, *Myrica*, *Engelhardia* (Pl. 1, fig. 2), Sapotaceae, Arecaceae, Sapindaceae, *Hedera*, and Magnoliaceae.

- Mesotherm elements

These correspond to mesotherm plants typical of warm-temperate forests (20°C > MAT > 14°C). This group includes *Carya*, *Quercus* (deciduous), *Ulmus-Zelkova*, *Ulmus*, *Buxus sempervirens* type (Pl. 1, fig. 3), *Carpinus*, *Juglans*, *Pterocarya*, *Corylus*, *Acer*, *Alnus*, *Salix*, *Populus*, *Fraxinus*, *Betula*, Ericaceae, and *Ligustrum*.

- Meso-microtherm elements

These correspond to plants growing in cool temperate forests at mid-altitudes, including *Cathaya* (Pl. 1, fig. 5), *Tsuga*, and *Cedrus* (14°C > MAT > 12°C).

- Microtherm elements

These are characteristic of high-altitude boreal conifer forests such as *Abies* and *Picea* (MAT < 12°C).

- Poaceae/Compositae ratio

This curve represents the ratio between Poaceae (Pl. 2, fig. 20) and Compositae, and reflects variations in humidity, particularly in xeric environments (COUR & DUZER, 1978). Dry conditions favor the development of Compositae (ratio < 20, when annual precipitation is less than 500 mm), whereas humid conditions favor the development of Poaceae (ratio > 20, when annual precipitation exceeds 500 mm). This contrasts with the genus *Lygeum* (Pl. 2, fig. 12), which currently occurs under arid climatic conditions characterized by a mean annual temperature between 16 and 21°C and a mean annual precipitation of approximately 150-400 mm (FAUQUETTE *et al.*, 1998b).

3.4.3. Marine environmental index

- Distality indexes

These indexes provide an overview of the sea-level variations that affected the Gulf of Hammamet during the latest Miocene, Pliocene, and the earliest stage of the Pleistocene. The following indicators were applied:

- Synthetic diagram with *Pinus* + undeterminable Pinaceae

Due to their pollen morphology, Pinaceae (balloon grains) (Pl. 1, figs. 6-7) are easily transported by air and water, which enables a wide dispersal. In contrast, halophytes are reliable indicators of coastal environments. Generally speaking, Pinaceae are proportionally more abundant in distal than proximal areas (HEUSSER & BALSAM, 1977; SUC & DRIVALIARI, 1991).

- D/S ratio

The ratio between the number of dinocysts (D) and the number of spores + pollen (S) is used to assess the marine influence (relative abundance of dinocysts) versus continental influence (pollen and spores) (WARNY, 1999). This ratio allows for the recognition of transgressive-regressive trends, thus providing an excellent indicator of sea-level dynamics in marine depositional settings.

4. Palynological results

The detailed palynological analysis of the Jiriba-1 borehole reveals a significant richness of pollen and dinoflagellate cysts. The latter have been previously studied in detail by BENZAKOUR (1992) and LONDEIX *et al.* (1999). Sediments at the base of the Zanclean were found to be devoid of palynomorphs, possibly due to oxidation of the organic matter (BENZAKOUR, 1992).

4.1. Continental inputs (pollen and spores)

This region has a diverse and relatively abundant pollen flora. A total of 15,671 palynomorphs were counted across 63 samples, which led to the identification of 75 pollen taxa. The detailed and synthetic diagrams (Figs. 3 - 4) reflect a rather homogeneous floristic composition from the latest Messinian to the Gelasian.

The genus *Pinus* (2 to 53%) dominates the pollen spectra throughout the section. Notably, *Pinus* declines at the top of the Lower Pliocene and in the basal part of the Upper Pliocene (2000 m to 1100 m), with slight increases at sample depths of 1720 m, 1660 m, 1280 m, 1260 m, and 1200 m (Figs. 3, 4.A).

Altitude elements (microtherm elements) ranging from 0 to 0.35% appear only at the top of the Upper Pliocene, with *Abies* (0.35%) and *Picea* (0.34%) (Figs. 3, 4.B).

Cathaya (0 to 1.53%) and Cupressaceae (0.7 to 2.5%) occur sporadically. *Cathaya* appears discontinuously, alternating with the histograms of steppe elements (*Artemisia* and *Ephedra*) (Figs. 3, 4.B).

Megatherm elements occur very rarely, with frequencies ranging from 0 to 0.68% (Figs. 3, 4.B).

Elements of the mega-mesotherm group (Arecaceae, Cupressaceae, *Engelhardia*, Magnoliaceae, *Myrica*, Sapindaceae, Sapotaceae, and *Sciadopitys*) are present along the profile at low frequencies, ranging from 0 to 4.89% (Figs. 3, 4.B).

► **Figure 3:** Detailed pollen diagram of the Jiriba-1 borehole.





Elements of the mesotherm group (ranging from 0.43 to 16.23%) include, in order of abundance, *Quercus* (deciduous) (2 to 16%) (Pl. 1, fig. 4), *Buxus sempervirens* type (0 to 3.38%), and *Juglans* (0 to 1%). Other elements (*Acer*, *Hedera*, *Alnus*, *Betula*, *Carpinus*, *Corylus*, *Ericaceae*, *Carya*, *Pterocarya*, *Fraxinus*, *Ligustrum*, *Populus*, *Salix*, and *Ulmus-Zelkova*) do not exceed 0.7% (Figs. 3, 4.B).

The Mediterranean group (0 to 3.40%) is characterized by the presence of *Quercus ilex*-type (Pl. 1, fig. 9) (1 to 3%), *Olea* (Pl. 1, fig. 10) (0 to 1.1%), *Phillyrea* (0 to 0.8%), and *Cistus* (Pl. 1, fig. 8) (0 to 0.6%) (Figs. 3, 4.B).

The herbaceous plants are very abundant, representing more than 83% of the pollen sum (Fig. 4.B). Within this group, the Compositae (Asteraceae) Asteroideae (Pl. 2, fig. 14) and Compositae (Asteraceae) Cichorioideae (Pl. 2, fig. 15) dominate the pollen spectra, with frequencies between 3 and 40% (Fig. 3). Poaceae are between 4 and 37%, and *Plantago* pollen (Pl. 2, fig. 19) reaches values up to 25% (Fig. 3). Note that where Poaceae pollen frequencies decrease (e.g., between 1860 m and 1800 m), those of Compositae (Asteraceae) increase; conversely, where Poaceae frequencies increase (e.g., between 1660 m and 1580 m), those of Compositae (Asteraceae) decrease (Fig. 3).

The Poaceae/Compositae ratio is close to or below 2 throughout the borehole, except for two horizons (2480 m and 1300 m) where it exceeds 2 (Fig. 6).

The aridity of the environment is indicated by the presence of subdesertic elements (*Lygeum*; 0-5.58%, excluding Pinaceae) and steppe elements [*Artemisia* (Pl. 2, fig. 13); 0-11%, excluding Pinaceae, and *Ephedra* (Pl. 2, fig. 11); 0-4%, excluding Pinaceae] (Figs. 3, 4.B).

Halophytes (2 to 24%) are represented by Amaranthaceae-Chenopodiaceae (Pl. 2, fig. 21) (3 to 23%), which are dominant in the Upper Pliocene, and by Caryophyllaceae pollen (Pl. 2, fig. 17) at 1640 m (4.8%). Plumbaginaceae do not exceed 1% in the basal part of the uppermost Messinian (2480m) (Figs. 3, 4.B).

Examination of the synthetic diagram without Pinaceae reveals that the peaks of some ecological groups show opposite variations, as observed for mega-mesotherms, *Cathaya*, mesotherms, sub-desertic elements, and halophytes (Fig. 4.B).

The frequency of Pteridophytes spores varies between 3 and 13%, including both monolete and trilete spores (up to 9%). The presence of *Concentricystes* reflects fluvial input influence at three levels (1680 m, 1520 m, and 1260 m) (Fig. 3).

Reworked pollen grains are distributed from the top of the Lower Pliocene to the Upper Pliocene (2000 m to 1140 m), with a notable increase at 1240 m (Fig. 3).

4.2. Marine inputs

The percentage of autochthonous elements (dino-flagellate cysts, chitinous tests of foraminifera, and acritarchs) is variable throughout the borehole (Fig. 3).

During the uppermost Messinian (2480 m to 2400 m), and from the Zanclean to the early Gelasian, the D/S curve generally shows low values, ranging from 0 to 0.5, reflecting the abundance of continental inputs (Fig. 6).

At the top of the Upper Pliocene (640 m to 500 m), the D/S curve is marked by higher ratios, exceeding 1. This reflects lower concentrations of terrestrial palynomorphs compared to dinocysts (Fig. 6).

Pinus + indeterminable Pinaceae are considered ecologically insignificant, as their pollen cannot be determined below the genus level at best. The genus *Pinus* includes species that span a very broad thermal range. Because of their pollen morphology, which favors wide dispersal, the abundance of these pollen grains tends to decrease in proximal marine areas and increase in distal environments (HEUSSER & BALSAM, 1977; SUC & DRIVALLIARI, 1991). Accordingly, the frequencies of *Pinus* + indeterminable Pinaceae generally follow the same trend as the D/S curve (Fig. 6).

Halophytes, in turn, are reliable indicators of coastal environments. These indicators of distal-versus-proximal settings vary inversely. In the case of the Jiriba-1 borehole, halophyte frequencies increase as those of *Pinus* + indeterminable Pinaceae decrease (Fig. 6).

