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How much did climate force the Messinian salinity crisis? Quantified climatic conditions from pollen records in the Mediterranean region

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Abstract

The latest Miocene (5.96 to 5.33 Ma) is characterised by an outstanding event: the desiccation of the Mediterranean Sea (Messinian salinity crisis). It has been suggested that this was caused by a tectonic event, with no climatic change playing a role in desiccation. Quantifying the climate of the region during this period will help support or refute this hypothesis. An effective method for reconstructing the climate from Neogene pollen data is the "Climatic Amplitude Method" based on the modern climatic requirements of plants to interpret fossil data. It has been conceived especially for periods devoid of modern vegetation analogue.

Twenty Messinian to Lower Zanclean pollen sequences are now available in the peri-Mediterranean region. Most of them do not cover the whole Messinian interval, particularly those along the Mediterranean shorelines where sedimentation was interrupted during the sea's desiccation. In contrast, sedimentation was almost continuous in such areas as the Atlantic side of Morocco, along the Adriatic coast (including the Po Valley), and to a lesser extent the Black Sea. The Mediterranean sites nonetheless provide a reliable if not a discontinuous record of vegetation variability in time and space.

A first examination of the pollen diagrams reveals a high regional variability controlled by local conditions, and throughout the interval a southward increase in herb pollen frequency in contrast to the tree pollen frequency. This indicates that open and

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probably dry environments existed in the southern Mediterranean region prior to, during and after the salinity crisis. Trees developed in areas close to mountains such as in the Po Valley, in Cerdanya and in the Black Sea region. Most variations observed in the pollen diagrams are constrained by fluctuations of *Pinus* pollen amounts, indicating eustatic variations. Climatic quantification from pollen data does not show obvious climatic changes due to the desiccation of the Mediterranean Sea, especially in the dry and warm southwestern Mediterranean area (Sicily, southern Spain and North Africa). At Maccarone, along the Adriatic Sea, a decrease in temperatures of the coldest month and, less importantly, a decrease in mean annual temperatures, corresponding to a drastic vegetation change, are reconstructed. These temperature variations are assumed to be controlled by regional environmental changes (massive arrival of waters in this basin) rather than to reflect cooling, because some authors link the second phase of evaporite deposition to a period of global warming. Some migrations of plants probably occurred as a response to Mediterranean desiccation. But the climatic contrast which has probably existed at that time between the central Mediterranean and the peripheral areas might be amplified.

Climatic reconstruction from pollen data in the western Mediterranean area shows that climate is not the direct cause of the Mediterranean desiccation, as the Mediterranean region had experienced continuously high evaporation long before the crisis. Therefore the main factor leading to this event seems to be the successive closures of the Betic and Rifian corridors, isolating the Mediterranean Sea from the Atlantic Ocean.

Keywords: Messinian; Climate quantification; Pollen; Mediterranean; Black Sea

1. Introduction

The second half of the Messinian stage (5.96 to 5.33 Ma) is characterised in the Mediterranean Basin by a dramatic event: the desiccation of the Mediterranean Sea, i.e. the so-called Messinian salinity crisis. As it is generally accepted, the event corresponds to the interruption of relationships between the Atlantic Ocean and the Mediterranean Sea, causing the desiccation of the Mediterranean and, as a consequence, a thick accumulation of evaporites within the abyssal parts of the basin and the cutting of deep subaerial canyons by rivers.

Since the discovery of the event (Hsü et al., 1973), several scenarios have been debated with most discrepancies concerning chronology and causes of the successive phases of the salinity crisis. Today, after concerted effort on (1) magnetostratigraphy of key-sections [Morocco: Hodell et al. (1994), Cunningham et al. (1997); Southeastern Spain and Sicily: Gautier et al. (1994), Krijgsman et al. (1999b); Po Valley and Adriatic realm: Krijgsman et al. (1999a), G. Napoleone (personal communication)] and (2) radiometric dating [Morocco: Cunningham et al. (1997), Roger et al. (2000), Cornée et al. (2002); Adriatic realm: Odin et al. (1997), H. Maluski (personal communication)], there is general agreement on the age of the onset of the salinity crisis (5.96 Ma) and its termination at 5.33 Ma (Lourens et al., 1996).

