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Climate and biomes in the West Mediterranean area during the Pliocene

Séverine Fauquette [a,*], Jean-Pierre Suc [b], Joël Guiot [a], Filomena Diniz [c], Najat Feddi [d], Zhuo Zheng [e], Ezzedine Bessais [f,1], Androniki Drivaliari [g]

[a] *Institut Méditerranéen d'Ecologie et de Paléoécologie, UPRESA CNRS 6116, Case 451, Faculté de Saint-Jérôme, 13397 Marseille cédex 20, France*
[b] *Centre de Paléontologie stratigraphique et Paléoécologie, UMR CNRS 5565, Université Claude Bernard Lyon I, 69622 Villeurbanne cédex, France*
[c] *Departamento de Geologia, Universidade de Lisboa, 1294 Lisbon codex, Portugal*
[d] *Département de Géologie, Faculté des Sciences 'Semlalia', Université de Cadi Ayyad, Boulevard Prince Moulay Abdellah, B.P. S 15, Marrakech, Morocco*
[e] *Faculty of Geology, Zhongshan University, 510275 Guangzhou, China*
[f] *Laboratoire de Palynologie, Institut des Sciences de l'Evolution, Université des Sciences et Techniques du Languedoc, 34000 Montpellier, France*
[g] *Centro de Geologia, 34 P. Karolidou, 54453 Thessaloniki, Greece*

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Abstract

A new pollen-derived method of climatic quantification, based on the mutual climatic range of plant taxa, has been applied to 17 Pliocene pollen sequences in the West Mediterranean area. The latitudinal gradient observed in the pollen data was confirmed by the climatic reconstructions: there is a gradient from north to south both for temperatures and precipitation. At the beginning of the Pliocene (5.32–5 Ma), the climate in the North Mediterranean area was, on average, warmer and more humid than today (respectively 1–4ºC and 400–700 mm). In the South Mediterranean region, the climate was both warmer and drier than today (respectively equal to or 5ºC higher and drier or equal humidity). The pollen-based climate estimates were then used to reconstruct biomes for the region. The results show the occurrence of three biomes: the broad-leaved evergreen/warm mixed forest, the xerophytic woods/scrub biome and the warm grass/shrub biome. These biomes are still represented today in the Mediterranean region despite different thermic and water conditions.

Keywords: climatic quantification; biomes; Pliocene; pollen data; West Mediterranean area

1. Introduction

The Pliocene period runs from 5.32 to 1.77 Ma. During this time interval, mid-latitude areas made the transition from relatively warm climates to the cooler climate of the Pleistocene. This transition, which also saw the emergence of early Man, contains the first glacial–interglacial cycles of the Northern Hemisphere (Leroy et al., 1998). In addition, the reconstruction of Pliocene climate is of prime importance, because the Pliocene is a period during which global average temperature was significantly

* Corresponding author. Tel.: +33-4-9128-8527; Fax: +33-4-9128-8668; E-mail: severine.fauquette@lbhp.u-3mrs.fr
[1] Deceased.

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higher than today, and may correspond to the future climate on Earth, resulting from the increasing greenhouse effects (Dowsett and Poore, 1991; Dowsett et al., 1992; Cronin and Dowsett, 1993). The Mediterranean region s.l. is the best disposed area for Pliocene climatic reconstructions (Suc et al., 1995b) because of: (1) its abundance in generally well chronologically calibrated sequences rich in pollen content; (2) the similarity of its paleogeographic features to those of the present-day, characterised by its longitudinal length and the presence of high mountains. These may provide an idea of the climate range through middle to high latitudes.

Since the seventies, Pliocene pollen records from the Mediterranean have been systematically studied using a modern botanical approach. This has allowed reliable vegetation reconstructions to be made (Suc, 1981; Cravatte and Suc, 1981; Suc and Cravatte, 1982; Diniz, 1984a,b; Zheng, 1990; Drivaliari, 1993; Bertini, 1994; Suc et al., 1992, 1995a,b). The lower Pliocene (Zanclean stage) is particularly rich in pollen data for the whole region.

In this paper we present the results of climatic quantification for 17 sites around the West Mediterranean area, firstly for the whole Pliocene, in order to observe temporal climatic variations, then for the period 5.32–5 Ma (the beginning of the Pliocene), to observe spatial climatic variations. From the second set of results, a biome reconstruction has been made for the same period. Finally, our results have been compared with the simulations obtained with the Goddard Institute Space Studies (GISS) general circulation model (Chandler et al., 1994).

2. Methodology

The climatic reconstruction of the Pliocene, based on pollen data, requires a new method of quantification. Methods based on associations of pollen-taxa (e.g. the best analogue method Guiot, 1990) cannot be used due to the presence within the fossil spectra of temperate, warm-temperate and subtropical plants that are no longer found in the Mediterranean region. So, a new climatic amplitude method, modified to take into account taxa abundances, was carried out by Fauquette et al. (1998a,b). This method is briefly described below.

The basis of the technique is the transposition of the climatic requirements of a maximum number of modern taxa to the fossil data. The first phase was to determine, from the literature, the present-day distribution of a few marker-taxa of the Mediterranean Pliocene. These were subtropical plants and some taxa that still exist in the Mediterranean region, which have well defined climatic ranges (Fauquette et al., 1998a).

The second phase was to define the climatic amplitudes of various pollen taxa on the basis of almost 8000 modern pollen spectra. These are surface samples or core-tops originating from Eurasia and North America, gathered by B. Huntley, P.J. Bartlein (pers. commun.) and Peyron et al. (1998). These samples cover a broad range of climate types, from boreal to warm-temperate climates.

In contrast with the best analogue method, this approach does not rely on the analysis of entire pollen assemblages, but on the relationship between the relative pollen abundance of each individual taxon and the climate.

The distribution of pollen percentages in relation to bioclimatic parameters has been analysed for some 60 taxa present in the modern spectra. Thresholds of presence/absence and of abundance were established. Above the presence/absence threshold the taxon is assumed to be present locally, and above the abundance threshold it is considered to have a substantial local presence. If the pollen percentage of a taxon exceeds one of these thresholds, the possible values for the corresponding climatic parameters may be restricted to a precise range. On the other hand, if this percentage is below the presence/absence threshold, the climatic range of the taxon is not taken into account, as the taxon is probably not locally present: pollen percentages below this level may reflect long-distance transport by wind or water.

So, in a given spectrum, each taxon exceeding the presence threshold provides a climatic range. This interval can be defined more accurately by comparison with the climatic ranges of other taxa exceeding their presence threshold. The most probable climate for a set of taxa exceeding their thresholds is therefore provided by the smallest climatic range suitable for a maximum number of taxa. The climatic estimate is given as a climatic range and a ‘most likely value’. This value is a mean, weighted to give importance to the subtropical taxa (Fauquette et al., 1998b).

The pollen of *Pinus* and non-identified Pinaceae (due to poor preservation) have been excluded from the pollen sum of the fossil spectra. The pollen grains of *Pinus* are over-represented in marine coastal sediments, due to its prolific production and overabundance in air and water transport (Suc and Drivaliari, 1991; Cambon et al., 1997). Their inclusion in the pollen sum limits the possible expression of the relative variations of the other taxa (Combourieu-Nebout, 1987). Tests made with and without *Pinus* in the pollen sum showed that its exclusion from the pollen sum does not alter the results of climatic estimates (Fauquette et al., 1998b).

As we wish to calculate climatic estimates for low and mid-low altitudes for each Pliocene site, the plants were separated into three groups: ubiquitous plants (U), plants growing in cold conditions (C) (at high altitudes and/or high latitudes) and plants growing in warm conditions (W) (at low altitudes and/or low latitudes) (Fauquette et al., 1998b). The climate at low and mid-low altitudes therefore corresponds to the interval defined by the taxa of group ‘W’. For the southern sites (North Africa, southern Spain, and Sicily), some taxa were re-indexed according to the north–south temperature increase. For example, *Cathaya* grew at middle altitude in the North Mediterranean area and Europe, but at higher altitudes in the South Mediterranean area. Therefore, in North Africa and southern Spain, it was assigned to the group ‘C’. The change in latitudinal level, then, is compensated by the change in altitudinal level (today, 1° in latitude corresponds to 110 m in altitude; Ozenda, 1989).

For the first part of this study concerning the evolution of the climate in each site through time, three climatic parameters have been estimated: mean annual temperature (T_A), mean annual precipitation (P_A) and available moisture, i.e. the ratio of actual evapotranspiration to potential evapotranspiration (E/PE). For the reconstruction of the climate at 5.32–5 Ma, two other parameters were included: the mean temperature of the coldest month (T_C) and of the warmest month (T_W). As biomes cannot be deduced directly from pollen data because of the lack of vegetation modern analogues, the two last climatic parameters together with the value of the ratio E/PE were used for the biome reconstruction.

3. Application to West Mediterranean pollen sequences

This method has already been applied to a Pliocene pollen sequence, Garraf 1 (Fauquette et al., 1998b). It appears to give reasonable climatic estimates when compared to the interpretation of numerous Pliocene pollen diagrams in the Mediterranean region and elsewhere in Europe (Zagwijn, 1960; Bertini, 1994; Suc et al., 1995a,b). Here, the technique has been applied to other sites in the Mediterranean region.

Based on qualitative and quantitative examination of the pollen diagrams, Suc et al. (1995b) have recognised four vegetational domains during the Pliocene: West Africa, West Europe, Southwest Mediterranean and Northwest Mediterranean.

In this paper, analysis was made on 17 sites (18 sites considering the site of Garraf 1 which has already been studied) (Fig. 1) from three of these vegetational domains.

(1) The Northwest Mediterranean domain: Saint-Martin du Var, La Combe and Saint-Isidore quarries, near Nice, France (Zheng and Cravatte, 1986; Zheng, 1990); Pichegu quarry in the Rhône Ria (Suc, 1981); Cap d’Agde 1 borehole (Suc, 1989) in Languedoc; Perpignan boreholes (Mutualité Agricole and Canet 1; Cravatte et al., 1984); and Vivès, Le Boulou, and Nidolères (Suc, 1976, 1989; Suc et al., 1995a) in Roussillon.

(2) The Southwest Mediterranean domain: Tarragona E2 borehole in Catalonia (Bessais and Cravatte, 1988); Andalucia G1 borehole in southern Spain (Suc et al., 1995b); Habibas 1 borehole (Suc, 1989) and Nador 1 borehole in Morocco (N. Feddi, in prep.); Oued et Tellil in Tunisia (Suc et al., 1995b); and finally Capo Rossello outcrop in Sicily (Suc and Bessais, 1990; Suc et al., 1995a).