The discrepancy between these distal indicators at 640 m and 1000 m may be related to tectonic activity (Fig. 6).

5. Discussion

After presenting a palynological synthesis of the studied borehole, this section discusses the results obtained in this study and their integration with existing data across three aspects. The first such aspect concerns the reconstruction of vegetation landscapes in the Gulf of Hammamet from the latest Messinian to the Gelasian as deduced from the pollen record. The second deals with the different climatic phases identified in the Jiriba-1 borehole based on the climatostratigraphic scale of SUC and ZAGWIJN (1983). The third aims to trace changes in vegetation, climate, and sea level in the Gulf of Hammamet over the same interval.

5.1. Plant landscapes

Overall, the pollen spectra from the Jiriba-1 borehole reflect a rather homogeneous floristic pattern and indicate fairly stable environmental conditions between the latest Messinian and the Gelasian (Figs. 3 - 4). Vegetation was characterized by a mosaic of plant associations inherited from the Tortonian and Messinian. Consequently, in North Africa, the pollen floras of Early Pliocene age are similar to those of the subsequent Messinian (CHIKHI, 1992a; BACHIRI TAOUFIQ, 2000; BARHOUN & BACHIRI TAOUFIQ, 2008; ACHALHI *et al.*, 2016; TARGHI *et al.*, 2023; BAHAJ *et al.*, 2024).

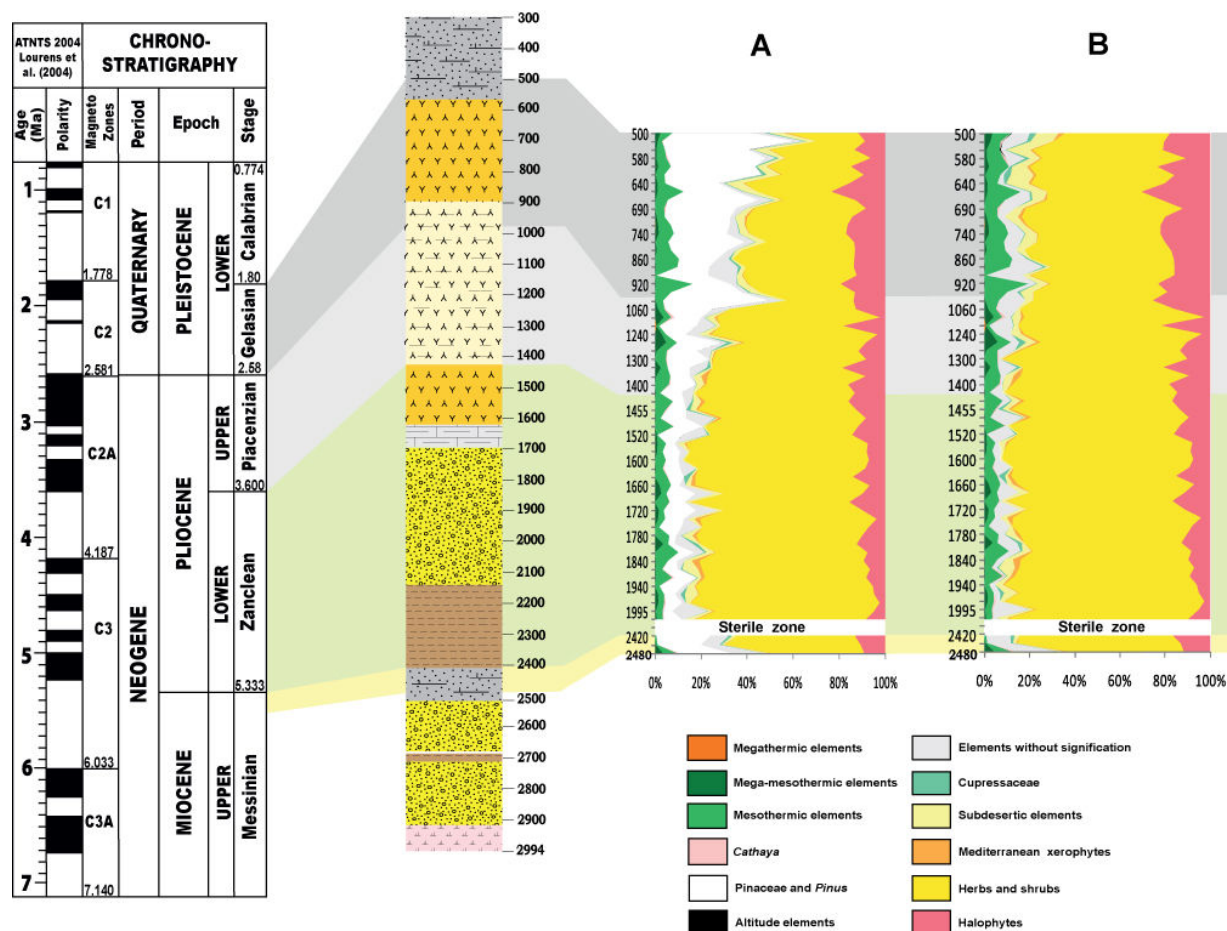


Figure 4: Synthetic pollen diagrams with (A) and without (B) Pinaceae from the Jiriba-1 borehole.

Pollen analysis of the Jiriba-1 sediments reveals a diverse flora, comprising elements currently inhabiting the intertropical (Euphorbiaceae, Sapindaceae) and subtropical to warm-temperate regions of America and Asia (*Engelhardia*, Sapotaceae, Arecaceae, etc.), as well as elements that are presently found in Europe (*Quercus*, *Ulmus*, *Acer*, *Salix*, *Populus*, Ericaceae, *Betula*, *Carpinus*, etc.), and the Mediterranean region (*Olea*, *Phillyrea*, *Quercus ilex-coccifera* type, *Fraxinus*, etc.). Elements representative of subdesertic environments and generally xeric open vegetation (Poaceae, *Lygeum*, *Ephedra*, *Artemisia*, Compositae, Amaranthaceae-Chenopodiaceae, Plumbaginaceae, *Plantago*, *Erodium*, etc.) occur at high percentages (Figs. 3, 4.B). Mid- and high-altitude elements such as *Cathaya*, *Tsuga*, *Cedrus*, *Abies*, and *Picea* are rare in the Miocene of North Africa but are well represented during the Pliocene and Gelasian (SUC, 1989; SUC *et al.*, 1995, 2018b; FEDDI *et al.*, 2011; BERRY *et al.*, 2025). Moreover, the vegetation was organized in altitudinal belts. By comparing the reconstructed vegetation of the latest Messinian-Pliocene in this region with modern vegetation in southeastern China (WANG, 1961), the Canary Islands, and the shores of the Red Sea, and based on current reference paleoenvironmental models (SUC, 1984; JIMÉNEZ-MORENO *et al.*, 2008, 2010; FEDDI *et al.*, 2011; SUC *et al.*, 2018b; TARGHI *et al.*, 2023), the main plant formations can be identified as follows:

- From the latest Messinian to the Zanclean (2480-1420 m depth), herbaceous plants such as *Lygeum*, *Ephedra*, *Artemisia*, Compositae, Poaceae, and Amaranthaceae-Chenopodiaceae (Figs. 3, 4.B) occurred on a vast, more or less arid coastal plain. These coastal environments, dominated by herbaceous plants and marked by the presence of subdesertic elements, are found in the north and south of the Alboran Sea (FEDDI *et al.*, 2011), at Habibas-1 in Algeria, and at Oued et Tellil in Tunisia (SUC *et al.*, 1995). At the same time, in Morocco, the Zanclean of the Boudinar Basin (work in progress) and the Alboran Sea (BERRY *et al.*, 2025) is characterized by an impoverished mangrove composed of *Avicennia* and halophytes. This open vegetation is followed by an arboreal group consisting of elements whose representatives are currently Mediterranean (*Olea*, *Quercus ilex-coccifera* type, *Phillyrea*). Trees and shrubs belonging to the Arecaceae, Sapotaceae, Sapindaceae, Euphorbiaceae, Rubiaceae, and Taxodiaceae may have developed in some moister areas. Above, this Mediterranean group had to extend to deciduous (*Quercus*, *Ulmus*, *Engelhardia*, *Acer*, *Salix*, *Populus*, Ericaceae, *Betula*, *Carpinus*, *Carya*) and evergreen elements (Abietaceae, *Cathaya*, Cupressaceae, Sapotaceae, *Engelhardia*, *Carya*, Arecaceae, etc.) (Figs. 3, 4.B). These plant associations are similar to those encountered at



Oued et Tellil in Tunisia and at Habibas-1 in Algeria (SUC *et al.*, 1995), and at Nador-1 in Morocco (FAUQUETTE *et al.*, 1999; FEDDI *et al.*, 2011). North of the Alboran Sea, in Andalucía G1 and at the IODP-401 site, the tree assemblage is more developed due to the proximity of topographic reliefs to the pollen deposition point (FEDDI *et al.*, 2011; BERRY *et al.*, 2025). During the Zanclean, the northwestern Mediterranean region was dominated by forests of Taxodiaceae (mainly *Sequoia*), *Cathaya*, and various angiosperms (*Engelhardia*, deciduous *Quercus*, *Ulmus*). At higher elevations, conifers (*Abies*, *Tsuga*, *Picea*) predominated (FEDDI *et al.*, 2011). This vegetation change from the northern to the southern Mediterranean reflects latitudinal gradients in terms of precipitation and temperature, with more pronounced rainfall and similar temperatures comparable to the present-day (FAUQUETTE *et al.*, 2007; FEDDI *et al.*, 2011). Contrasting with this pattern, climate reconstructions (using the climatic amplitude method by FAUQUETTE *et al.*, 1998a, 1998b) indicate that the southwestern Mediterranean region experienced a warmer and drier climate than today (FEDDI *et al.*, 2011; SUC *et al.*, 2018b).