The ongoing debate about the Messinian salinity crisis concerns its nature, a two-step event is envisioned by Clauzon et al. (1996) but a synchronous event is envisioned by Krijgsman et al. (1999b) (Fig. 1). According to Clauzon et al. (1996), marginal evaporites and deep basin evaporites are chronologically disconnected, being separated by 260 kyr. A transgressive event occurred between evaporitic phases which corresponds to the Sicilian Upper Evaporites. In addition, this scenario takes into consideration a regional diversity with appropriate responses to the salinity crisis (perched basins, margins, deep basin) (Clauzon et al., 1996; Clauzon, 1997, 1999) (Fig. 1). The so-called «Lago Mare event» appears as two invasions of the Mediterranean Sea by eastern Paratethyan surface waters during high sea-level phases (Clauzon et al., 2005). This scenario has recently received strong support from oceanographic studies in the southern hemisphere (Vidal et al., 2002; Warny et al., 2003). In contrast, Krijgsman et al. (1999b, 2001) use an astrochronological approach to argue uniformity for the whole Mediterranean, in which marginal basins are isolated between 5.6 and 5.5 Ma by isostatic uplift during the desiccation phase of the Mediterranean (Fig. 1). Their paper concerns only the chronological location of the Sicilian Upper Evaporites, as illustrated by the Eraclea Minoa section. According to Clauzon et al. (1996, 2005), the Sicilian Upper Evaporites represent a transgressive episode at the end of the marginal evaporitic phase, and they precede the desiccation of the Mediterranean Sea (i.e. the deposition of evaporites in the desiccated abyssal plains and the cutting of canyons). According to Krijgsman et al. (1999b), they correspond to the termination of the salinity crisis, i.e. to the transgressive interval which immediately preceded

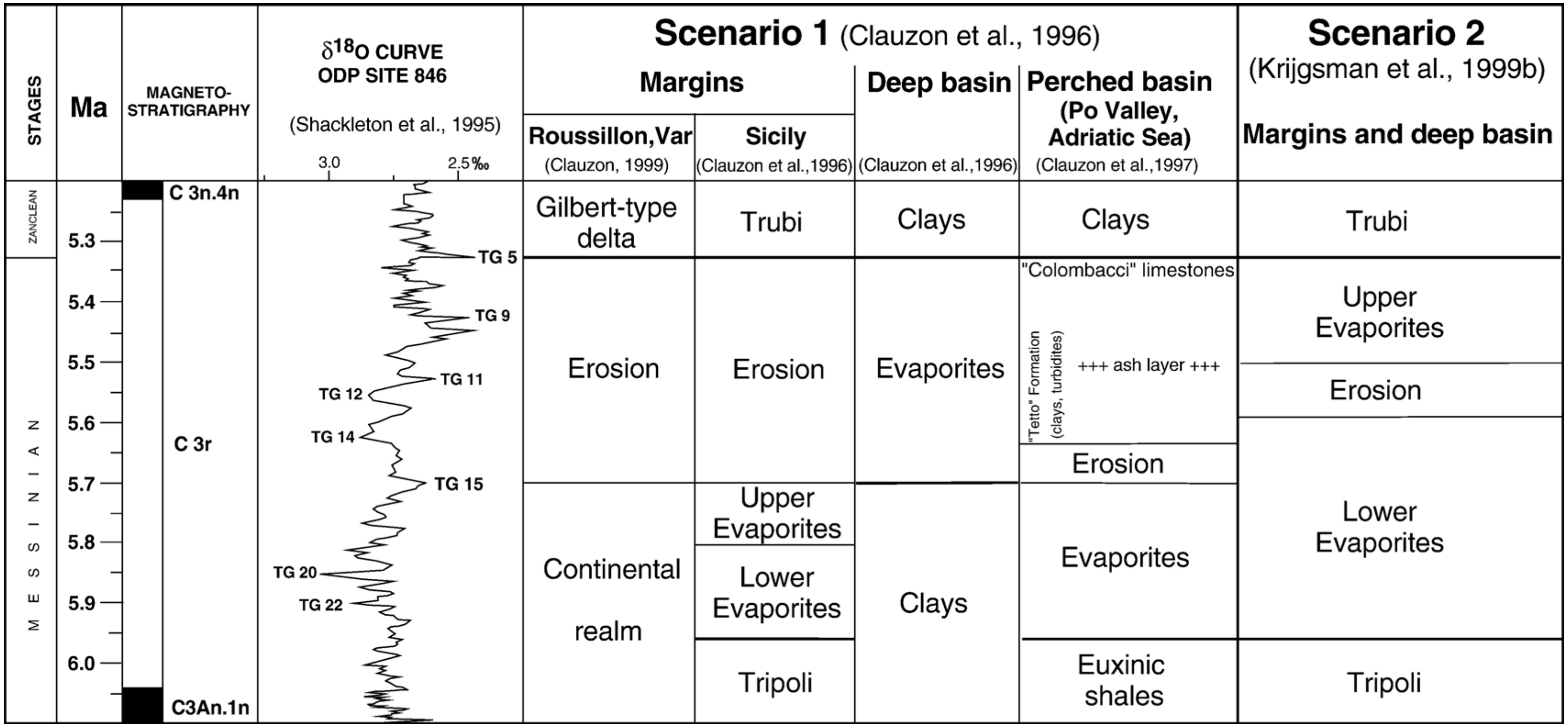

Fig. 1. Comparison of the two principal hypotheses of the Messinian salinity crisis (scenario 1 by Clauzon et al., 1996; scenario 2 by Krijgsman et al., 1999a,b). The thick horizontal lines respectively indicate (1) the onset of the salinity crisis (diachronous in the first scenario according to the basin status, isochronous in the second scenario), (2) the beginning of the Pliocene. The curve from Shackleton et al. (1995) has been chronologically re-calibrated to take into account the new date for the end of C3An.1n Chron established by Krijgsman et al. (1999a,b) at 6.04 Ma.