(3) For comparisons, a site from the West European domain has been chosen: Rio Maior F16 borehole in southern Portugal (Diniz, 1984a,b).

Most of these sequences have been dated using foraminifera, and/or nannoplankton, magnetostratigraphy, mammal biochronology (Fig. 2). The base of the Pliocene is easily identifiable in all the Mediterranean marine sections. The Pliocene sequences follow the erosional phase corresponding to the deep Mediterranean salinity crisis (Clauzon et al., 1990),

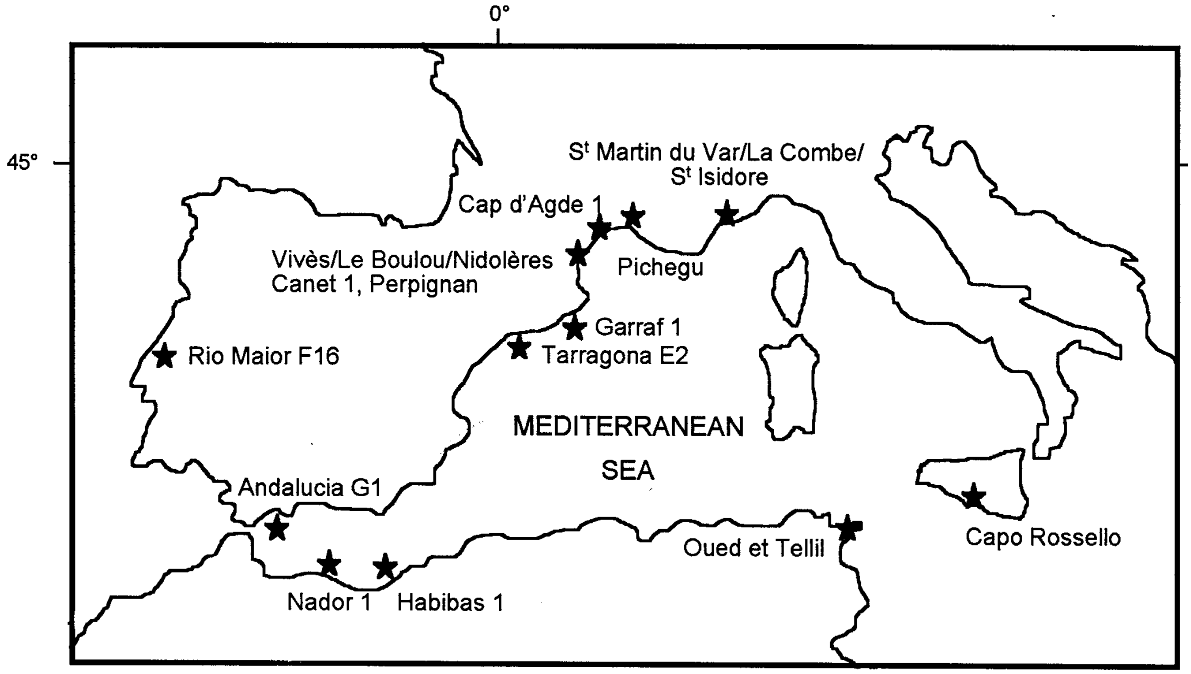

Fig. 1. Location map of the studied Pliocene sites around the West Mediterranean region.

so lower Pliocene sediments overlie the Messinian erosional surface. The sequence of Rio Maior is climatostratigraphically correlated to the synthetic pollen zones of Zagwijn (1960) and Suc (1982) and, therefore to the standard marine biostratigraphy via the Mediterranean pollen diagrams (Suc and Zagwijn, 1983).

Some of these sequences cover the earliest to the latest Pliocene: Rio Maior, Andalucia, Tarragona, Nador and Garraf. The others cover shorter periods, mainly to the lower Pliocene (Fig. 2).

The sediments of the sequences used in this study are derived from diverse sources, but none are deep marine sediments. Comparisons may be made between deltaic, continental or littoral sediments, if the differences in pollen transport are taken into account. For example, fluvial transport is the dominant pollen source for deltaic or marine littoral sediments, as seen in the Rhône River in France (Cambon et al., 1997) or as in California (Heusser, 1988). However, the climatic reconstruction method has been tested on several types of pollen spectra (Fauquette et al., 1998b): modern surface pollen spectra (mosses or core-top) and also on sub-modern coastal marine spectra (KTR05 core from the Rhône River, France; Cambon et al., 1997). The results obtained are consistent and allow us to apply the method to the diverse Pliocene sites.

4. Pliocene climate in the West Mediterranean area

4.1. Climatic evolution during the Pliocene

4.1.1. Alpes-Maritimes (southern France)

This region is represented by three discontinuous sequences (Saint-Martin du Var, La Combe and Saint-Isidore). These records have allowed the reconstruction of climate from the beginning of the Zanclean to the first part of the Piacenzian (Fig. 3).

Within each pollen sequence, some slight oscillations are recorded for both the annual temperature and the annual precipitation. The ratio E/PE, however, is stable along the sequences. For this region, the climatic estimates indicate that annual temperatures and annual precipitation were higher, approximately 1.5–5°C and 500–900 mm higher than today,

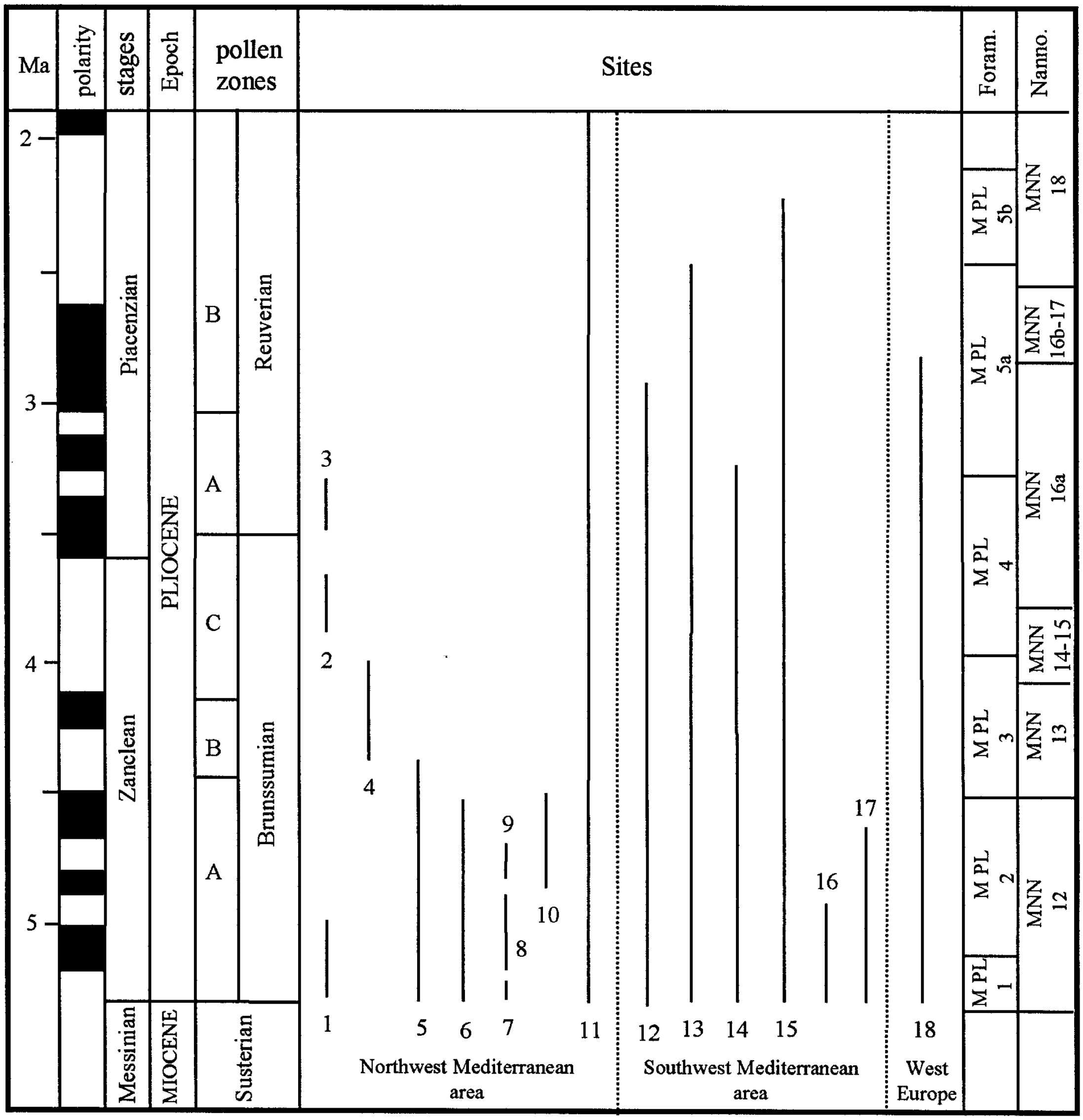

Fig. 2. Chronostratigraphic position of the 18 sites studied. *1* = Saint-Martin du Var; *2* = La Combe; *3* = Saint-Isidore; *4* = Pichegu; *5* = Cap d'Agde 1; *6* = Canet 1; *7* = Vivès; *8* = Le Boulou; *9* = Nidolères; *10* = Perpignan (Mutualité Agricole F1); *11* = Garraf 1; *12* = Tarragona E2; *13* = Andalucia G1; *14* = Habibas 1; *15* = Nador 1; *16* = Oued et Tellil; *17* = Capo Rossello; *18* = Rio Maior F16. Pollen zones according to Zagwijn (1960) and Suc (1982). Foraminifer zones after Cita (1975), nannoplankton zones after Rio et al. (1990).

respectively. The ratio E/PE was also elevated, between 80 and 100% (70% today).