- During the Piacenzian (1420-960 m depth), plant environments changed very little. Pollen from herbaceous plants remained abundant, but the open vegetation was characterized by a decrease in *Lygeum* and Poaceae, an increase in Compositae (Asteraceae), and the initial development of steppes dominated by *Artemisia* and *Ephedra* (Figs. 3, 4.B). The gradual increase in *Pinus* pollen frequencies (Fig. 4.A) reflects the sea-level rise during the earliest Zanclean transgression, as evidenced by the increase in distal dinocyst frequencies (BENZAKOUR, 1992). The Zanclean plant environment of the Gulf of Hammamet is similar to that testified by the southern Alboran Sea (Nador). In contrast, in the north, in Andalucía, tree formations are more developed, and high-altitude trees such as *Cedrus*, *Tsuga*, and *Cathaya* are present alongside Mediterranean xerophytes (FEDDI *et al.*, 2011). This shift in vegetation can be explained by the presence of a cooler and more humid climate, which favored forest development. In contrast, in the northern Mediterranean regions, forests were gradually substituted by open lowland environments and coniferous forests at high and mid-altitudes (ZHENG & CRAVATTE, 1986; ZHENG, 1990; SUC *et al.*, 1992; FEDDI *et al.*, 2011). Swamp forests of *Sequoia* and Taxodiaceae disappeared, being replaced by less thermophilous conifers such as *Tsuga*, *Cedrus*, *Abies*, and *Picea* (BERTINI, 1994, 2001). This change, which is observed at both the European and Mediterranean scales, resulted from cooling, particularly in terms of winter temperatures, leading to a more pronounced seasonal contrast (FEDDI *et al.*, 2011). Compared to the

previous period, in regions adjacent to the study area, whether Andalucía or Morocco, climatic estimates based on pollen data show no variation in precipitation, preventing forest establishment at low altitudes. However, annual temperatures experienced marked oscillations, occasionally reaching levels comparable to those of today (FEDDI *et al.*, 2011).

- During the Gelasian (960-500 m depth), steppes dominated by *Artemisia* and *Ephedra* continued to expand noticeably. *Lygeum* declined, and Poaceae decreased progressively while Compositae (Asteraceae) increased. Pinaceae became increasingly abundant, indicating a sea-level rise (Figs. 3 - 4). Among trees, mega-mesotherm species (Taxodiaceae, *Engelhardia*) and Mediterranean xerophytes declined compared to the Zanclean and Piacenzian, and *Sciadopitys* disappeared. High-altitude tree formations became more diverse, with *Betula*, *Abies*, and *Picea* appearing alongside *Tsuga* and *Cedrus*, which were already present during the Piacenzian and reappeared in the Gelasian in the Gulf of Hammamet (Figs. 3, 4.B). Notably, *Cedrus* first appeared in North Africa at the end of the Messinian (~5.6 Ma), likely facilitated by the desiccation of the Mediterranean, which allowed its migration from Sardinia, Calabria, or Sicily, or from relict populations in the Rif. Its expansion was further favored by the uplift of the Rif and Atlas Mountains, which protected the local *Cedrus* communities from the European glaciations (SUC *et al.*, 2018b). These changes, and particularly the expansion of the steppes, are observed both in northern Morocco and southern Spain and can be explained by the presence of a colder climate.

5.2. Climate and climatostratigraphic correlation

5.2.1. Climate

Pollen analysis allows for a refined reconstitution of climate evolution. The major climatic phases described by ZAGWIJN (1960) in the Netherlands, SUC (1984) in the northwestern Mediterranean, DINIZ (1984) in Portugal, and POPESCU *et al.* (2010) in the Black Sea and Poland have been correlated over long distances (SUC & ZAGWIJN, 1983; SUC *et al.*, 1995, 2018a; POPESCU, 2001) (Fig. 7), and include:

1. From 5.333 to 3.600 Ma, a very warm period (Brunssumian A and C of ZAGWIJN, phases P Ia and Ic of SUC) interrupted by a slight cooling from 4.75 to 4.0 Ma (Brunssumian B of ZAGWIJN, phase P Ib of SUC).
2. From 3.600 to 2.58 Ma, a transitional period with moderate cooling, marked by significant climatic fluctuations (Reuverian of ZAGWIJN, phase P II of SUC).
3. From 2.58 to 1.80 Ma, the onset of glacial-interglacial cycles forced by obliquity (41 kyr), corresponding to the Praetiglian of ZAGWIJN and phase P III of SUC.

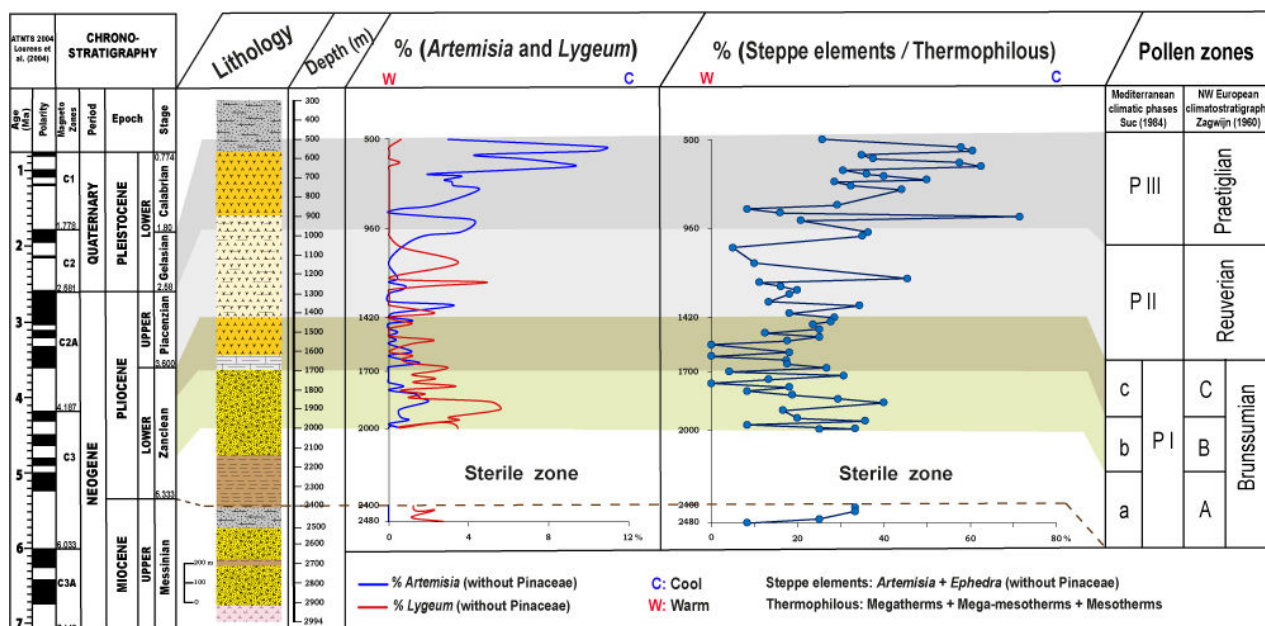


Figure 5: Climatostratigraphic division of the Jiriba-1 borehole based on the *Artemisia*, *Lygeum*, and steppe/thermophilous elements (S/T) curves, and their correlation with the climatostratigraphies developed in the Netherlands (ZAGWIJN, 1960) and in the northwestern Mediterranean region (SUC, 1984).

These major climatic phases correspond perfectly to the twofold division of the Pliocene and the Gelasian, respectively.

This pollen-based climatostratigraphic scale provides a benchmark for identifying the various climatic phases recorded in the Jiriba-1 borehole, corresponding to those defined by the same authors (Fig. 5).

The synthetic and detailed pollen diagrams from the Jiriba-1 borehole (Figs. 3 - 4) reflect a repetitive change between steppe elements (*Artemisia* and *Ephedra*) and thermophiles (comprising megatherms, mega-mesotherms, and mesotherms), with no abrupt variation that facilitates the identification of major climatic phases. Consequently, it was difficult to define the exact position of any division.

It is established that *Artemisia* is a good indicator of cold steppes in the western Mediterranean (SUBALLYOVA, 1997) and central continental environments (NEBOUT & GRAZZINI, 1991).

However, *Lygeum* is a subdesertic element indicative of a hot, dry climate. The S/T ratio curve ("Steppe elements/Thermophilous elements") is a reliable indicator of climate change (SUC *et al.*, 2018b). Figure 5 shows that the *Lygeum* and *Artemisia* curves are in complete opposition, with maxima of *Lygeum* coinciding with minima of *Artemisia*. Furthermore, from the base to the top of the borehole, *Lygeum* and *Artemisia* show a progressive decrease and increase, respectively. These opposing curves of *Artemisia* and *Lygeum* also correlate perfectly with the S/T ratio curve.

Thus, we used these three indicators (*Artemisia*, *Lygeum*, and S/T) to distinguish between warm and cold conditions (Fig. 5).