the flooding of the Mediterranean Basin by the Zanclean sea. This discrepancy has no bearing on climate, and so we choose to follow the scenario of Clauzon et al. (1996, 2005):

- 5.96–ca. 5.8 Ma, moderate global sea-level drop (less than 100 m), a period including two glacial Antarctic isotopic stages TG22 and TG20 (Shackleton et al., 1995; Vidal et al., 2002), causing deposition of Mediterranean marginal evaporites such as those of Sicily, Sorbas, Po Valley, Tyrrhenian realm;
- ca. 5.8–5.7 Ma, sea-level rise, a period including isotopic stage TG15 (Shackleton et al., 1995; Vidal et al., 2002) and corresponding to the Upper Evaporites of Sicily (at the top of which are located the Lago Mare and the Arenazzolo facies);
- 5.7–5.33 Ma, tectonic isolation of the Mediterranean realm, fast desiccation of the Mediterranean Sea, deposition of evaporites in the desiccated abyssal plains, cutting of subaerial canyons;
- 5.33 Ma, instantaneous flooding of the Mediterranean Basin by Atlantic waters (Blanc, 2002).

The question of a climatic cause (increasing dryness) for the desiccation of the Mediterranean Sea, even if not always clearly expressed, is more or less implied for scenarios favouring a deep-water model for basin evaporite deposition (Busson, 1979, 1990; Krijgsman et al., 1999b). Suc and Bessais (1990), Bertini (1994a,b) and Bertini et al. (1998), using pollen analyses, have suggested discarding increasing dryness as an explanation for the salinity crisis. Another climatic change (increasing precipitation) has been considered to explain Lago Mare facies in the Eastern Mediterranean (Orszag-Sperber et al., 2000; Rouchy et al., 2001).

For more than 20 years we have pursued high-quality pollen research on the Messinian deposits around the Mediterranean realm, and results have emerged that contrast with previous and current studies (Trevisan, 1967; Benda, 1971; Bertolani Marchetti and Cita, 1975; Heimann et al., 1975; Traverse, 1978; Bertolani Marchetti, 1984; Ioakim and Solounias, 1985; Mariotti Lippi, 1989; Ediger et al., 1996; Ioakim et al., 1997; etc.). Differences lie in the reliability of botanical pollen identification, in quantity of pollen counted and in density of samples.

The aim of our study is to address some crucial questions concerning the Messinian salinity crisis and the prevailing climate: 1) did climate play a role in triggering the desiccation of the Mediterranean Sea? 2) did climate change in the Mediterranean region during the salinity crisis and, if so, was it related to the desiccation of the Mediterranean? To help answer these questions, (1) we present a synthesis of Messinian to Early Zanclean pollen records in the Mediterranean realm, and (2) we provide the reconstructed climate of the western Mediterranean area before, during, and after the Messinian salinity crisis, using pollen data from several selected localities in the western Mediterranean region.

2. Pollen data and vegetation reconstruction

Twenty Messinian to Zanclean pollen sequences, all based on high-quality pollen analyses (following the criteria established above), are now available for the peri-Mediterranean region (Fig. 2). Bou Regreg (Atlantic seaboard of Morocco) excepted, none of these sequences covers the entire period 6.7–5.2 Ma (Fig. 3). They provide a reliable but discontinuous record of vegetation variability in time and space. The period of evaporite deposition within deep parts of the desiccated basin (5.7–5.33 Ma) is poorly documented in the Mediterranean region: only the Maccarone section and, in part, the Torre Sterpi section, in the Adriatic Sea–Po Valley area, belong to this interval (Fig. 3). Within this perched basin, sedimentation was continuous because of a positive water balance (Clauzon et al., 1997, 2005) (Fig. 1). The evaporitic phase on the Mediterranean margins is better documented, especially in the Po Valley and in Sicily (Fig. 3). Several pollen diagrams have been generated from offshore boreholes (Andalucia G1, Habibas 1, Tarragona E2, Naf 1) that have been drilled in relatively shallow waters (less than 300 m). For each of these pollen records, the earliest Pliocene is well identified using planktonic foraminifers (*Sphaeroidinellopsis* acme-zone, followed by first appearance of *Globorotalia margaritae*). A gap probably separates the earliest Zanclean sediments from the underlying Messinian ones, corresponding to erosion of the margin during evaporite deposition in deep parts of the desiccated basin. Nevertheless, this gap might be longer than expressed on Fig. 3 owing to possible erosion of the uppermost Messinian deposits before desiccation of the basin.