Subtropical trees (especially *Sequoia*-type) decrease from Saint-Martin du Var (earliest Zanclean) to Saint-Isidore (earliest Piacenzian). At Saint-Isidore, mesophilous and herbaceous taxa progressively replace Taxodiaceae (Zheng, 1990). The variations observed in the pollen spectra represent changes in vegetation. These changes may be attributed to the climatic change which took place at approximately 3.5 Ma (Zagwijn, 1960; Suc, 1982; Dowsett et al., 1992) and is recorded in some localities, in partic-

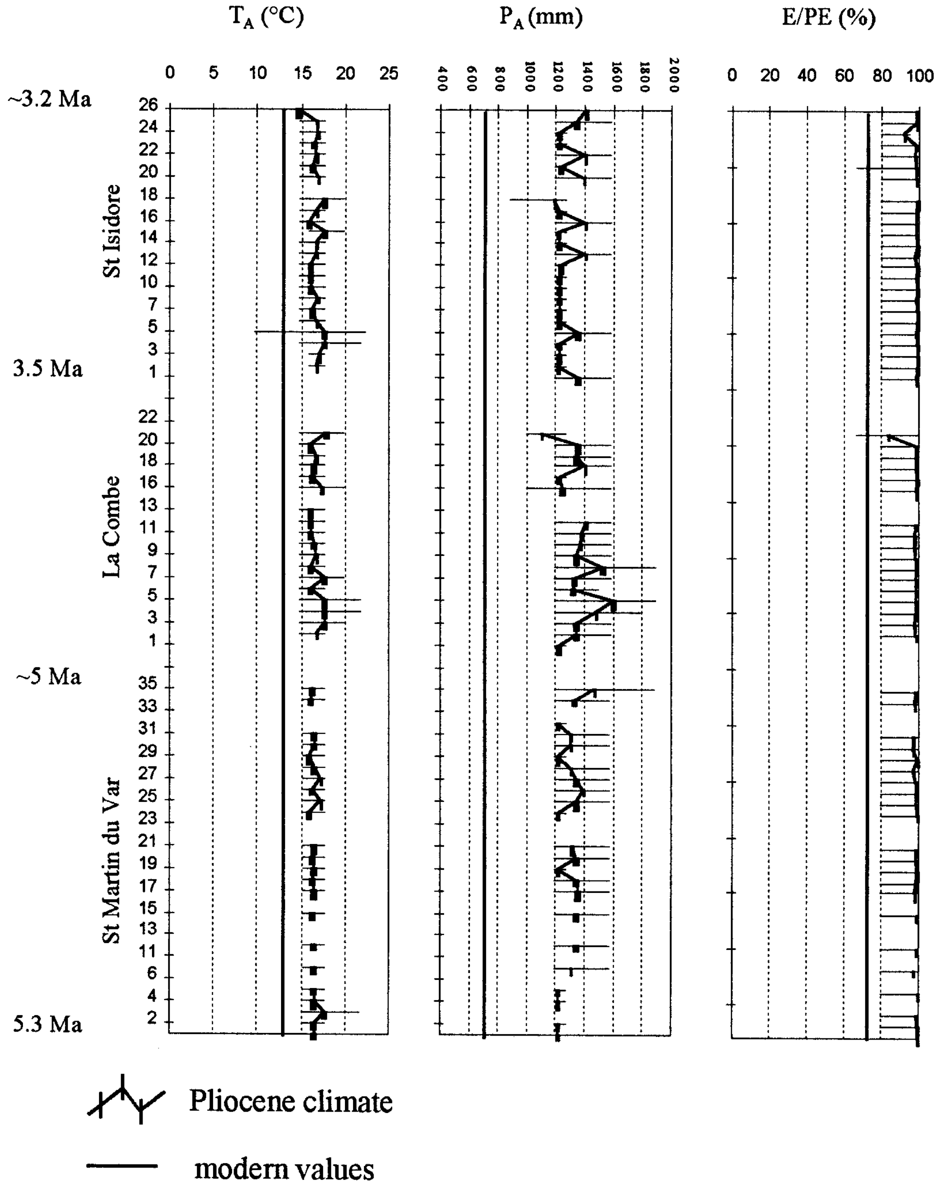

Fig. 3. Climatic evolution in the Alpes-Maritimes (France) during the early Zanclean (Saint-Martin du Var), the late Zanclean (La Combe) and the early Piacenzian (Saint-Isidore).

ular at Garraf 1 (Suc and Cravatte, 1982; Fauquette et al., 1998b) but not in the climatic estimations of Saint-Isidore.

This change may correspond to the appearance of a seasonal thermal regime in the West Mediterranean region, also characterised by a decrease in annual rainfall, more extreme in humid areas (Suc, 1989). In our climatic reconstructions, no decrease in temperatures (annual and also of the coldest month, not presented in this paper) were recorded at Saint-Martin du Var and Saint-Isidore, but a slight decrease in annual precipitation was detected at Saint-Isidore (around 1200 mm versus 1200 to 1600 mm at Saint-Martin du Var and La Combe). No change was observed in the ratio E/PE, the humidity was, therefore, still sufficient to ensure that the Taxodiaceae forest persisted, albeit with a slight decline.

4.1.2. Rhône (southern France)

The pollen sequence of Pichegu was taken from deltaic sediments sampled in an exposed section of the Rhône Ria (Suc, 1981). It covers a relatively short period, from about 4.3 to 4 Ma. This sequence is dominated by arboreal pollen grains, indicating a forest environment. Taxodiaceae are abundant, particularly in the lower part of the section. In the upper part, corresponding to the transition between the marine clays and the continental deposits, they suddenly decrease, with a corresponding increase in taxa such as *Olea*, *Phillyrea*, *Platanus*, *Vitis* and *Cistus*.

Many pollen spectra do not provide climatic estimates in this sequence (as few taxa exceed their threshold). As a result, the calculation was made based on a single spectrum summed from the whole sequence. Annual temperatures were between 15 and 17.7ºC (i.e. 1.6 to 4.2ºC higher than today), precipitation and E/PE were similar to those of Saint-Martin du Var (respectively 1200 to 1500 mm and 80 to 100%).

4.1.3. Languedoc (southern France)

This region is represented by the sequence Cap d'Agde 1 (Suc, 1989). Cap d'Agde is included in the same vegetational zone as the sites of Saint-Martin du Var and Pichegu, the Northwest Mediterranean area, but lies to the west. This sequence covers the period between 5.32 and about 4.3 Ma.

The climatic variations along this sequence are slight. Annual temperatures were 1 to 6ºC higher than today and precipitation 350 to 800 mm higher. So, during that period, there is a good correspondence between the climate of this region and of the Var region. Here the ratio E/PE is also high, coherent with the presence of a Taxodiaceae forest (mainly *Sequoia*-type; Suc et al., 1995b).

4.1.4. Roussillon (southern France)

For this region, just south of Languedoc, five relatively short records were available. The boreholes in Perpignan, Mutualité Agricole F1 (Cravatte et al., 1984) covering the period from about 4.8 to 4.5 Ma, and Canet 1 (Cravatte et al., 1984; Suc et al., 1995a) covering the period from about 5.32 to 4.5 Ma. The sites Vivès and Le Boulou (Suc, 1989; Suc et al., 1995a) together with Nidolères (Suc, 1976) cover the period from about 5.1 to 4.9 Ma.

All these sequences are dominated by arboreal taxa at the beginning of the Pliocene, particularly Pinaceae and Taxodiaceae. Taxodiaceae and other subtropical taxa such as *Engelhardia* and *Symplocos* are then progressively replaced in the pollen spectra by Mediterranean xerophilous taxa (*Olea*, *Phillyrea*, *Pistacia*, *Quercus ilex*-type), situated at a drier substratum, e.g. limestone.

Climatic variations are recorded along these sequences but generally, temperatures were equivalent to 6ºC higher than today and precipitation was 350 to 600 mm higher. The values of E/PE, between 70 and 100%, are coherent with the presence of a forest in the region.

4.1.5. Catalonia (northern Spain)

This region is split into the Northwest and the Southwest Mediterranean (Suc, 1989), each represented by one site: Garraf (Suc and Cravatte, 1982) in the Northwest Mediterranean zone and Tarragona in the Southwest Mediterranean (Suc et al., 1995b). At Garraf subtropical trees were dominant, among them *Taxodium distichum*-type indicating swamp conditions, *Engelhardia*, and *Symplocos*. The end of the pollen sequence is marked by the decrease of arboreal taxa to the advantage of herbaceous taxa (notably *Artemisia*, Asteraceae), indicating the beginning of the first glacial–interglacial cycles (Suc and Cravatte, 1982). Conversely, Tarragona is characterised by a predominance of herbs (mainly Asteraceae and Poaceae). Some herbaceous taxa such as *Lygeum*, *Nitraria* and *Calligonum* have been found, indicating very dry and hot conditions. Today these taxa are found in North Africa under subdesertic conditions (Fauquette et al., 1998a). There are decreased values of arboreal pollen grains compared to the Northwest Mediterranean zone, predominantly Taxodiaceae, *Engelhardia* and deciduous *Quercus*, as before. The Mediterranean xerophytes are regularly represented in this pollen diagram. In fact, the pollen assemblages resemble the modern thermo-Mediterranean formation (Bessais and Cravatte, 1988).

The climatic reconstruction made from the sequence of Tarragona, covering the period from 5.32

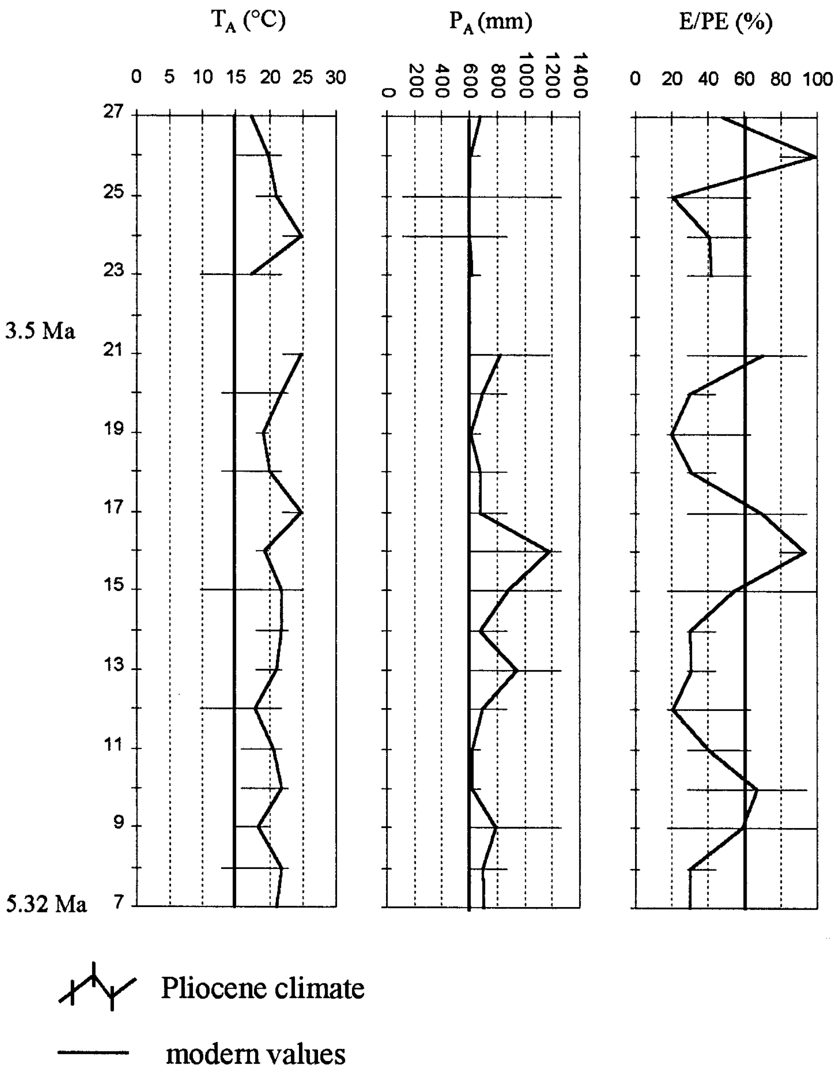

Fig. 4. Climatic evolution in Catalonia, at Tarragona during the Pliocene (between 5.32 and ~2.4 Ma).

to 3 Ma, shows temperatures between 1 and 10ºC higher than today and precipitation equal to or higher than today (as much as 600 mm more) (Fig. 4). At Tarragona, the mixture of taxa of different vegetation types, subtropical trees and subdesertic herbs gives important variations in the climatic estimations from one spectrum to the next, particularly for annual precipitation and E/PE. Even with these variations, the amount of precipitation and the ratio E/PE are lower than at sites in the northwestern domain (in particular Garraf 1; Fauquette et al., 1998b), indicating the transition to a different climate regime. The climatic estimations show an increasing latitudinal gradient both in temperature and dryness from north to south.