Analysis of these three curves reveals perfect correspondence with the climatic phases defined by SUC and ZAGWIJN (1983), SUC *et al.* (1995), POPESCU (2001), and SUC *et al.* (2018a) (Fig. 5).

Based on the comparison of the *Lygeum*, *Artemisia*, and S/T ratio curves, the following climatic phases have been identified:

- **The uppermost Messinian, from 5.5 Ma to 5.333 Ma (2480 m to 2400 m)**

This period partly coincides with the second (central and paroxysmal) stage of the Messinian Salinity Crisis, ranging from 5.60 to 5.46 Ma (BACHE *et al.*, 2012; POPESCU *et al.*, 2021; SUC *et al.*, 2023; DIK *et al.*, 2023).

The latest Messinian corresponds to the absence of *Artemisia*. Mean frequencies of *Lygeum*, mega-mesotherms, and mesotherms (Figs. 3, 5) are consistent with a warm and dry climate, similar to that recorded during the Messinian in Morocco (BACHIRI TAOUFIQ, 2000; BACHIRI TAOUFIQ *et al.*, 2008; ACHALHI *et al.*, 2016; TARGHI *et al.*, 2021), Algeria (CHIKHI, 1992a, 1992b), and southwestern Spain (JIMÉNEZ-MORENO *et al.*, 2013), which overall indicates that the southern Mediterranean region experienced xeric conditions climatically predisposed to desiccation (SUC *et al.*, 2023). This evidence suggests that global sea-level changes (global glacio-eustatism) contributed, at least in part, the onset and completion of the Messinian Salinity Crisis in the Mediterranean (SUC *et al.*, 2023).

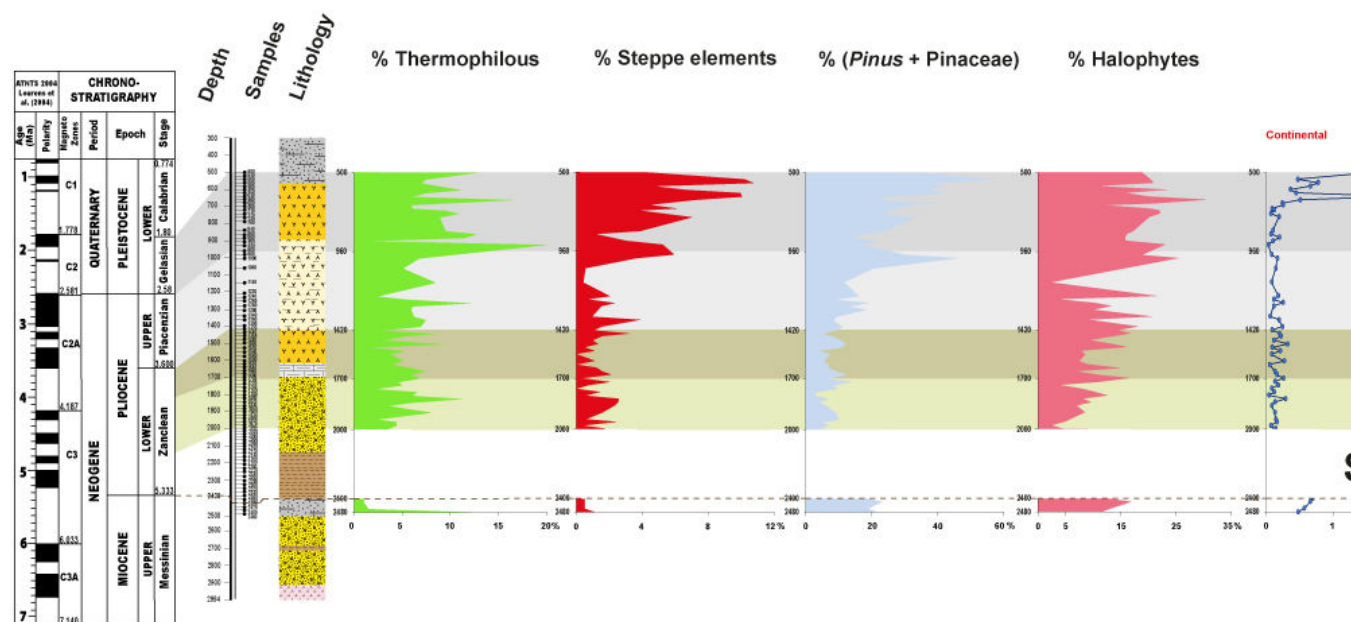


Figure 6: Quantitative results of paleoclimatic parameters from the Jiriba-1 borehole in the Upper Miocene and Lower Pleistocene with the pollen zonation proposed by SUC and ZAGWIJN (1983) and their correlation with the reference oxygen isotope curve of the ODP 846 site (SHACKLETON *et al.*, 1995b, in SUC *et al.*, 2018b). Pollen groups: 1. Thermophilous: Megathermic elements (Euphorbiaceae, Rubiaceae) + Mega-Mesothermic elements (Taxodiaceae, Cupressaceae, Ericaceae, *Myrica*, Arecaceae, Sapotaceae, Hamamelidaceae, etc.) + Mesothermic elements (*Quercus* (deciduous), *Carya*, *Juglans*, *Buxus sempervirens* type, *Ulmus-Zelkova*, *Corylus*, *Populus*, etc.); 2. Steppe elements (*Artemisia*, *Ephedra*); 3. Halophytes (Amaranthaceae Chenopodiaceae, Caryophyllaceae, Plumbaginaceae).

- **The Lower Pliocene (Zanclean), from 5.333 Ma to 3.600 Ma (2400 m to 1420 m): P I zone**

Sub-zone P I b: from 4.75 Ma to 4.0 Ma (2000 m to 1700 m)

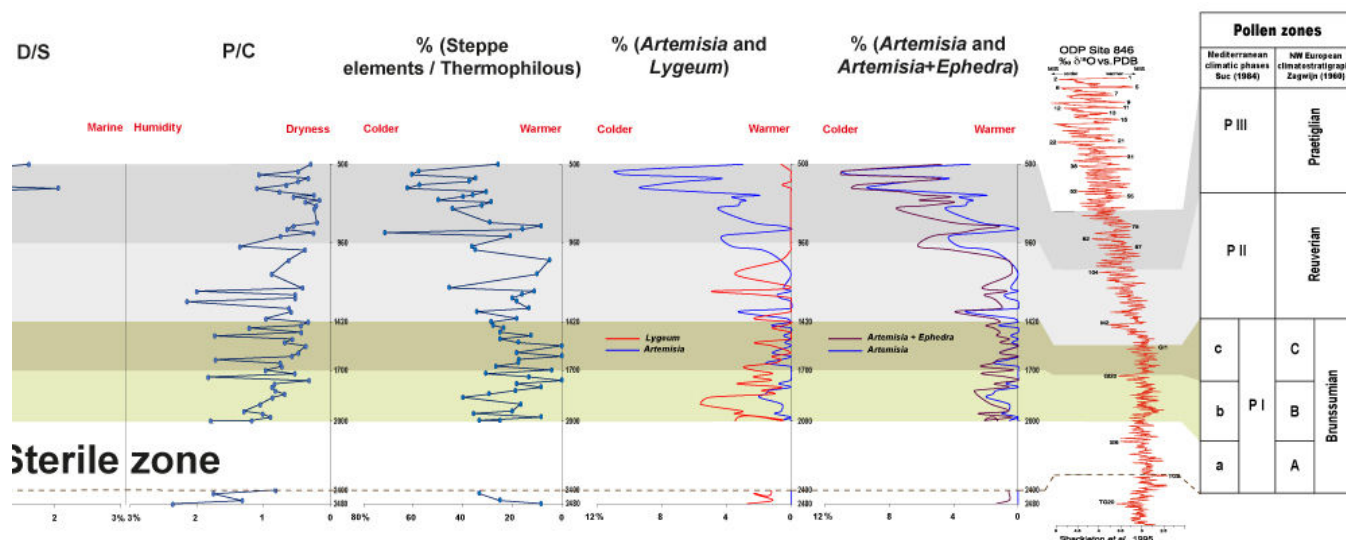
Around 4.5 Ma, in the northwestern Mediterranean region of the Iberian Peninsula (Garraf-1 area, Catalonia, northeastern Spain, and Andalucía G1, offshore southeastern Spain), a cooling is indicated by the pollen data, being marked by a decrease in thermophilic trees and an increase in herbs (SUC *et al.*, 1995; JIMÉNEZ-MORENO *et al.*, 2010). This cooling is also recorded in the Dacian Basin (POPESCU, 2006; POPESCU *et al.*, 2006) and the Netherlands (ZAGWIJN, 1960; SUC & ZAGWIJN, 1983; SUC, 1984). Compared to the previous phase, this phase corresponds in the Jiriba-1 borehole to an increase in *Lygeum* frequency as well as to the appearance of the cold element *Artemisia*. The S/T curve confirms this result, indicating a trend towards climatic cooling. This variation coincides with SUC's pollen sub-zone P Ib (SUC & ZAGWIJN, 1983; SUC, 1984; SUC *et al.*, 1995) and ZAGWIJN's Brunssumian B (1960), characterized by a moderately cold climate (Fig. 5).

Sub-zone P I c: from 4.0 Ma to 3.600 Ma (1700 m to 1420 m)

This interval shows a decrease in the frequency of *Artemisia* and a slight decline in *Lygeum*, while the S/T ratio indicates warm conditions. It corresponds to the P Ic pollen sub-zone (SUC & ZAGWIJN, 1983; SUC, 1984; SUC *et al.*, 1995) and to the Brunssumian C of ZAGWIJN (1960), reflecting a warm climate (Fig. 5).