Deep Sea Drilling Project (DSDP) Site 380A in the Black Sea (Popescu, this volume) has been included in this study as it enlarges our considered area and may help to understand evolution of the Mediterranean climate within a more global framework. Its inclusion is also very useful for validating results based on climate and vegetation modelling (Fluteau et al., 2003; François et al., 2006-this volume). The Black Sea is considered

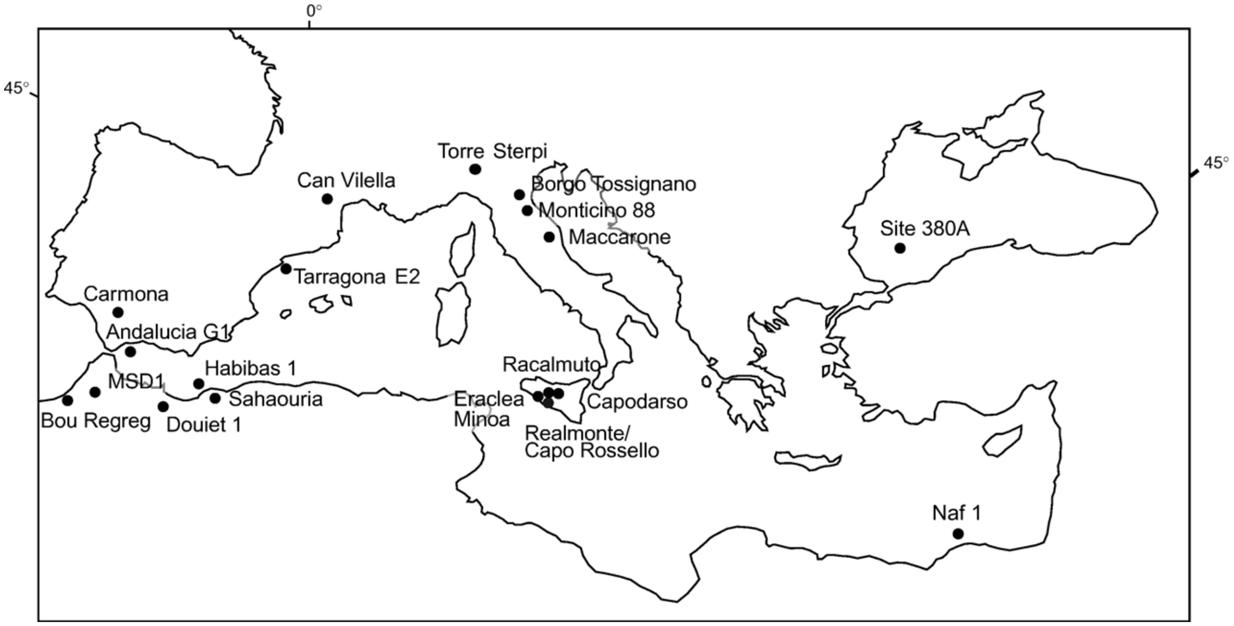

Fig. 2. Location map of the pollen localities considered in this paper.

also to have been involved with the Messinian salinity crisis (Hsü and Giovanoli, 1979), based on erosion observed along seismic lines (Letouzey et al., 1978) and on the presence of a coarse breccia (including blocks of a stromatolitic dolomite) at the same level at DSDP Site 380A (Ross et al., 1978). This borehole was drilled in 2107 m water depth, indicating that it represents abyssal plain upon which the deep desiccated basin evaporites were deposited. This evaporitic phase has probably produced a shorter break in the pollen record (corresponding to the breccia) than on the shelf because it corresponds to an area of sedimentation rather than erosion (Fig. 3). For the same reasons, we have used a section located in southern Spain (at Carmona), on the Atlantic seaboard for comparative purposes and to assess the influence of the Atlantic Ocean on southern Spain's environments and climate before the salinity crisis (Fig. 3).

Some additional information on areas containing our climatically quantified sites is given below before we describe their pollen contents, but more details may be obtained from the literature as most of data have been published.

2.1. Atlantic realm at southern Mediterranean latitude

Two pollen records document this area: Carmona in the Guadalquivir Basin (southern Spain) and Bou Regreg (Salé section, northwestern Morocco) (Fig. 2).

Pollen diagrams from Carmona come from two sections. The lower section is located immediately southward of the city along the road to El Arahal. It belongs to the Andalusian Clays underlying the famous «Calizza Tosca» calcarenite (Perconig, 1974). *G. margaritae* occurs continuously and the deposits are normally magnetised, allowing assignment to Chron C3An.1n (F.J. Sierro and W. Krijgsman, personal communications). This section predates the Messinian salinity crisis (Sierro et al., 1996) (Fig. 3). The upper section has been cored within the Green Clays overlying the «Calizza Tosca» calcarenite; it is reversely magnetised (W. Krijgsman, personal communication) and belongs to Chron C3r but more precise assignment is not possible. This section can therefore be considered as floating between the late Messinian and earliest Pliocene, but its shallow-water status (perhaps in relation with the «Calizza Tosca» regressive conditions) suggests association with the global sea-level fall at 5.9–5.85 Ma (isotopic stages TG22 and TG20) (Fig. 3). Pollen flora of the two sections (analyses by J.-P. Suc, N. Feddi and J. Ferrier, unpublished) is dominated by herbs (alternating Poaceae and Asteraceae mainly) including rare subdesertic elements such as *Lygeum* and *Neurada*. *Pinus* is abundant and shows several fluctuations. Tree frequencies are low and are mostly constituted by deciduous *Quercus*.