4.1.6. Andalucia G1 (southern Spain)

Situated further south, the composition of the pollen spectra at Andalucia is more or less similar to that of Tarragona, i.e. large quantities of herbs, including subdesertic herbs. Trees are well represented due to the presence of nearby relief.

Climatic fluctuations are recorded along the sequence of Andalucia (Fig. 5). The cooling event which occurred at around 4.5 Ma (Suc and Zagwijn,

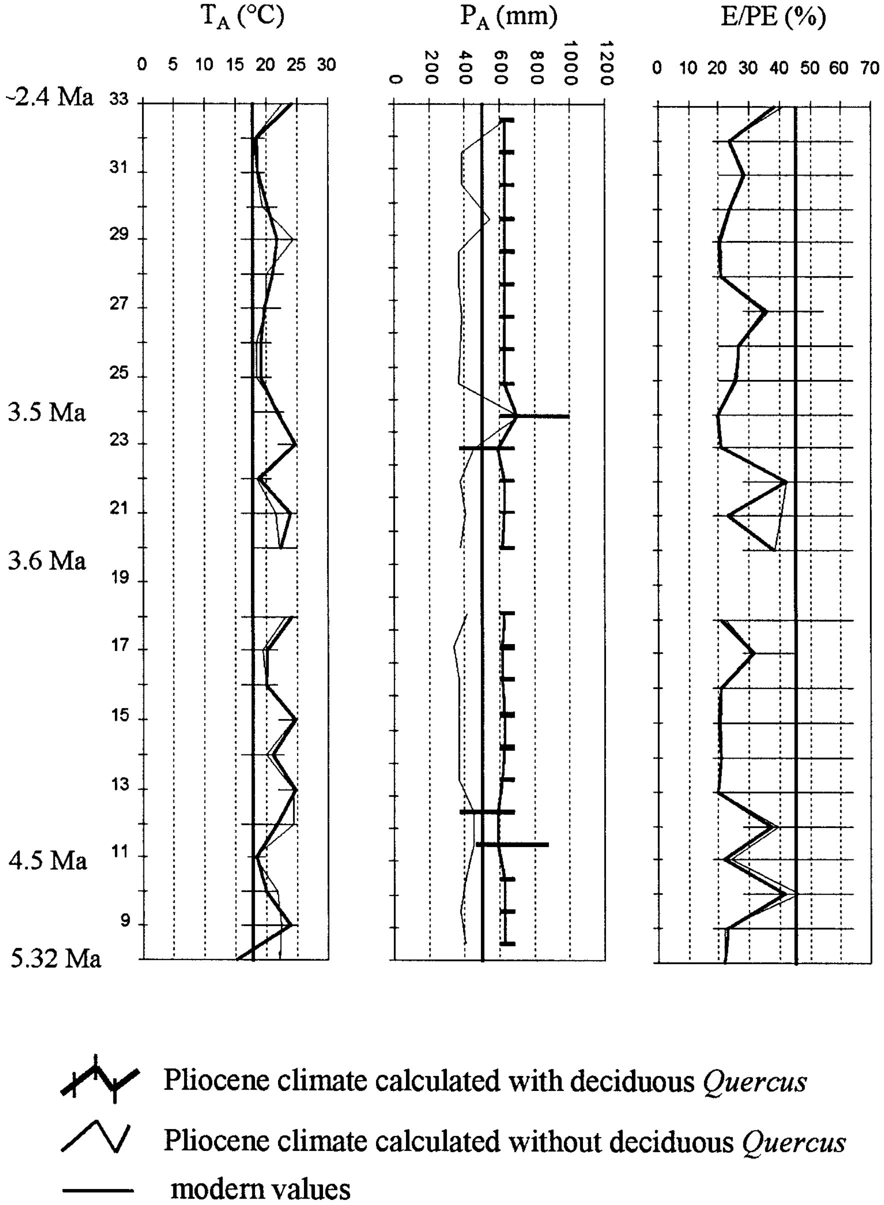

Fig. 5. Climatic evolution in Andalucia during the Pliocene (between 5.32 and ~2.4 Ma).

1983), and is recorded in the pollen data (Suc et al., 1995b), is evident in the mean annual temperature reconstruction (sample No. 11, where T_A is the same as today). Other less important oscillations follow this event and, finally, the decrease in temperature which occurs at samples Nos. 24 and 25 corresponds to the cooling that took place at 3.5 Ma (Zagwijn, 1960; Suc and Zagwijn, 1983; Suc, 1984). At Andalucia, annual temperatures were equivalent to 6ºC higher than today. Some oscillations are recorded for the mean value of E/PE, but in general the interval is relatively stable with low values. Few changes are recorded for P_A, which was around 100 to 300 mm higher. In fact, the precipitation should be lower and may have been as low as it is under modern conditions. The spectra contain pollen derived from higher elevations, in particular large amounts of *Quercus* (deciduous) pollen grains that grew at middle elevations. If deciduous *Quercus* is classified, for this site, in the 'C' group of taxa (high latitude/altitude taxa), the precipitation curve is shifted towards lower values (Fig. 5), which is more probable than the first calculated values. With this reclassification, no modifications are recorded for T_A and E/PE.

During the Pliocene, this region was characterised by a more or less similar vegetation type as today, i.e. an open subdesertic landscape (Suc et al., 1995b) but with more thermophilous taxa, found today in North Africa.

4.1.7. Nador 1

This site is situated at the North African seacoast, on the opposite coast of the Andalusian site. The sequence of Nador begins at 5.32 Ma and is correlated to the Andalusian sequence by the foraminiferal stratigraphy (J. Cravatte, pers. commun., 1998). The most important differences between these two diagrams are the higher frequencies of subdesertic elements, Cupressaceae and steppic elements at Nador than at Andalucia. Again, the pollen diagram indicates an open subdesertic landscape, with the presence of deciduous *Quercus* growing at higher altitudes. The climatic estimations have been calculated, as for Andalucia, with deciduous *Quercus* in the 'C' group of taxa (Fig. 6). Annual temperatures were equivalent to 6ºC higher than today and the annual precipitation was between the same as and 350 mm higher than today. The low values of the ratio E/PE confirm the hypothesis that a forest could not grow along the seacoast. A few minor climatic oscillations are recorded along the sequence but the first important one occurs just before 3.58 Ma (dated by biostratigraphy, J. Cravatte, pers. commun., 1998) and may correspond to the cooling taking place at 3.5 Ma (Suc et al., 1995b). According to the biostratigraphy, the first glacial–interglacial cycles begin before levels 18 and 19, perhaps at level 17 (Fig. 6) when the percentages of *Artemisia* increase.

4.1.8. Habibas 1

This site is situated in Algeria. Here again, herbaceous pollen were largely dominant, as it is today, notably Asteraceae, Poaceae and Amaranthaceae–Chenopodiaceae.

Climatic estimations have been calculated, as for Andalucia and Nador 1, with deciduous *Quercus* in the 'C' group of taxa. In our reconstruction, oscillations of annual temperatures are regularly recorded along the sequence, the significance of which is difficult to assess. In the upper part of the sequence, temperatures decrease toward the modern value (18.8ºC). This may be attributed to the cooling event taking place at 3.5 Ma, and this has been confirmed by the biostratigraphy (J. Cravatte, pers. commun., 1998). Elsewhere in the sequence, temperatures were 6ºC higher than today. Annual precipitation was very low and relatively stable along the sequence, at levels a little higher than today. The value of E/PE lies between 20 and 60%, with a most likely value oscillating between 25 and 45%, indicating very dry environments, where forest cannot develop, similar to today.

4.1.9. Oued et Tellil

This site in Tunisia is represented by a sequence covering a short period, from about 5.32 to 5 Ma (Suc et al., 1995b). The pollen data have been interpreted as a subdesertic landscape dominated by herbs such as Poaceae (including *Lygeum* which is represented by large amounts of pollen grains along the sequence), Amaranthaceae–Chenopodiaceae, Asteraceae, Plumbaginaceae and Geraniaceae, a typical association of very dry environments (Le Houérou, 1995). The two last spectra are marked by occurrences of Mediterranean non-subdesertic taxa, such as *Rhus*, *Vitis*, and *Olea*.

The climate appears stable along this sequence, but temperatures decrease at the end of the sequence when Mediterranean xerophytes appear. Annual temperatures were equal to or higher than today, from 19º to 25ºC (19ºC today), whereas annual precipitation and E/PE were lower than today (or equivalent), respectively between 300 and 450 mm (600 mm today) and between 20 and 60%.