- **The Lower - Upper Pliocene boundary (Zanclean/Piacenzian) at 3.600 Ma (1420 m)**

The boundary between the Zanclean and Piacenzian lies directly above the Gilbert/Gauss magnetostratigraphic transition (BERGGREN *et al.*, 1985), which has recently been calibrated to 3.596 Ma (HILGEN *et al.*, 2009). Around 3.6 Ma, the Northern Hemisphere glaciation began to intensify, culminating with the first major glacial episode, M2, at 3.3 Ma (KARAS *et al.*, 2020). This cooling is also recorded in oceanic isotope curves that appear to be generalized (BLANC *et al.*, 1983; THUNELL & WILLIAMS, 1983; SHACKLETON *et al.*, 1995b; KARAS *et al.*, 2020), and may be attributed to the rapid expansion of the Antarctic ice cap and the development of glaciers in the Northern Hemisphere around 3.4 Ma, both contributing to the global temperature decline (BERGER & MOREL, 1992). The closure of the Panama Strait (5 Ma ago), the Betic (7.2 Ma) and Rifan corridors (7.1-6.9 Ma in its southern branch and 7.35-7.25 Ma in its northern branch), as well as the opening of the Bering Strait (at the Zanclean-Piacenzian boundary), triggered the North Atlantic thermohaline circulation, and probably also the intensification of Northern Hemisphere glaciation (HAUG & TIEDEMANN, 1998; BARTOLI *et al.*, 2005; BERG, 2016; CAPPELLA *et al.*, 2019). Around 3.65 Ma, the weakening of the Atlantic Meridional Overturning Circulation (AMOC), along with colder and cooler surface waters in the North Atlantic, enabled the extension of sea ice in the Arctic Ocean, which may have preconditioned the climate for the subsequent expansion of the continental ice sheet (KARAS *et al.*, 2020).



In the Nabeul-Hammamet region (northeastern Tunisia), DERBEL-DAMAK and ZAGHBIB-TURKI (2002) showed that the enrichment of cold-water foraminiferal species marks the Zanclean-Piacenzian boundary. A sharp increase at the 1360 m level in the *Artemisia* frequency (from 0 to 3.5%) and S/T ratio (from 3.57% to 30%) indicates the first cooling event at the beginning of the Upper Pliocene in the southwestern Mediterranean (Fig. 5). In the northwestern Mediterranean, the *Artemisia* steppes began to spread around 3 Ma, with a further significant expansion occurring around 2.6 Ma (SUC *et al.*, 2018b). At that time, tundra-type vegetation appeared in the Netherlands (SUC & ZAGWIJN, 1983). In Anatolia, between 5.8 and 5.6 Ma, a pronounced expansion of *Artemisia* and *Ephedra* steppes likely correlates with the Antarctic glaciation and, subsequently, with the desiccation of the Mediterranean Sea (SUC *et al.*, 2018b).

- **The Upper Pliocene (1420 m to 960 m) Zone P II : Piacenzian from 3.600 Ma to 2.58 Ma (1420 m to 960 m)**

According to DE SCHEPPER *et al.* (2009, 2013), the early Late Pliocene (3.600 to 3.0 Ma ago) was characterized by a warm global climate. However, a peak global glaciation during Marine Isotope Stage (MIS) M2 interrupted this warm phase around 3.30 Ma. Increased Pacific-to-Atlantic flow via the Central American Seaway, marked by a decline in *Operculodinium centrocarpum*, weakened the North Atlantic Current (NAC) between approximately 3.330 and 3.283 Ma, reducing the northward heat transport some 23-35 ka before MIS M2. The sea-level drop during this glaciation interrupted the Pacific inflow into the Atlantic, which restored the northward heat transport and ended the (MIS) M2 phase (DE SCHEPPER *et al.*, 2009, 2013).

On the other hand, according to SUC *et al.* (2018b), the period from 3.37 to 2.6 Ma can be considered as representing a transitional phase

corresponding to a Mediterranean-type seasonal rhythm characterized by summer droughts and cold winters. At 3.4 Ma, a temperature decrease corresponded to the cooling event that occurred in Europe (ZAGWIJN, 1960; SUC & CRAVATTE, 1982; SUC & ZAGWIJN, 1983; DINIZ, 1984; SUC, 1984; DRIVALIARI *et al.*, 1999; POPESCU, 2001) linked to an increase and more significant variations in the frequency of *Artemisia* (POPESCU, 2006; FEDDI *et al.*, 2011). At Jeriba-1, this zone includes several cycles and is characterized by an increase in *Lygeum* frequency and a decline in *Artemisia* frequency following its abrupt rise at 1360 m (Fig. 5). The percentage of *Artemisia* is lower than in P Ib but higher than in P Ic, while the S/T ratio shows a slight decrease compared to P Ib and an increase compared to P Ic. The climate during this phase may have been slightly warmer than in P Ib and cooler than in P Ic. This zone is consistent with pollen zone P II (Reuverian) (SUC & ZAGWIJN, 1983; SUC, 1984) (Fig. 5).

In BENZAKOUR'S (1992) study, on the same borehole, between 1420 and 960 m (in the detailed dinocyst diagram), a cooling of the sea-surface waters is also observed as an increase in the percentage of cold-water taxa (*Operculodinium centrocarpum*) and a decrease in warm-water taxa such as *Operculodinium israelianum*.

- **The Pliocene/Pleistocene (Piacenzian/Gelasian) boundary (2.58 Ma; 960 m)**

The boundary between the Piacenzian and Gelasian coincides with the Gauss/Matuyama magnetostratigraphic reversal at 2.6 Ma and also marks the onset of pronounced glacial-interglacial (G/I) fluctuations, expressed in the sawtooth pattern of the benthic $\delta^{18}\text{O}$ record. Such variations, which have been documented by numerous studies (e.g., SHACKLETON *et al.*, 1995a; LISIECKI & RAYMO, 2005, 2007; BERTINI *et al.*, 2025), represent one of the major features of the Pleistocene. At the onset of glacial/interglacial (G/I) cyclicity,

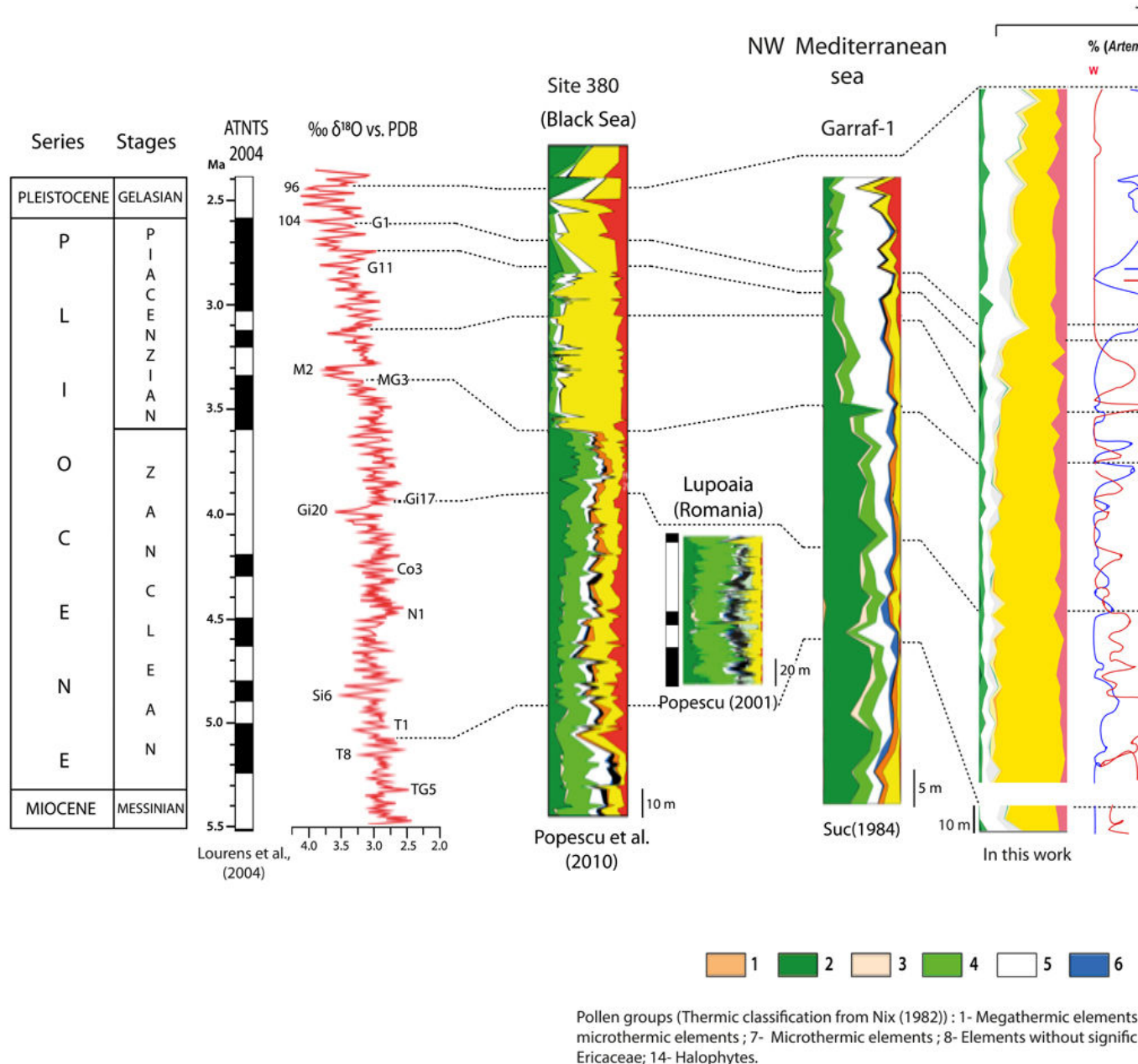


Figure 7: Pliocene and Lower Pleistocene climatostratigraphic correlations between the synthetic pollen diagram of Jiriba-1, Site 380, Lupoia, Garraf-1, Susteren 752.72, Rio Maior F16 and Wólka Ligezawska; the climatostratigraphic succession of northwestern Europe (Suc *et al.*, 2018a); and the reference oxygen isotope curve (SHACKLETON *et al.*, 1995b, in Suc *et al.*, 2018a).