The Bou Regreg pollen diagram comes from exposed and cored sections at the Salé Briqueterie (close to

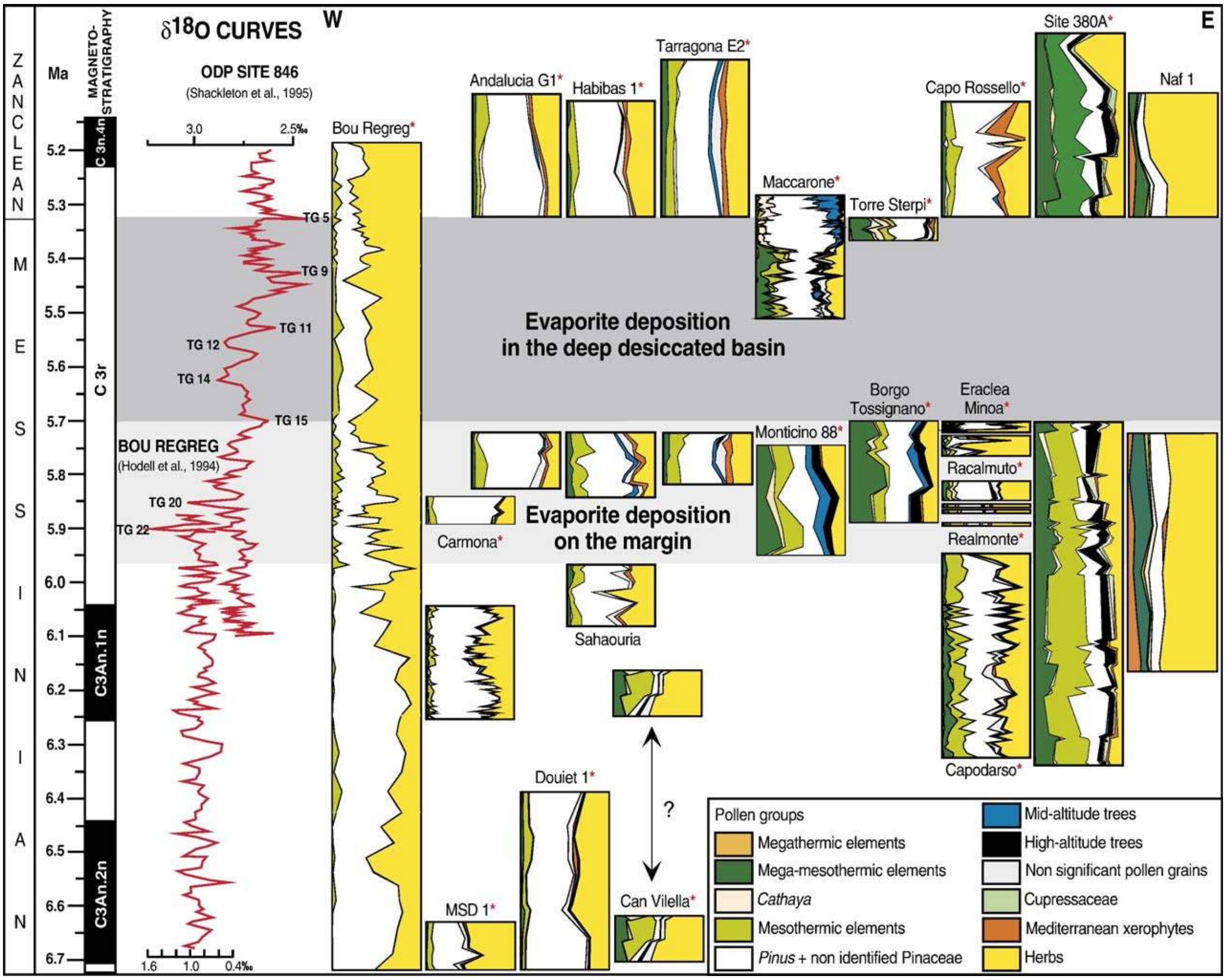

Fig. 3. Synthetic pollen diagrams analyzed in the Mediterranean region between ca. 6.7 and ca. 5.0 Ma according to their chronological location with respect to interrelated δ^{18}O curves (Hodell et al., 1994; Shackleton et al., 1995) within the frame of the scenario of the salinity crisis of Clauzon et al. (1996). The two light grey and dark grey strips respectively highlight the two successive evaporitic phases evidenced by Clauzon et al. (1996). Pollen flora on which climate has been quantified is indicated by a red star. Taxa have been grouped according to their ecological significance as follows: 1. megathermic (= tropical) elements (*Avicennia*, *Amanoa*, *Alchornea*, *Fothergilla*, *Exbucklandia*, Euphorbiaceae, Sapindaceae, Loranthaceae, Arecaceae, Acanthaceae, *Canthium* type, Passifloraceae, etc.); 2. mega-mesothermic (= subtropical) elements (Taxodiaceae, *Engelhardia*, *Platycarya*, *Myrica*, Sapotaceae, *Microtropis fallax*, *Symplocos*, *Rhoiptelea*, *Distylium* cf. *sinensis*, *Embolanthera*, *Hamamelis*, Cyrillaceae–Clethraceae, Araliaceae, *Nyssa*, *Liriodendron*, etc.); 3. *Cathaya*, an altitudinal conifer living today in southern China; 4. mesothermic (= warm-temperate) elements (deciduous *Quercus*, *Carya*, *Pterocarya*, *Carpinus*, *Juglans*, *Celtis*, *Zelkova*, *Ulmus*, *Tilia*, *Acer*, *Parrotia* cf. *persica*, *Liquidambar*, *Alnus*, *Salix*, *Populus*, *Fraxinus*, *Buxus sempervirens* type, *Betula*, *Fagus*, *Ostrya*, *Parthenocissus* cf. *henryana*, *Hedera*, *Lonicera*, *Elaeagnus*, *Ilex*, *Tilia*, etc.); 5. *Pinus* and poorly preserved Pinaceae pollen grains; 6. mid-altitude trees (*Tsuga*, *Cedrus*); 7. high-altitude trees (*Abies*, *Picea*); 8. non-significant pollen grains (undetermined ones, poorly preserved pollen grains, some cosmopolitan or widely distributed elements such as Rosaceae and Ranunculaceae); 9. Cupressaceae; 10. Mediterranean xerophytes (*Quercus ilex* type, *Carpinus* cf. *orientalis*, *Olea*, *Phillyrea*, *Pistacia*, *Ziziphus*, *Cistus*, etc.); 11. herbs (Poaceae, *Erodium*, *Geranium*, *Convolvulus*, Asteraceae Asteroideae, Asteraceae Cichorioideae, Lamiaceae, *Plantago*, *Euphorbia*, Brassicaceae, Apiaceae, *Knautia*, *Helianthemum*, *Rumex*, *Polygonum*, *Asphodelus*, Campanulaceae, Ericaceae, Amaranthaceae–Chenopodiaceae, Caryophyllaceae, Plumbaginaceae, Cyperaceae, *Potamogeton*, *Sparganium*, *Typha*, Nympheaceae, etc.) including some subdesertic elements (*Lygeum*, *Neurada*, *Nitraria*, *Calligonum*) and steppe elements (*Artemisia*, *Ephedra*). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Rabat) (Warny, 1999). It benefits from a very detailed time control including biostratigraphy, magnetostratigraphy, stable isotope stratigraphy and astrochronological tuning (Hodell et al., 1994, 2001; Warny and Wrenn, 2002). It covers the uppermost Tortonian, the entire Messinian and reaches the earliest Pliocene (Fig. 3). This section is particularly poor in pollen grains and does not show great taxonomic diversity. *Pinus* is abundant at the base but strongly decreases from the mid-section up to the top. Pollen analysis evidences an open environment dominated by herbs, especially subdesertic herbs. Arboreal taxa are less well represented than in the other North African sites.

2.2. Alboran Sea area and Rifian Corridor

Five sections document the vegetation in the Rifian Corridor and Alboran Sea regions: MSD1 and Douiet 1 boreholes respectively on the west and east sides of the Rifian Corridor, Andalucia G1 and Habibas 1 boreholes respectively on the north and south shorelines of the Alboran Sea; and Sahaouria in the Chelif Basin (Algeria) (Fig. 2).

The chronostratigraphic position of these sections is well known (Fig. 3). According to planktonic foraminifers (Barhoun, 2000), the MSD1 and Douiet 1 sections refer to the early Messinian, i.e. long before the salinity crisis. Borehole Andalucia G1, where planktonic foraminifers have been studied (Elf-Aquitaine, unpublished data), covers the early Messinian before the desiccation phase and part of the Pliocene, until around 2.4 Ma. Planktonic foraminifers from borehole Habibas 1 have been studied by J. Cravatte (personal communication): the section covers the pre-evaporitic Messinian and the early Pliocene up to around 3.2 Ma. The Sahaouria section is well dated by planktonic foraminifers and immediately predates the Chelif Basin marginal evaporites (Rouchy, 1981).

The pollen content of these sections has been studied as follows: MSD1 and Douiet 1 (Bachiri Taoufiq, 2000), Andalucia G1 (Bessais, unpublished; only Pliocene pollen data have been published: Suc et al., 1995b), Habibas 1 (Suc, 1989), Sahaouria (Chikhi, 1992). Climatic quantification has already been undertaken on the Pliocene parts of the Andalucia G1 and Habibas 1 pollen records (Fauquette et al., 1999).