4.1.10. Capo Rossello (Sicily)

The sequence of Capo Rossello covers a short period from 5.32 to 4.5 Ma and is represented by few pollen spectra. During this period, annual temperatures were similar to modern ones. The pollen spectra contain the same subdesertic plants as today, i.e. *Lygeum* and *Calligonum*; the fossil assemblages

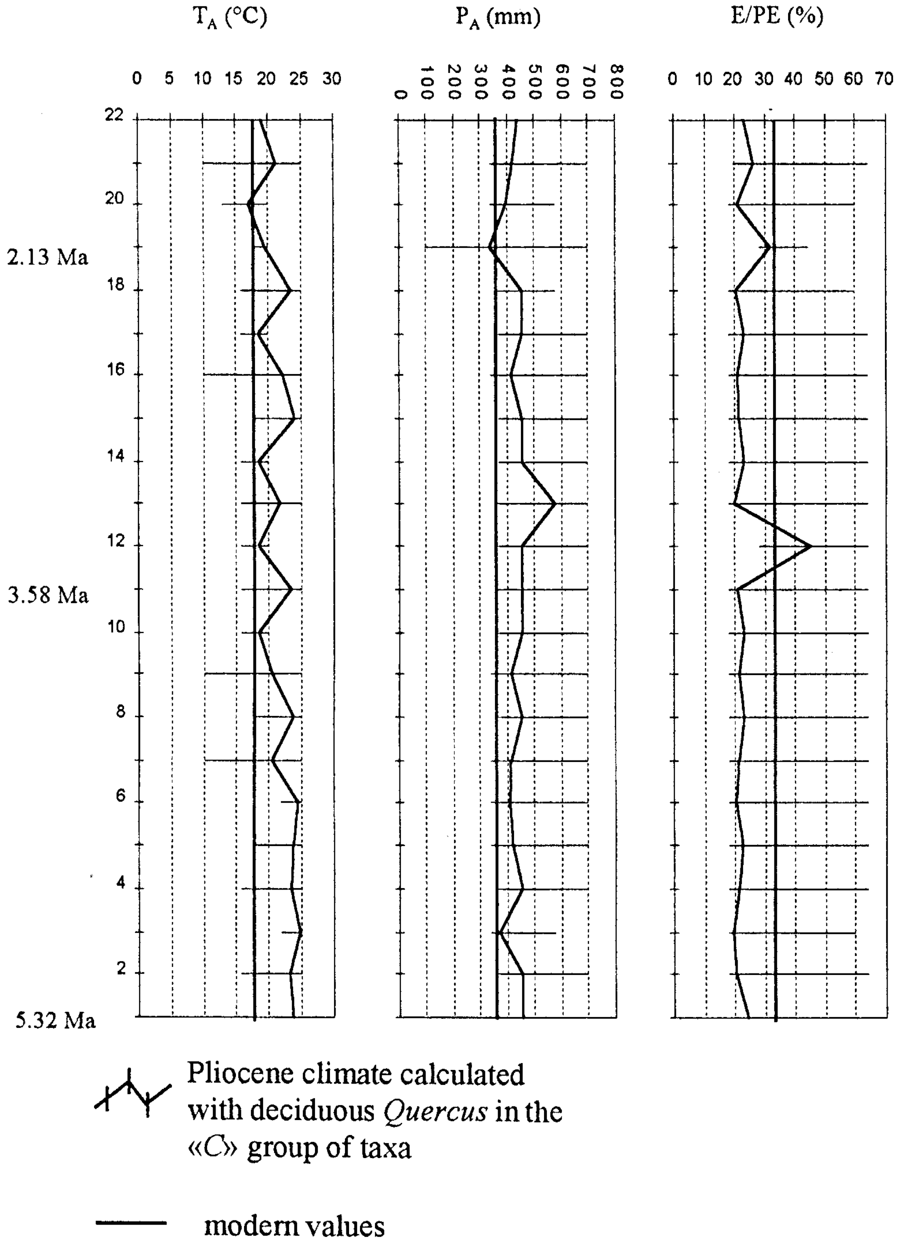

Fig. 6. Climatic evolution in North Africa, at Nador, between 5.32 and ~3.0 Ma, with deciduous *Quercus* in the 'C' group of taxa.

therefore appear to resemble the modern thermo-Mediterranean formation. Precipitation was slightly lower than today as was the E/PE ratio. One of the spectra contained occurrences of *Distylium*, *Engelhardia*, *Microtropis fallax*, *Parrotia persica* and *Ulmus*, indicating a less open environment at that time.

4.1.11. Rio Maior (Portugal)

This site is included in another, non-Mediterranean, vegetational domain: the West European zone. This zone differs from the other ones by the high representation of Ericaceae, which still characterises the Atlantic coast today (Oldfield, 1959). The pollen diagram of Rio Maior (Diniz, 1984a,b) shows the dominance of subtropical trees (*Cathaya*, *Engelhardia*, *Sequoia*, *Myrica*, *Taxodium* . . .). Mediterranean xerophytes such as *Olea*, *Phillyrea*, *Cistus*, Rhamnaceae and *Quercus ilex*-type were also well represented.

In this pollen diagram, montane elements such as *Abies*, *Tsuga*, *Sciadopitys* were weakly represented, thus indicating that relief was far away or else had no important influence.

The mixture of Mediterranean xerophytes and subtropical taxa shows a complex vegetation structure, which makes the reconstruction of climate difficult. Mediterranean xerophytes may have been either an integral part of the forest associations or already adapted to drier conditions, allowing colonisation of some areas, e.g. calcareous areas (Diniz, 1984a). This mixture of ecological types has resulted in the climatic variations seen in the reconstruction, particularly for annual precipitation and E/PE (Fig. 7). In

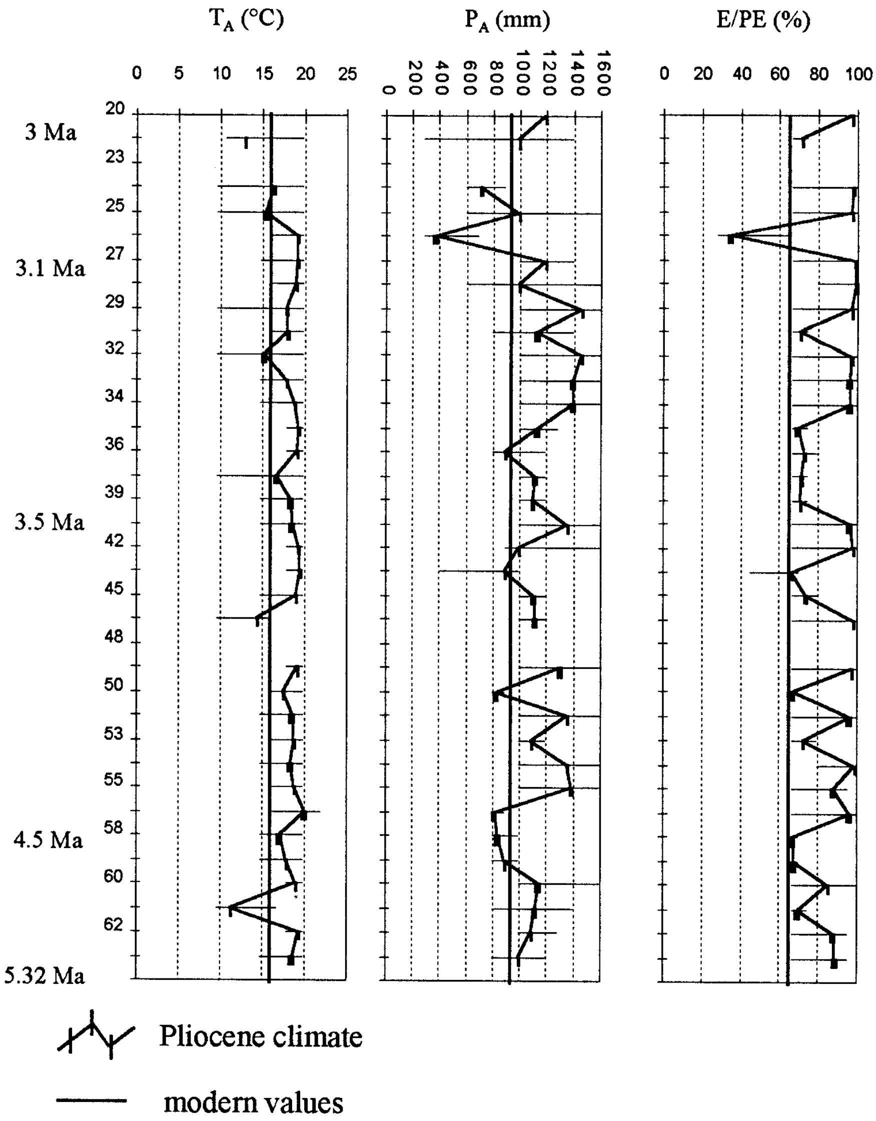

Fig. 7. Climatic evolution on the Atlantic coast, at Rio Maior, during the Pliocene.

general, annual temperatures and precipitation were equal or higher than today (respectively up to 4ºC and 400 mm more than today). However, precipitation may have been lower than today, during phases characterised by high frequencies of Mediterranean taxa.

Neither our climatic reconstructions nor the pollen data (Suc et al., 1995a) show important changes at the period corresponding to the emergence of the Isthmus of Panama (4.6 Ma; Haug and Tiedemann, 1997). These authors have suggested that the closure of the seaway between the North and the South American continents modified the global thermohaline circulation, intensifying the Gulf Stream and introducing warm and saline water masses to high northern latitudes. They think that this phenomenon could favour, in particular, Early Pliocene warming of the high latitudes of the Northern Hemisphere and the increased availability of moisture. Although triggered by incremental changes in insolation, the closure of the Panamanian seaway was the ultimate cause of the progressive Pliocene intensification of the Northern Hemisphere glaciation (Hay, 1996). This finalised the Cenozoic cooling trend by the build up of the northern ice sheet.

At the same time, at 4.5 Ma, in the Mediterranean Sea, the presence of the foraminifer *Globorotalia puncticula* (Zachariasse and Spaak, 1983) marks the appearance of cooler conditions. However, this cooling is not recorded in every pollen sequence and thus in the climatic reconstructions.

The changes in Atlantic Ocean thermohaline circulation inferred from the formation of the Isthmus of Panama appear to be progressive. The resulting glacial phases appear to occur progressively, and do not always cause large changes in the vegetation.

From our reconstructions, the climate appears to be relatively stable during the period between 3.1 and 2.5 Ma, the period of intensification of Northern Hemisphere glaciation. This period seems to be characterised by a progressive cooling (Vergnaud-Grazzini et al., 1990; Tiedemann et al., 1994) which was not strong enough to rapidly or radically alter the vegetation. Therefore, as our reconstructions are based on variations of the vegetation composition, the slight climatic changes are not discerned.

4.2. The climate around the Mediterranean area at 5.32–5 Ma

For this period, the differences in vegetation due to latitude may be easily identified (Suc, 1989; Suc et al., 1995a). This is particularly notable between the Languedoc–Roussillon area and Catalonia, where the difference is marked by higher percentages of thermophilous plants to the south. The Mediterranean mixed forest of the northwestern domain gave way to Mediterranean open xeric assemblages in the lower latitudes. The latitudinal organisation of the vegetation appears, therefore, to be of ancient origin, although it becomes increasingly pronounced in recent periods. Since the Zanclean, a thermal threshold existed between Barcelona and Tarragona, as it does today, separating thermo-Mediterranean from meso-Mediterranean formations (Suc et al., 1995a).