around 2.6 Ma, open landscapes with abundant steppe taxa became more frequent and more widespread in the northern Mediterranean (JOANNIN, 2007; BERTINI, 2010, 2013; FEDDI *et al.*, 2011; COMBOURIEU-NEBOUT *et al.*, 2015). The Pliocene/Pleistocene (PII/PIII) boundary in Figure 5 is marked by a drop in *Lygeum* frequency to 0% and a rise in *Artemisia* from 0% to 4.28%. At the same time, the S/T curve increases from 5% to 37%.

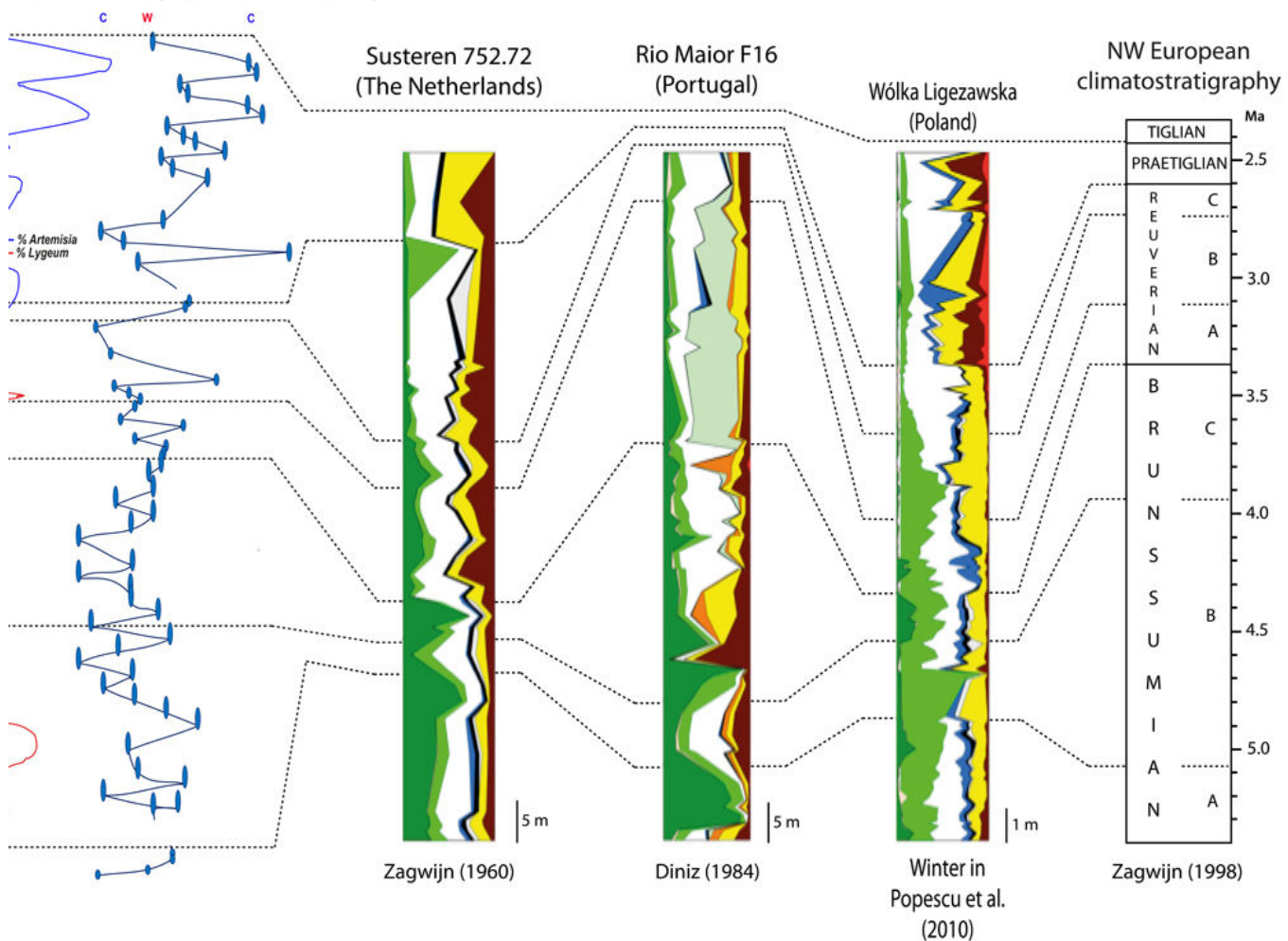
• **The Pleistocene (960 m to 500 m)**
Zone P III: Gelasian, from 2.58 Ma to 1.80 Ma (960 m to 500 m)

The pollen zone P III (Praetiglian) (SUC & ZAGWIJN, 1983; SUC, 1984) features a significant pulse of *Artemisia* in the northern Mediterranean - one that is associated with the onset of glacial-interglacial cycles after 2.6 Ma (POPESCU, 2006; FEDDI *et al.*, 2011; BERTINI, 2013).

Mediterranean
sea

Jiriba-1

Artemisia and Lygeum) % (Steppe elements / Thermophilous)



2- Mega-mesothermic elements; 3- *Cathaya*; 4- Mesothermic elements; 5- *Pinus*; 6- Meso-
 ation; 9- Cupressaceae; 10- Mediterranean xerophytes; 11- herbs; 12- Steppe elements; 13-

During the Gelasian, the D/S ratio reflects a dominance of marine over continental inputs (Fig. 6). This was explained by BENZAKOUR (1992) and LONDEIX *et al.* (1999) by evoking the successive and progressive appearance of boreal taxa (*Impagidinium pallidum*, *Bitectatodinium tepikiense*, and *Impagidinium pacificum*) that depict phases of cooling in surface waters and low relative sea levels (or possibly enhanced seasonality) associated with the first Northern Hemisphere glaciations between ~2.5 and 2.1 Ma (BENZAKOUR, 1992; LONDEIX *et al.*, 1999). This study further indicates that the interval from 960 m to 500 m is marked by a sharp rise in *Artemisia* frequency, reaching maximum values (11%) along this zone, reflecting an initial development of cold-climate steppe elements along with a marked decline in

Lygeum frequency, which drops to 0% (Fig. 5). Simultaneously, the S/T ratio also rises, reaching a peak of 60%, indicating a corresponding decrease in thermophiles as well as cold conditions. The *Artemisia* and *Lygeum* curve peaks appear to be globally homogeneous during the Brunssumian phase, becoming more pronounced during the Praetiglian (Fig. 5). This is in line with previous studies (POPESCU, 2006; POPESCU *et al.*, 2006), which highlight a more intense regional differentiation of vegetation during the Praetiglian compared to the Brunssumian.

It is also concluded that in the southwestern Mediterranean (and the whole Mediterranean region for that matter) the significant vegetation interruption observed at the base of the Praetiglian (MIS 104) was marked by the development of Ar-



temisia steppe, whereas in the Netherlands and Poland this disruption is characterized by a tundra-type environment and by Cupressaceae forest in Portugal (POPESCU *et al.*, 2006; SUC *et al.*, 2018b).

5.2.2. Climatostratigraphic correlation

The *Lygeum*, *Artemisia* and S/T ratio curves correspond perfectly with the climatic phases defined by SUC and ZAGWIJN (1983), SUC *et al.* (1995, 2018a), and POPESCU (2001). They allow for a refined climatostratigraphic succession of the Jiriba-1 borehole (SUC's pollen sub-zones P Ib = ZAGWIJN's Brunssumian B; P Ic = Brunssumian C; pollen zone P II = Reuverian; pollen zone P III = Praetiglian) (ZAGWIJN, 1960; SUC & ZAGWIJN, 1983; SUC, 1984; SUC *et al.*, 1995) (Fig. 5).

A correlation between these climatic phases identified here for the first time in the southwestern Mediterranean and those encountered in the northwestern Mediterranean, the Black Sea, and northwestern Europe (SUC & CRAVATTE, 1982; DINIZ, 1984; ZAGWIJN, 1998; POPESCU *et al.*, 2006) is proposed (Fig. 7). Overall, this climatic subdivision is also consistent with the reference $\delta^{18}\text{O}$ isotope curve (SHACKLETON *et al.*, 1995b).

Moreover, the major phases recorded by the isotope curve are reflected across all pollen diagrams, as illustrated in Figure 7.