All these sections show, whatever their age before or after the Messinian salinity crisis, open environments (Fig. 3), rich in herbs, mainly Asteraceae, Poaceae, *Nitraria*, *Neurada* and *Calligonum*, indicating very dry and warm conditions, as these taxa are found today in North Africa under hyper-arid conditions (Saharan elements, with *Neurada* and *Calligonum* indicating dunes). Within the Poaceae, *Lygeum* is also present. This taxon, characteristic of south-Mediterranean steppes, is found today in southern Spain, southern Italy, Sicily, Crete and in North Africa but not in the Sahara (Fauquette et al., 1998a,b). Mediterranean xerophytes are present. Arboreal taxa are frequent, dominated by deciduous *Quercus*, Taxodiaceae, *Myrica*, *Alnus*, indicating the existence of more humid places in the hinterland or moister conditions at higher altitudes. *Pinus* continues to show important percentages.

At MSD 1, Douiet 1, and Sahaouria, megathermic elements (*Canthium* type, Sapotaceae, *Alchornea*, etc.) are regularly represented. More particularly, *Avicennia*, the only mangrove element able to grow out of the tropical zone, has been found within the Messinian sediments of MSD 1, Douiet 1, Habibas 1 and Sahaouria. However, it has never been recorded in northern Africa within the earliest Pliocene sediments (Habibas 1: Suc, 1989; Nador 1: N. Feddi, personal communication).

2.3. Cerdanya

The section of Can Vilella is situated in Cerdanya and comprises lacustrine to palustrine sediments. Paleomagnetism indicates that the section straddles the passage from a reverse event to a normal one (Agusti et al., this volume). The mammal fauna allows us to place the section either at the base of Chron C3An.2n or C3An.1n, i.e. a long time before the salinity crisis (Agusti and Roca, 1987; Agusti et al., 2006-this volume) (Fig. 3).

The pollen flora has been studied by Perez Villa (Agusti et al., 2006-this volume). It reveals a riparian forest environment (Taxodiaceae, *Alnus*, *Myrica*, Cyrillaceae–Clethraceae, *Engelhardia*, *Cephalanthus*, *Pterocarya*, *Populus*, *Nyssa*, *Salix*, etc.) with many associated herbs (Cyperaceae, Poaceae, *Typha*, etc.) (Fig. 3). *Pinus* has a very low frequency.

2.4. Southern Catalonia

According to planktonic foraminifers, borehole Tarragona E2 covers the late Messinian, just before the desiccation phase of the deep basin, and also most of the Pliocene, up to around 2.4 Ma (Bessais and Cravatte, 1988) (Fig. 3).

Pollen data from borehole Tarragona E2 have been published in Bessais and Cravatte (1988). Climatic quantification has already been undertaken on the Pliocene part of this section (Fauquette et al., 1999).

The pollen flora of the locality (Fig. 3) is characterised by the predominance of herbs (mainly Asteraceae and Poaceae, *Lygeum*, *Nitraria* and *Calligonum*), indicating dry to very dry environments. Mediterranean xerophytes are very frequent, making pollen assemblages very close to the modern thermo-mediterranean association (Bessais and Cravatte, 1988). The presence of pollen grains of arboreal taxa (mainly deciduous *Quercus*, Taxodiaceae, *Alnus*, *Carya*) indicates more humid places in the hinterland and along the rivers. *Pinus* is moderately abundant. As for Andalucia G1, pollen data do not show any distinct variation in the vegetation between the Messinian and Pliocene parts of the section.

2.5. The Adriatic Sea–Po Valley area

The Borgo Tossignano and Monticino 88 (also named Cava Li Monti) sections have been sampled in the Vena del Gesso Basin, in eastern Italy (Fig. 2), and correspond to the Gessoso-Solfifera Formation (Vai and Ricci Lucchi, 1977). The age of the sections is well constrained by paleomagnetic and cyclostratigraphic studies (Krijgsman et al., 1999a) (Fig. 3). The pollen data have been established by Bertini (1992, 1994a,b) and illustrate the vegetation during the evaporitic phase. Because of the barren nature of the gypsum beds, only the euxinic shales of the Gessoso-Solfifera Formation were analysed.

The Maccarone section is located southward, in the Marchean outer basin of east-central Italy (Fig. 2). Messinian clays and marls [lower post-evaporitic sequence «p-ev1» of Roveri et al. (2001), also named «di tetto» Formation], which are interbedded at the top of the formation with evaporitic limestones [upper post-evaporitic sequence «p-ev2» of Roveri et al. (2001), also named Colombacci Formation which includes the Lago Mare facies], are overlain by the Argille Azzurre Formation. A volcanic ash layer in the lower part of the section has provided two ^{40}Ar/^{39}Ar plateau ages of 5.51 and 5.44 ± 0.04 Ma (Odin et al., 1997), a similar age being obtained by H. Maluski (personal communication). Based on this absolute age and biostratigraphy (Carloni et al., 1974), and to its continuously reversed paleomagnetic signal (G. Napoleone, personal communication), the Maccarone section covers the time interval from the end of the Messinian (from ~5.6 Ma) to the Early Pliocene. The palynology of the Maccarone section has been published by Bertini (1994a,b, 2002).