In order to study this latitudinal gradient, climatic estimations have been calculated for all the sites covering the period 5.32–5 Ma (Fig. 8). At each site, the sum of three or four pollen spectra was used in the calculations, in order to have coherent values between all the sites.

The latitudinal climatic gradient seen in the pollen data is obvious in the reconstructions. Temperatures, precipitation and E/PE are similar at Saint-Martin du Var, Cap d'Agde 1 and Canet 1 (T_A from 15º to 17.7ºC, P_A from 1180 to 1580 mm and E/PE from 79 to 100%). However, the site of Canet 1, characterised at that time by a higher level of Asteraceae and Amaranthaceae–Chenopodiaceae, appears a little drier than the other sites, with P_A around 1200 mm and E/PE between 66 and 100%. The climate at Garraf 1 was similar, i.e. warm and humid.

At Tarragona, a different type of climate was reconstructed, with higher temperatures and very low precipitation levels, between 575 and 880 mm (most likely value of 670 mm). These values are concordant with the change of vegetational zone: Tarragona is the northernmost site included in the Southwest Mediterranean zone. It is characterised by higher frequencies of herbaceous taxa and by the occurrence of some subdesertic taxa.

At Andalucia, south of Tarragona, precipitation is once again lower, between 300 and 700 mm (most likely value of 400 mm), but the temperatures are similar to those at Tarragona.

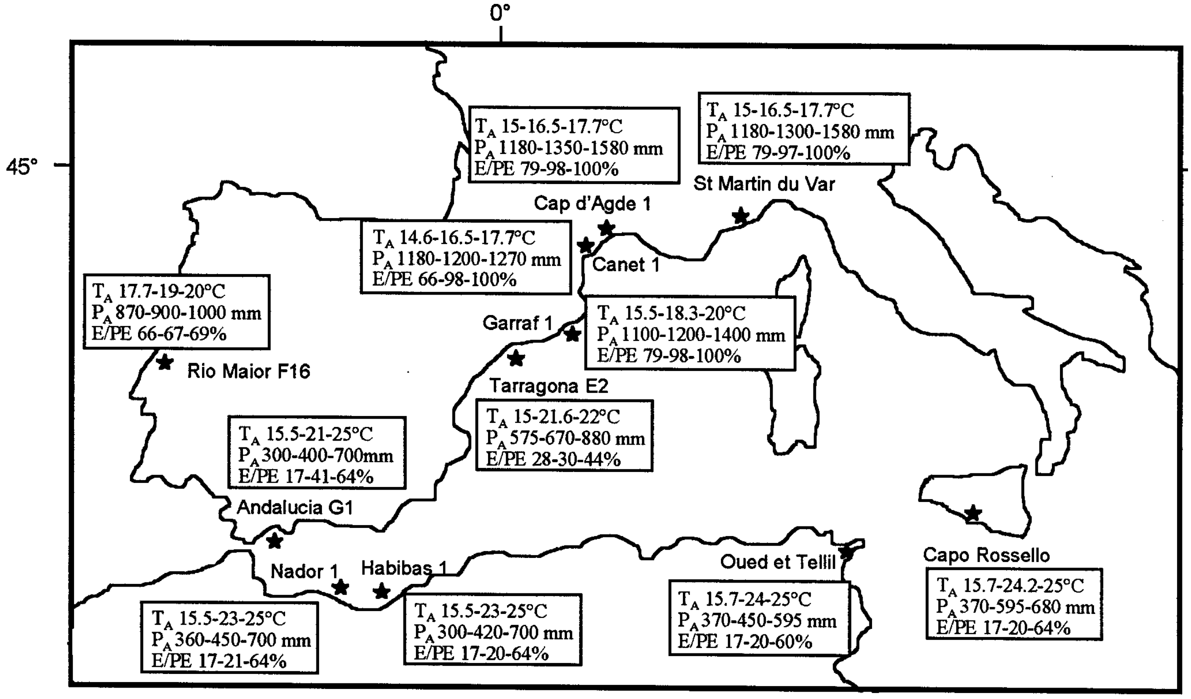

Fig. 8. Climatic variations around the West Mediterranean area at 5.32–5 Ma.

In North Africa (Nador, Habibas, Oued et Tellil) and in Sicily (Capo Rossello) temperatures are uniformly very high (T_A from 15.5° to 25°C with a most likely value of about 23°C). The very low values calculated for E/PE and annual rainfalls are consistent with the open vegetation type deduced from pollen data.

At Rio Maior, included in the West European vegetational domain, annual temperatures were between 17.7° and 20°C (most likely value of 19°C) and precipitation between 870 and 1000 mm (most likely value of 900 mm). These values are in agreement with the presence of both Mediterranean xerophytes and subtropical taxa, such as *Engelhardia*, *Nyssa*, *Symplocos*. The value of E/PE (between 66 and 69%) is also consistent with the presence of a mixed forest.

These results confirm that: (1) at 5.32–5 Ma, temperatures were higher than today (1° to 5°C on average), more notably in the Northwest Mediterranean area, precipitation was higher in the Northwest Mediterranean area and more or less similar to the modern one in the Southwest Mediterranean area; (2) a climatic gradient from north to south existed at the beginning of the Pliocene, increasing for temperature and decreasing for precipitation; (3) the limit between the northwestern and the southwestern regions occurred between Garraf and Tarragona; the site of Rio Maior is distinct, coming under the Atlantic influence with a higher precipitation than at Tarragona or Andalucia.

The estimates are consistent with the climatic hypothesis of van der Hammen et al. (1971) that proposed a mean annual temperature ranging from around 11° to 16–17°C for the Netherlands during the Brunssumian (lower Pliocene) with high humidity.

Various mechanisms may be proposed to explain the differences between the Pliocene and the modern climatic situation in the West Mediterranean area.

(1) The existence of climatic forcing at a global scale; e.g. increase in solar radiation, increase of atmospheric CO_2 concentration, increase in ocean heat transport (Rind and Chandler, 1991) due to changes in the ocean's thermohaline circulation).

(2) An atmospheric circulation identical to today (i.e. zonal circulation), but shifted a few degrees in

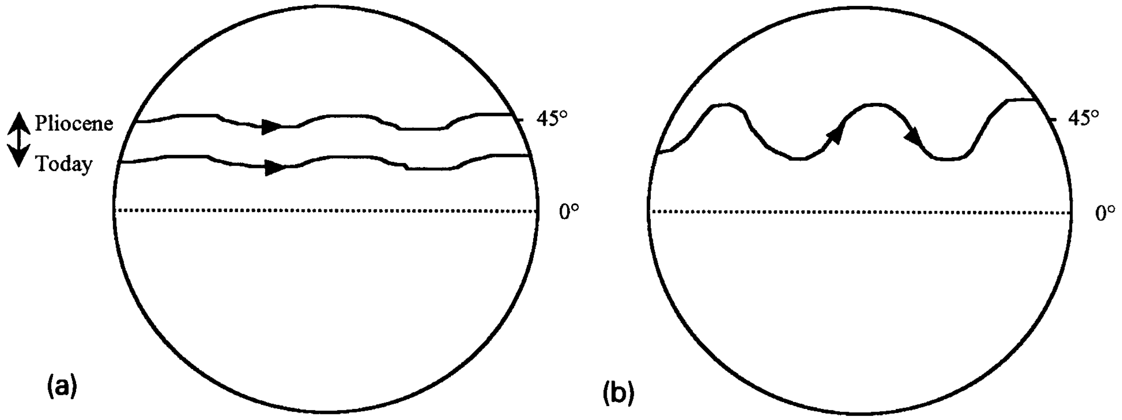

Fig. 9. Climatological hypothesis to explain the climate of the Pliocene: (a) same atmospheric circulation as today shifted to the north; (b) different atmospheric circulation with more accentuated waves.

latitude to the north (Fig. 9a). This would result in a northward displacement of the anticyclones situated today above the Saharan region at the beginning of the Pliocene. This would explain the higher temperatures but not the higher precipitation in southern France. On the contrary, the summer drought should have been more pronounced than today; this is not the case, however, as shown by the presence of the Taxodiaceae and other subtropical plants, despite a progressive increase in the summer drought (Suc, 1984).

(3) The atmospheric circulation may have been different, for example, with more accentuated waves of the jet stream (Fig. 9b). In such a case, the Mediterranean area would have been in a southwestern air flux which would have increased temperatures. Precipitations would also have been higher, particularly at the foot of mountains (e.g. in southern France). However, in this situation, some regions around the world, under the influence of northwestern air fluxes, would have lower temperatures than at present. Currently, all paleoclimatological studies for this period show temperatures more or less higher than at present (Edwards et al., 1991; Thompson, 1991; Dowsett et al., 1992; Willard, 1994). Not all areas of the earth have been explored and it may be that, currently, no paleoclimatological data exist for regions under the northwestern air fluxes.

Several other scenarios could be suggested but it is impossible to know at present the real cause of these climates. However, one of the most probable hypotheses is a combination of a global process with the superimposition of another phenomenon (for example, a different atmospheric circulation).

Although no analogues of the Pliocene vegetation can be found today (in terms of pollen spectra), it is possible to find modern analogues of the Pliocene climate. Comparison of our climatic estimates with modern values gathered by Leemans and Cramer (1991) indicates where such climate types exist today. Based on the annual values of the different parameters, the climate existing in southern France at the beginning of the Pliocene may be found today in southern China (although the different precipitation regime must be taken into account), northern India, North America (in California or the southeastern states), South America (around Buenos Aires in Argentina), and in eastern Australia (close to the Tropic of Capricorn in Queensland). If only the lower value of the climate range is considered, a similar climate can be found in France (around Bordeaux). The climate estimated for the regions of Tarragona and Andalucia is found today in southern Europe (southern Spain, Greece, Cyprus), Syria and Lebanon, North Africa (e.g. northern Tunisia), Central Africa (Botswana, Zambia, if only the higher limits of the climatic estimations are considered), and in northwestern Mexico and southern Australia. Finally, the climate existing in North Africa during the Pliocene may be found today in northern Egypt and Libya, Namibia, the Sonora region in northern Mexico, central Australia, and also along the southwestern coast of Australia.