5.3. Evolution of vegetation, climate, and sea-level variation in the Gulf of Hammamet from latest Messinian to Gelasian

5.3.1. Vegetation and climate change

Pollen diagrams from the Jiriba-1 borehole reveal a repetitive change in vegetation. Overall, the development of thermophilous elements (comprising megatherms, mega-mesotherms, mesotherms) appears to be related, on the one hand, to the decline of steppe elements (*Artemisia* and *Ephedra*) and halophytes, and on the other hand, to the increase in Pinaceae (Fig. 6). It can be safely assumed that annual precipitation was well below 500 mm. These estimates are consistent with the P/C ratio (Poaceae/Compositae), which is generally below 2. We conclude that, in most sediments from the Jiriba-1 borehole, Compositae dominate over Poaceae, indicating a trend towards drought in the lowlands (Fig. 6). We also conclude that climatic conditions were warm and humid at higher elevations. These conditions were subject to slight thermal variations marked by alternations between thermophilous and steppe elements (Fig. 6).

In addition to the P/C ratio, another indicator of this climatic evolution is provided by the *Artemisia*, *Lygeum*, *Artemisia* + *Ephedra* and S/T curves, which show an overall positive correlation with the $\delta^{18}\text{O}$ isotope curve (Fig. 6). The curve is considered the reference curve for global climate change, and oceanic isotope curves have long been correlated with cold/warm (glacial/interglacial) phases (SUBALLYOVA, 1997; JOANNIN, 2007; POPESCU *et al.*, 2010; SUC *et al.*, 2010, 2018b; OHNEISER *et al.*, 2015). The oxygen isotope ratio of

seawater increases during cold phases. This increase in isotopic composition from the Early Pliocene to the Early Pleistocene and the expansion of *Artemisia* steppes are attributed to global cooling and the development of the first Northern Hemisphere ice caps at 2.6 Ma. The onset of these glaciations led to widespread xericity and cold conditions with highly contrasting seasons, while interglacials were milder and moister (SVENNING, 2003; SUC *et al.*, 2004, 2018b). These climatic trends were repeated during secondary fluctuations (SUC, 1978; COMBOURIEU-NEBOUT *et al.*, 2000). During this time interval, the progressive aridification of the Mediterranean region also occurred (SUC, 1984; LEROY & DUPONT, 1994; FAUQUETTE *et al.*, 1998b; KHÉLIFI *et al.*, 2009; POPESCU *et al.*, 2010), with the establishment of the Mediterranean-type seasonal precipitation rhythm (summer drought) at 3.4 Ma (SUC, 1984; SUC & POPESCU, 2005; BARRÓN *et al.*, 2010; JIMÉNEZ-MORENO *et al.*, 2010). Simultaneously, the East African monsoon exerted a specific influence that preserved moisture in the northeastern Mediterranean region (SUC & POPESCU, 2005; POPESCU *et al.*, 2006; BILTEKIN *et al.*, 2015).

On the other hand, SUC (1984) and POPESCU *et al.* (2010) considered the 3.37-2.6 Ma time interval as a transitional phase characterized by the emergence of a Mediterranean-type seasonal rhythm with summer droughts and cooler winters.

5.3.2. Sea-level variation

The distality markers (dinocysts, D/S ratio, *Pinus* and indeterminable Pinaceae, and halophytes) indicate that the depositional environment was epicontinental and strongly influenced by continental inputs. The inverse evolution of these distality indicators depicts a transition from proximal to distal neritic settings (Fig. 6). These findings are fully consistent with those of earlier studies by BENZAKOUR (1992), LONDEIX *et al.* (1999), and FEDDI *et al.* (2011). According to these authors, the distality index reflects the alternation of proximal neritic and distal neritic environments, suggesting relative sea-level variations linked to eustatic fluctuations. They also noted that the distality index curve parallels the isotope curves from oceanic environments. Additionally, HILGEN *et al.* (2009) demonstrated that Pliocene marine sedimentation in the central Mediterranean (Sicily) was strongly controlled by the orbital parameter variability.

The influence of astronomical forcing could explain the aforementioned repetitive changes in vegetation in the Gulf of Hammamet. The decrease in thermophilous elements, dinocysts and *Pinus* + indeterminable Pinaceae, along with the increase in steppe elements and halophytes, can be attributed to the influence of a cold phase (Fig. 6). On one hand, this phase led to a relative drop in sea level that favored the colonization of the coastline by halophytes and steppe elements; on the other hand, it caused a decrease of thermophilous elements (including megatherms, mega-mesotherms, and mesotherms) (Fig. 6). Conversely, the warm phases caused the depositional



setting to shift offshore, the halophytes and steppe elements to decrease, and the thermophiles to proliferate (Fig. 6). It is worth recalling here that the Late Pliocene climate was characterized by cyclic variability, which led to these vegetation changes (dominated by herbaceous plants) (TZEDAKIS, 2007; POPESCU *et al.*, 2010; FEDDI *et al.*, 2011), mainly due to precession (KLOOSTERBOER-HOEVE *et al.*, 2006; TZEDAKIS, 2007; SÁNCHEZ GOÑI *et al.*, 2008), obliquity (JOANNIN *et al.*, 2007, 2008, 2011; POPESCU *et al.*, 2010; SUC *et al.*, 2010, 2018b), and eccentricity.

6. Conclusions

The palynological analysis conducted on the uppermost Messinian to Gelasian marine sediments of the Jiriba-1 borehole- dated by BENZAKOUR (1992) and LONDEIX *et al.* (1999) based on planktonic foraminifera, and calibrated here using the timescales of LOURENS *et al.* (2004), IACCARINO *et al.* (2007), and LIRER *et al.* (2019) - provided, for the first time, vegetation and climate information for the Gulf of Hammamet during this time interval.

Pollen analysis of the sedimentary formations from the Jiriba-1 borehole revealed a floral diversity that includes elements currently inhabiting the intertropical, subtropical, and warm-temperate regions of America and Asia, as well as elements currently living in the Euro-Mediterranean region. High percentages correspond to taxa representative of subdesertic environments and, more generally, xeric open plant formations.

The vegetation and climate reconstruction was based on the East China vegetation and climate model (WANG, 1961), whose ecological and climatic affinities closely resemble those of the Pliocene Gulf of Hammamet. Low-altitude regions were characterized by open subdesertic formations. At mid-altitude, mixed forest plant formations developed, while a tree grouping was established in-between, consisting of elements whose extant representatives display a Mediterranean distribution.

The evolutionary trajectories of the three curves of *Lygeum*, *Artemisia*, and the ratio of steppe elements to thermophilous elements (S/T) exhibit a strong concordance with the major climatic phases established by SUC and ZAGWIJN (1983), SUC *et al.* (1995), POPESCU (2001), and SUC *et al.* (2018a), thus enabling the identification of corresponding phases in the Gulf of Hammamet region, namely:

1. From 5.5 Ma to 5.333 Ma (uppermost Messinian; 2480 to 2400 m), the climate was hot and dry, and characterized by the absence of *Artemisia*. This corresponds to the paroxysmal phase of the Messinian Salinity Crisis and the onset of Mediterranean re-flooding.
2. From 4.75 Ma to 4.0 Ma (Zanclean; Brunsumian B of ZAGWIJN, P I b pollen sub-zone of SUC; 2000 to 1700 m), the climate was moderately cold, marked by an increase in

the frequency of *Artemisia* and *Lygeum*. Concurrently, the S/T curve indicates a trend towards cooler conditions.

3. From 4.0 Ma to 3.600 Ma (Zanclean; Brunsumian C of ZAGWIJN, P I c pollen sub-zone of SUC; 1700 to 1420 m), the climate was warm, as shown by the S/T ratio as well as by a decrease in *Artemisia* frequency.
4. At 3.600 Ma (Zanclean/Piacenzian boundary), the climate experienced its first significant cooling event, as indicated by a high frequency of *Artemisia* and increased S/T values.
5. From 3.600 Ma to 2.58 Ma (Piacenzian; Reuverian of ZAGWIJN, P II pollen zone of SUC; 1420 to 960 m), the climate was generally warm at the onset of the Late Pliocene (3.600 to 3.0 Ma), which was followed by a phase of maximum glaciation during the Marine Isotope Stage (MIS) M2 (between 3.330 and 3.283 Ma). This interval likely represents a transitional period with significant climatic fluctuations, with conditions slightly warmer than P Ib and cooler than P Ic.
6. At 2.58 Ma (Piacenzian/Gelasian boundary), the climate saw the beginning of glacial-interglacial cycles forced by obliquity, with *Artemisia* and the S/T ratio reaching high values, while *Lygeum* dropped remarkably.
7. From 2.58 Ma to 1,80 Ma (Gelasian; Praetiglian of ZAGWIJN, P III pollen zone of SUC; 960 m to 500 m), the climate was cold, which resulted in a major increase in *Artemisia* and the S/T ratio, with *Lygeum* reaching down to negligible levels.

This study further proposes a correlation between the climatic phases identified for the first time in the Gulf of Hammamet and the southwestern Mediterranean and those previously established by SUC *et al.* (2018a).

The climatic evolution indicated by the two curves of *Artemisia* and the steppe elements (*Artemisia* and *Ephedra*) from the Jiriba-1 borehole exhibits parallelisms with the $\delta^{18}\text{O}$ isotope curve.

The distality markers indicate, on the one hand, that the depositional environment of the Jiriba-1 borehole was epicontinental and influenced by significant fluvial inputs, and on the other hand, an alternation between proximal and distal neritic conditions.

The repetitive changes in plant composition between the steppe elements (*Artemisia* and *Ephedra*), thermophiles (megatherms, megamesotherms, and mesotherms), and halophytes in the Gulf of Hammamet could be explained by the impact of astronomical forcing.





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Plates

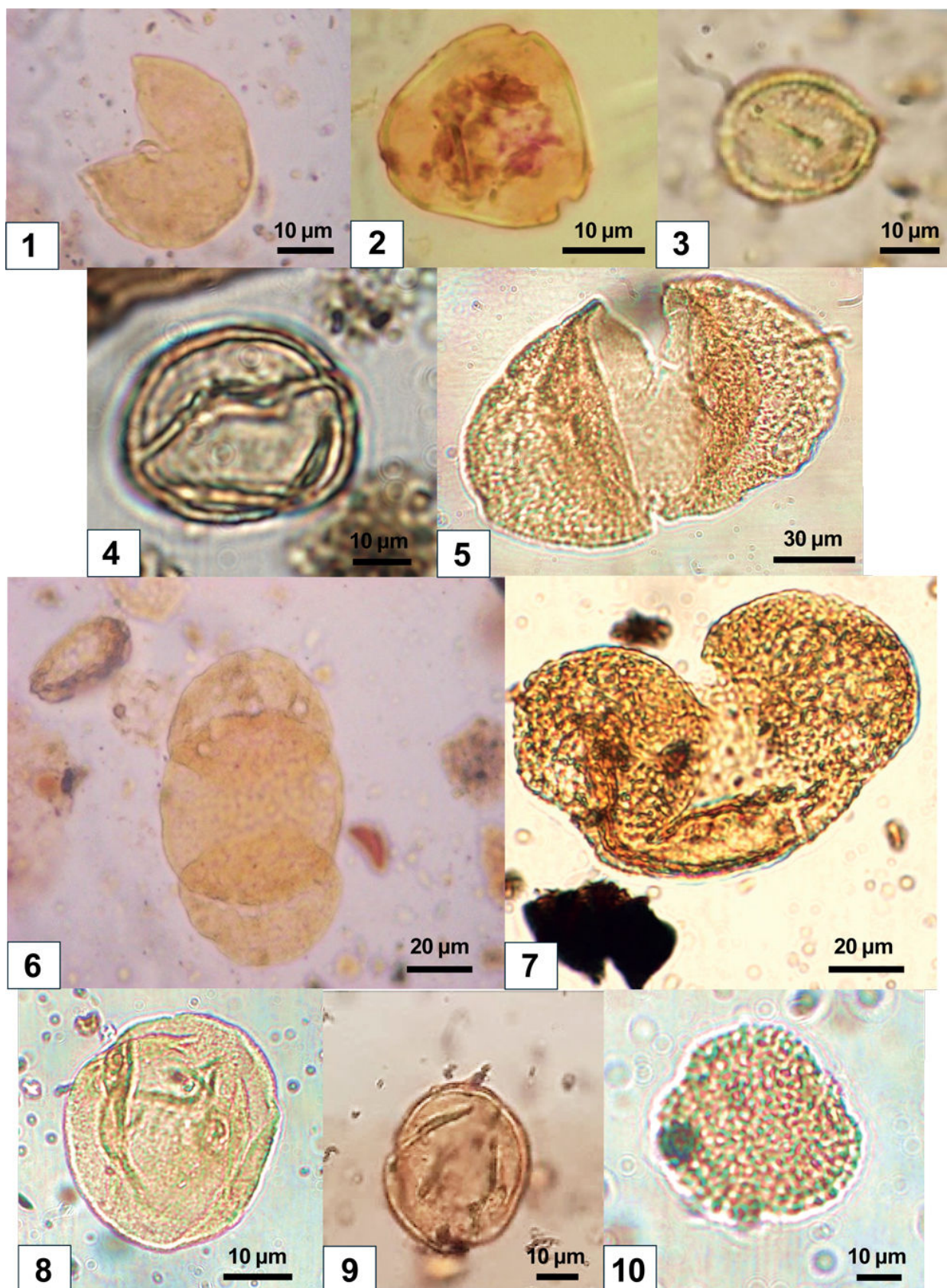


Plate 1: **1)** *Taxodium* (JR-1, 1140 m, Mega-mesotherm element); **2)** *Engelhardia* (JR-1, 2480 m, Mega-mesotherm element); **3)** *Buxus sempervirens* type (JR-1, 1400 m, Mesotherm element); **4)** *Quercus* (JR-1, 920 m, Mesotherm element); **5)** *Cathaya* (JR-1, 1140 m); **6-7)** Pinaceae (JR-1, 540 m); **8)** *Cistus* (JR-1, 620 m, Mediterranean xerophyte); **9)** *Quercus ilex-coccifera* type (JR-1, 1840 m, Mediterranean xerophyte); **10)** *Olea* (JR-1, 1860 m, Mediterranean xerophyte); (.../...)

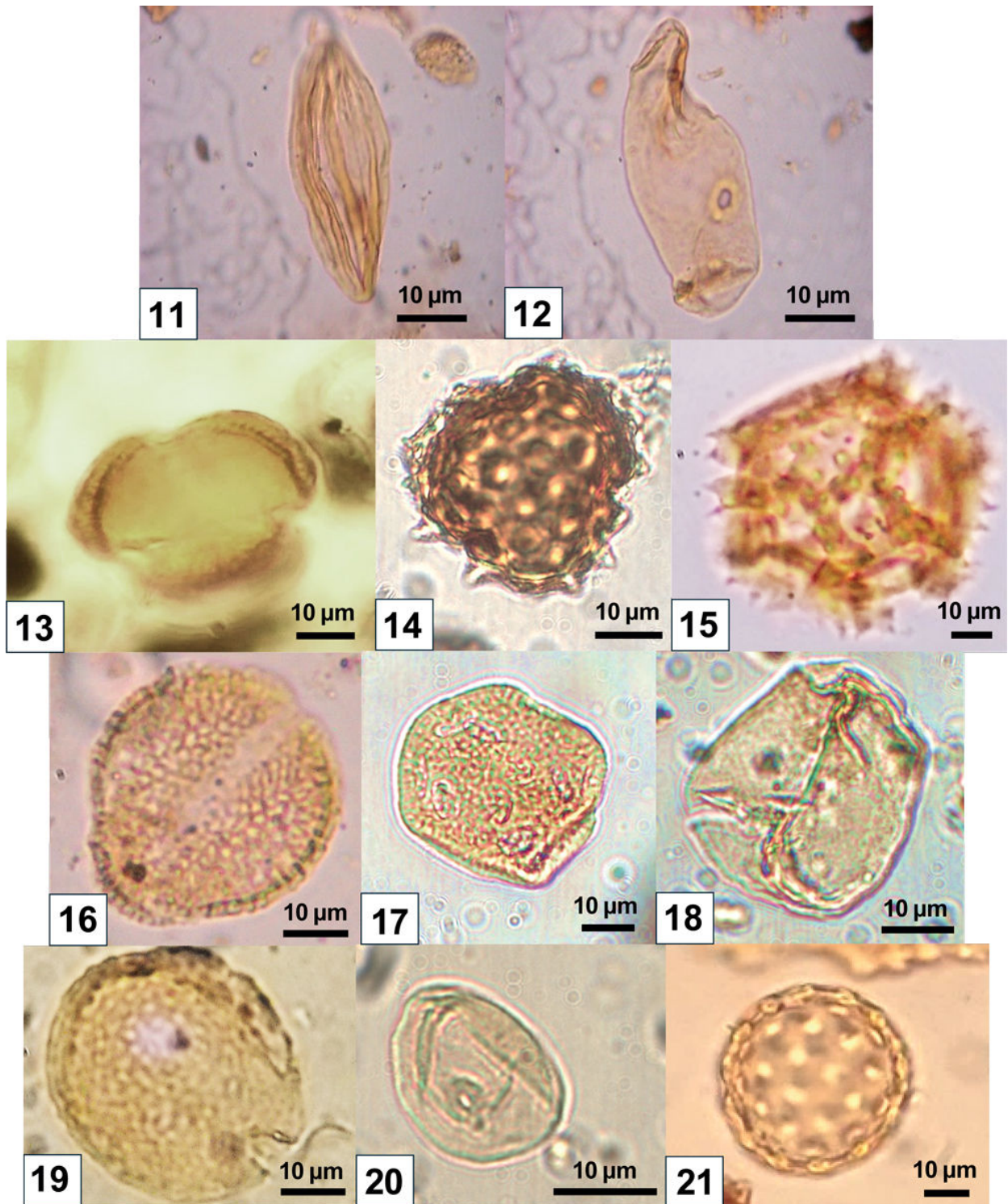


Plate 2: **11)** *Ephedra* (JR-1, 680 m, Subdesertic element); **12)** *Lygeum* (JR-1, 640 m, Subdesertic element); **13)** *Artemisia* (JR-1, 640 m, Subdesertic element); **14)** Compositae (Asteraceae) Asteroideae (JR-1, 1820 m, Herb); **15)** Compositae (Asteraceae) Cichorioideae (JR-1, 1760 m, Herb); **16)** Brassicaceae (JR-1, 710 m, Herb); **17)** Caryophyllaceae (JR-1, 1640 m, Herb); **18)** Cyperaceae (JR-1, 1975 m, Herb); **19)** *Plantago* (JR-1, 1240 m, Herb); **20)** Poaceae (JR-1, 1300 m, Herb); **21)** Amaranthaceae-Chenopodiaceae (JR-1, 660 m, Halophyte).