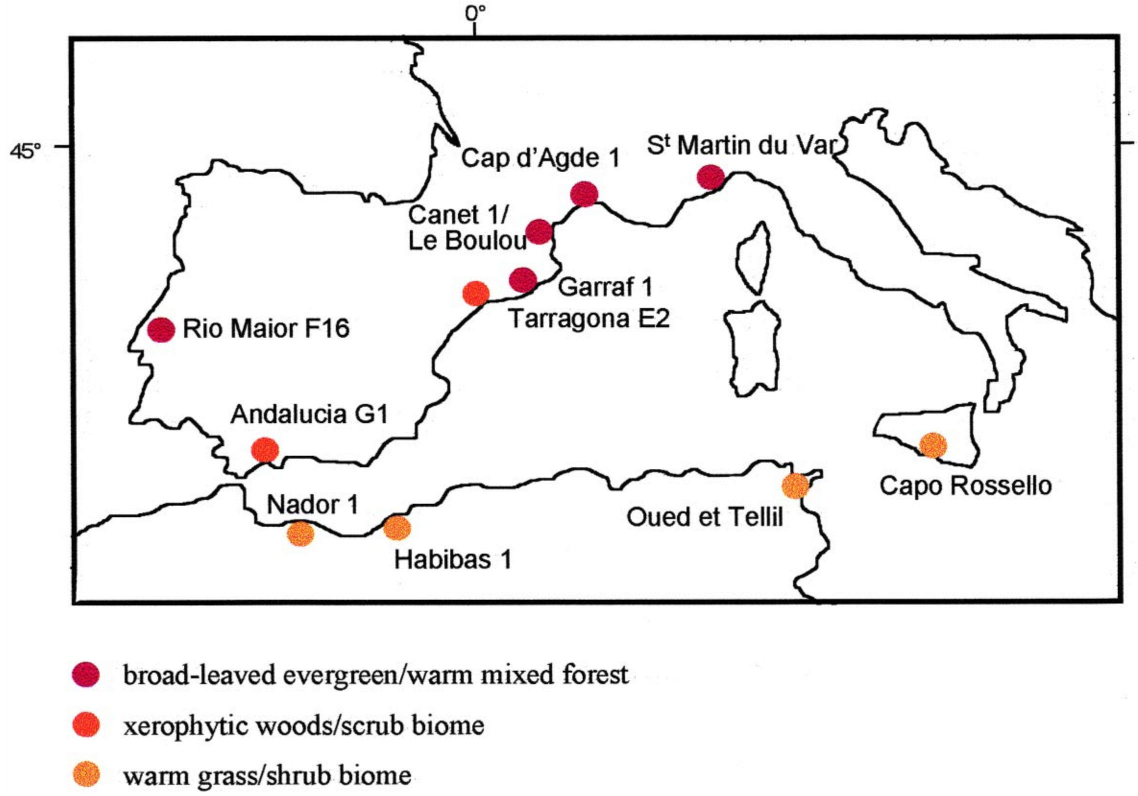

Fig. 10. Biome reconstruction at 5.32–5 Ma using the typology established by Prentice et al. (1992), our climatic estimations, and the vegetation description based on pollen data.

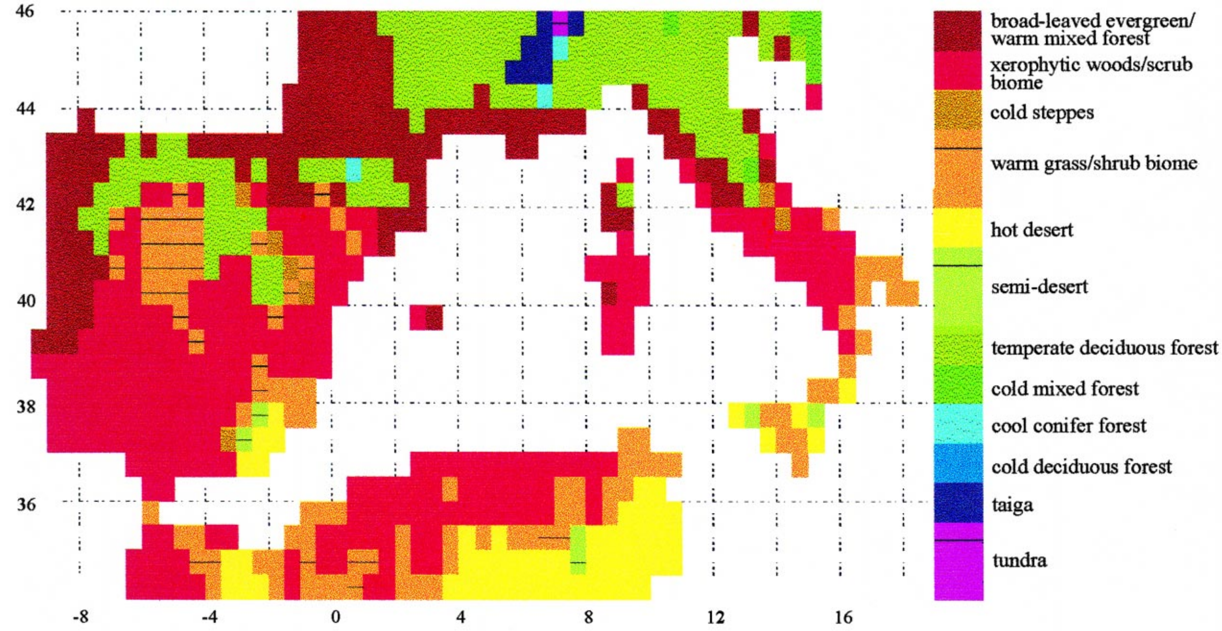

Table 1
Reconstruction of the E/PE ratio, of the mean temperature of the coldest month (T_C) and of the warmest month T_W) for the West Mediterranean area at 5.32–5 Ma

Sites	E/PE (%)			T_C (ºC)			T_W (ºC)		
Saint-Martin du Var	79	97	100	5	6.6	9.8	20	22.6	24.6
Cap d'Agde 1	79	98	100	5	8	9.8	15	20	24.6
Canet 1	66	98	100	4.5	9.4	14	19.8	25	26.8
Garraf 1	79	98	100	5	9.8	14.6	24.6	25.8	26.6
Tarragone E2	28	30	44	5	14.5	16	24.6	25.5	26
Andalucia G1	17	41	64	7.3	10.5	14.6	22	25	28
Nador 1	17	21	64	7.3	12	14.6	22	25.5	28
Habibas 1	17	20	64	7.3	12	14.6	22	25.2	28
Oued et Tellil	17	20	60	7.3	9.4	14.4	22.8	25.9	27.7
Capo Rossello	17	20	64	7	12	14.4	22	26	28
Rio Maior F16	66	67	69	9.8	11.5	14.6	24.6	25.2	26.6

For each parameter, the first and the third values correspond, respectively, to the lower and the upper limits of the estimated climatic interval. The second value corresponds to the weighted mean of the interval.

5. Biomes around the Mediterranean area at 5.32–5 Ma

The estimation of biomes for a given region enables climate modellers to improve their models by establishing more precise boundary conditions for that region. A biome reconstruction for the period 5.32–5 Ma around the Mediterranean area has been attempted, using the typology established by Prentice et al. (1992). These reconstructions are based on the climatic estimates of the temperature of the coldest month, of the warmest month and the E/PE ratio (Table 1). A biome has been assigned to each site according to the climatic parameter limits established by Prentice et al. (1992). This assignation was further determined by using the vegetation description based on the pollen data. The environmental constraint values of Prentice et al. (1992) were used to determine biomes corresponding to the pollen spectra, compatible with both our climatic estimations and the vegetation composition.

Three biomes have been found at 5.32–5 Ma at the different sites studied: the broad-leaved evergreen/warm mixed forest, the xerophytic woods/scrub biome and the warm grass/shrub biome (Fig. 10). The climatic and vegetational criteria that define these biomes are the following.

(1) The broad-leaved evergreen/warm mixed forest is indicated when the temperature of the coldest month ranges from 5º to 15.5ºC and E/PE is above 65%. This biome includes all vegetation types where warm-temperate evergreen trees, whether broad- or needle-leaved, are dominant (Prentice et al., 1992). At the beginning of the Pliocene, this biome is represented in the south of France where Taxodiaceae forests are dominant and it resembles the broad-leaved evergreen/warm mixed forest found today in eastern China or in California. It can be also attributed to Rio Maior where subtropical taxa are largely dominant, although the Mediterranean assemblages were more important. This biome was also found at Garraf. The *Taxodium* swamps, which characterised this site, were due to particular local edaphic conditions (Suc and Cravatte, 1982). Today, this biome is found in the south of France, but with lower temperatures and precipitation.

(2) The xerophytic woods/scrub biome is defined by the dominance of tall xerophytic plants (i.e.

Fig. 11. Map of the interpolated biomes at 5.32–5 Ma. First, anomalies between Pliocene and modern climate have been calculated and then interpolated on the Leemans and Cramer (1991) grid to obtain the Pliocene climate for the whole grid. According to these results, using the scheme of the Biome 1 model (Prentice et al., 1992), biomes are reconstructed around the Mediterranean Sea.

Mediterranean sclerophylous shrubs, succulents and tropical thorns), temperature of the coldest month above 5ºC and E/PE between 28 and 65%. This biome occurs where the climate is too dry for warm-temperate evergreen trees. Xerophytic woods/scrub biome can be attributed to the sites of Tarragona and Andalucia where Mediterranean taxa are well represented and where the climatic values established by Prentice et al. (1992) are respected. Once again the limit between the northern and the southern parts of the West Mediterranean region is well-defined. This biome is still represented in these regions with more or less similar annual rainfall but lower temperatures.

(3) The warm grass/shrub biome occurs under climates with a temperature of the warmest month higher than 22ºC and a very low value of E/PE (between 18 and 28%). This biome is attributed to sites where vegetation corresponds to an open xeric environment. All these characteristics are found at Capo Rossello and in the sites in North Africa (Nador, Habibas and Oued et Tellil). This biome occurs today to the south of these sites or in subdesertic regions in central Spain.

The boundary conditions necessary for climate models can be interpolated from these data on a regular grid around the Mediterranean area, using the climatic data gathered by Leemans and Cramer (1991). Anomalies between Pliocene and modern climate are calculated (for T_C, T_W and E/PE) and then interpolated on Leemans and Cramer's grid. By adding these anomalies to the modern climatic values of Leemans and Cramer (1991), we obtain the Pliocene climate for the whole grid. Then, using the scheme of the Biome 1 model (Prentice et al., 1992), biomes have been reconstructed around the Mediterranean Sea (Fig. 11).

At the beginning of the Pliocene, the North African coast appeared to be covered by two biomes, the warm grass/shrub biome and the xerophytic woods/scrub biome. However, there are not enough sites along the coast to confirm the occurrence of this last biome. In Sicily, two biomes were represented: the warm grass/shrub biome, and the hot desert biome which occurs when the temperature of the warmest month is higher than 22ºC and E/PE is comprised between 0 and 18% (Prentice et al., 1992). Sicily was thus very close to North Africa, from a climatic and vegetational point of view. In Spain, between Tarragona and Andalucia, the biome was principally the same as today, i.e. a xerophytic woods/scrub biome, despite higher temperatures. Some other biomes occurred locally (the warm grass/shrub biome and the hot desert), but the paucity of data prevents any confirmation of this.

North of Tarragona the biome changed at the same limit as today, as the broad-leaved evergreen/warm mixed forest succeeded the xerophytic woods/scrub biome. It covered the whole southern France and probably extended northward into Europe; again, the lack of data prevents any confirmation. In northern Italy, Bertini (1994) indicated that the vegetation was a mixed mesophytic forest, with the presence of subtropical and warm-temperate elements. The author mentions that the Italian Zanclean sections are characterised by the abundance of Taxodiaceae, and by the scarcity of herbaceous plants, similar to that seen in the Ligurian (Zheng, 1990) and French sections (Suc, 1976, 1981; Cravatte et al., 1984; Zheng, 1990). The author mentions also that the sections are strikingly different from those found at Capo Rossello (Suc and Bessais, 1990). Thus, the biome attributed to the northern Italian coast (the broad-leaved evergreen/warm mixed forest) using the interpolation technique is consistent with the qualitative interpretation of the Pliocene data. It is hazardous to attribute a biome to central and southern Italy, as no data are available for these regions. Moreover, geomorphologic studies suggest that only a part of central Italy had emerged (Boccaletti et al., 1990). Lastly, the Atlantic coast of the Iberian Peninsula is covered by two biomes: the broad-leaved evergreen/warm mixed forest to the north and the xerophytic woods/scrub biome to the south. Rio Maior is placed at the limit between these two biomes, which is consistent with the oscillations between the Mediterranean xerophytes and the subtropical plants seen in the pollen diagram (Diniz, 1984a).

Using this technique, a biome has been attributed to each grid cell. It must be stressed that the interpolation is based on only ten Pliocene sites for the whole West Mediterranean area and the results are perhaps wrong for regions where no corroborative data exist. Further, precise limits between the biomes cannot be established (except between the North and the South Mediterranean regions, i.e. between Tarragona and Barcelona, because of the proximity of these two sites). If, however, we assume that climatic changes are homogeneous within a large region and that lapse rates have not changed we can be reasonably confident in this distribution of the biomes.

Attempts have been made to relate the Mediterranean Pliocene with modern vegetation. For example, the Pliocene vegetation described for southern France has been compared to Chinese and to Californian modern vegetation (Zheng, 1990). The biome reconstruction realised in this study confirms this previous work, as the broad-leaved evergreen/warm mixed forest is present today in California and China (southern and eastern China). Initially, the comparison with the Chinese vegetation appeared to be the most accurate as there is a large number of Pliocene taxa in China. However, in terms of climatic conditions and geographic location (i.e. the west side of a continent), the Californian model seems better related. The eastern Chinese coast is under monsoon influence with a maximum rainfall during the summer, the contrary of California. During the Pliocene in Europe and in the Mediterranean region, the presence of Mediterranean taxa indicates that there was no monsoon regime. The Californian model, therefore, may be closer to the Pliocene vegetation type.

6. Comparison with simulations of the Pliocene climate

A great number of models have been used by the members of the PMIP (Paleoclimate Modeling Intercomparison Project) to simulate the climate for some phases of the Quaternary period. For the Pliocene, a model has been established by the Goddard Institute for Space Studies (GISS). The aim of the GISS is to develop tools for simulating future climate change. Predictions of future changes gain credibility when models can accurately simulate changes that have occurred in the past. Whilst the climate of many past time periods has been simulated, the most interesting periods to simulate are those during which the average global temperature was more than 1ºC higher than today. These periods may resemble the future climate on Earth, if the increased greenhouse effect is taken into account. The Early Pliocene appears to be the more appropriate period, as we have calculated temperatures of 1º to 6ºC higher than today in the Mediterranean region.

Chandler et al. (1994) have used the GISS General Circulation Model and data generated or compiled by the PRISM (Pliocene Research, Interpretation and Synoptic Mapping) project (pollen data, dinocysts, foraminifers, ostracodes and diatoms). The boundary conditions of one of their simulations are deduced from reconstruction of Pliocene SST, terrestrial vegetation and modern geographic conditions (topography, land ice, Southern Hemisphere SSTs, atmospheric conditions . . . , M. Chandler, pers. commun., 1998). Although these simulations do not constitute a full Pliocene reconstruction, it is interesting to compare them to our results. A difficulty in comparing the sets of results is the grid cell size of the model simulation (7.83º $\times$ 10º) which encompasses vast areas: the area studied in this paper is divided into just six grid cells in this model (Fig. 12).

For the Northern Mediterranean sites, the simulated annual temperatures are close to the values reconstructed from pollen data, even for the southwestern European region (cf. Rio Maior). For the annual precipitation, the comparison is more complicated. The model results are good for the grid cell corresponding to the site Saint-Martin du Var and also for the Atlantic coast of the Iberian Peninsula. The results are less good for the central grid cell where the simulation gives an annual precipitation value that is too low at Cap d'Agde, and a value too high for the region of Tarragona. This grid cell covers two different vegetational and climatic domains, which are merged in the climatic simulation.

For the Southern Mediterranean sites, the annual temperature simulation fits well with the values obtained from pollen data for the three grid cells. However, the GISS model gives values of annual precipitation which are too high and not compatible with the vegetation type deduced from pollen data (subdesertic vegetation). Here again, the cause of these discrepancies is probably the size of the grid cells, which encompasses more humid mountainous regions.

The values of T_C and T_W have been also compared to our estimations but the results of the simulations are not good for these parameters. Their T_C estimates are too high and the T_W estimates, whilst better, are often too low, which implies an over-reduced thermic seasonality.

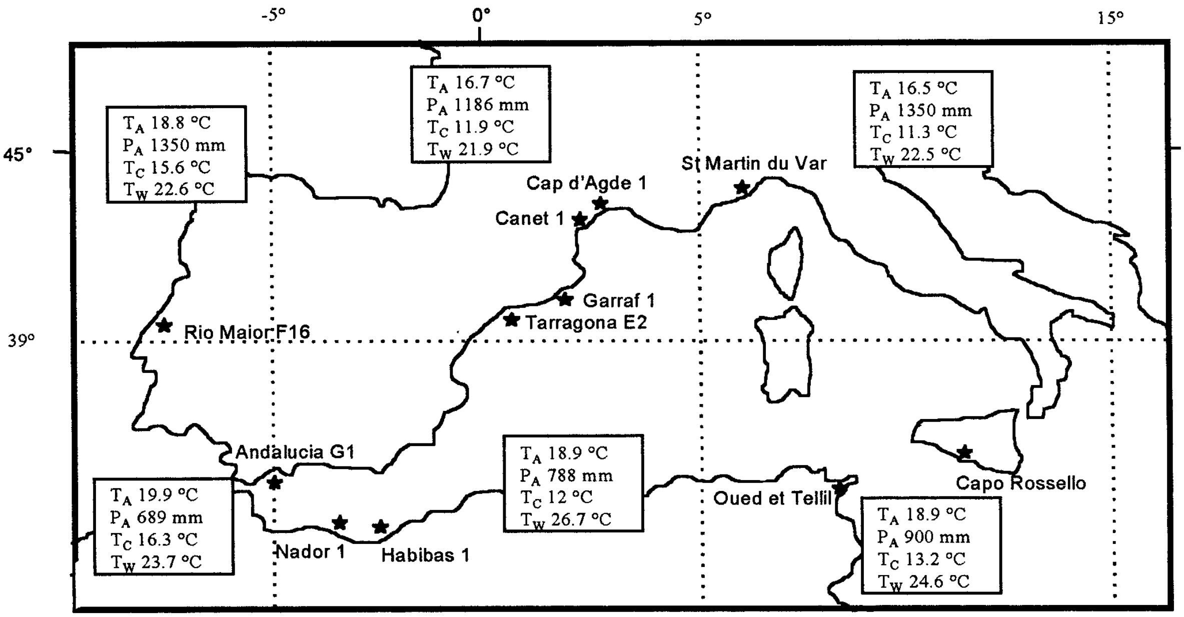

Fig. 12. Climatic estimations obtained with the GISS model (M. Chandler, pers. commun., 1998). The resolution of the grid cell is 7.83° × 10°.

Although the results of this model represent a first and non-complete approach to the simulation of the climate of the Pliocene, the comparison with our results shows some agreement for T_A and P_A for almost all the Mediterranean region. A higher-resolution grid would allow better simulations and perhaps a closer fit to the data-based estimates.

A new model experiment is currently being carried out with full Pliocene paleogeographic reconstructions and a variety of experiments testing the model's sensitivity to various climate-forcing mechanisms, e.g. atmospheric CO_2 and ocean heat transport (M. Chandler, pers. commun., 1998). This may yield results better correlated with the estimations obtained from the pollen data.

7. Conclusion

The climatic estimations calculated for the West Mediterranean Pliocene show that temperatures and precipitation were higher than today, especially in the North Mediterranean domain. The climate was, on average, warm and humid in the North Mediterranean domain (respectively 1° to 4°C and 400 to 700 mm higher than today), and warm and dry in the South Mediterranean domain (respectively equal to or 5°C higher and drier than or equal to today). At Rio Maior, situated in the Atlantic domain, the climate was warmer and drier than in the North Mediterranean area but colder and more humid than in the South Mediterranean domain.

The latitudinal gradient of climate that is revealed by the pollen data (one of the starting points of this climatic quantification) is clearly visible in our reconstructions. The direction of this gradient appears to be similar to today, i.e. the climate was warmer and drier in the South than in the North Mediterranean domain.

Following the environmental constraints of Prentice et al. (1992), biomes were defined for each site for the period 5.32–5 Ma. The biomes were reconstructed using the climate estimate obtained earlier in the study, together with a description of the vegetation, based on the pollen flora. For this period in the Mediterranean region, three biomes have been identified: (1) the broad-leaved evergreen/warm mixed forest which was dominated by Taxodiaceae, resembling the broad-leaved evergreen/warm mixed forest found today in eastern China or in California; (2) the xerophytic woods/scrub (dominance of tall xerophytic plants) which occurred where the climate was too dry for warm-temperate evergreen trees; and (3) the warm grass/shrub biome corresponding to an open xeric environment.

These biomes have been interpolated along the West Mediterranean littoral, on a regular grid, using T_C, T_W and E/PE estimates. Anomalies between Pliocene and present-day climate have been calculated and then interpolated for the Mediterranean region. It is obvious that precise limits between the biomes cannot be determined, unless two biomes are represented by sites in close proximity, e.g. the limit between the North Mediterranean (Tarragona) and the South Mediterranean (Barcelona).

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