The Torre Sterpi section is located in the Po Valley, near Tortone and corresponds to the Lago Mare Formation (Corselli and Grecchi, 1984). The Adriatic–Po region is considered to have evolved as a perched basin in the latest Messinian, i.e. independently from the Central Mediterranean Basin (Corselli and Grecchi, 1984; Clauzon et al., 1997) (Fig. 1). The pollen data have been established by Suc (unpublished) and recently completed by Sachse (2001).

The pollen flora is very diverse (Fig. 3). Tropical elements (i.e. the megathermic elements) living under warm and moist or dry conditions are present in low quantities in the lower part of Maccarone section (Bertini, 1994a,b), especially those (*Agave*, *Cordyline*, *Nolina*, *Bombax*, *Canthium* type, etc.) that disappeared from the northwestern Mediterranean region in the earliest Serravallian (Bessedik et al., 1984), and from the southwestern Mediterranean region in the latest Messinian [Sicily: Suc and Bessais (1990); North Africa: Chikhi (1992), Bachiri Taoufiq (unpublished)]. Subtropical elements (i.e. the mega-mesothermic elements) and warm-temperate elements (i.e. the mesothermic elements) living under a year-long humid and warm climate (*Engelhardia, Taxodium*, *Myrica*, *Nyssa*, etc.) are common and uniformly represented at Borgo Tossignano, Monticino 88, Maccarone and at Torre Sterpi. Deciduous forest elements indicative of warm-temperate and temperate climates (*Quercus*, *Carya*, *Ulmus–Zelkova*, etc.) record a gradual decrease from the Messinian to the Zanclean. The Mediterranean evergreen elements (*Quercus ilex* type, *Olea*, *Phillyrea*, etc.) are sporadic. In the upper part of the Maccarone pollen diagram, *Cathaya*, *Cedrus* and *Tsuga* (the mid-altitude trees), are overall fairly abundant. Mountain elements such as *Picea* and *Abies* are always present but in low quantities. Herbaceous pollen grains (Asteraceae, Poaceae including *Lygeum*, Amaranthaceae–Chenopodiaceae etc.) are numerous in the basal part of the Maccarone succession. *Pinus* is not very abundant, except in the upper part of the Maccarone pollen diagram.

The coastal vegetation was characterised by widespread lagoonal zones, where *Taxodium* thrived alongside *Myrica*, *Nyssa* and others. The size of the basin probably reduced somewhat during the two steps of the salinity crisis, providing a continuous and important record of coastal environments in the distal pollen localities. A break occurred at about 5.4 Ma in the Maccarone section which probably became more distant from the shoreline as it corresponds to an increasing frequency of disaccate pollen grains (*Pinus* and the high altitude elements *Tsuga*, *Cedrus*, *Abies* and *Picea*) which are favoured by transport, compared to non-disaccate pollen grains, and consequently are relatively more abundant offshore (Bertini, 1994a). This pollen flora characterise marine sediments of the early Zanclean high-sea level (Bertini, 1994a).

The pollen flora of the lower half of the Maccarone section shows similarities with the Sicilian herbaceous vegetation (about 5° farther south in latitude), with abundant Poaceae including *Lygeum* and the presence of some megathermic elements (although less important than in Sicily). But abundance of Taxodiaceae and of mid- to high-altitude elements, and scarcity of herbaceous plants at Torre Sterpi and in the second half of the Maccarone section, make the pollen flora very close to those of Zanclean sections from Liguria and French Southern Alps (Zheng and Cravatte, 1986) but strikingly different from those found for the same time interval at Capo Rossello in Sicily (Suc and Bessais, 1990), as detailed immediately below. This northward migration of thermophilous taxa (some of them being adapted to dryness) will be discussed later.

2.6. The Central Mediterranean margins: example of Sicily

The Capodarso section, situated in the Caltanissetta basin, consists of 170 m of claystones overlain by the Tripoli Formation and the Calcare di Base. This section is overlain by the Lower Sicilian Evaporites. Many samples from the Tripoli Formation were analysed for foraminifers, dinocysts, palynofacies, $CaCO_3$, pollen grains and clay minerals (Suc et al., 1995c). These data together showed that the general evolution of the basin was from normal marine conditions to confinement and that the sedimentation of the Caltanissetta basin up to the beginning of the Messinian salinity crisis was controlled by global sea level.

The micropaleontology of clayey layers within halite and kainite bodies in the Salt Member of the Lower Evaporitic Complex in the Messinian Gessoso-Solfifera Formation, has been studied in samples taken from the Racalmuto and Realmonte salt mines, also located in the Caltanissetta basin (Bertini et al., 1998). The Upper Evaporites, represented in the reference-section of Eraclea Minoa in the Caltanissetta basin, are composed of six major gypsum–clay alternations (Decima and Wezel, 1973; Mascle and Heimann, 1976), the last one corresponding to clays of the Lago Mare facies and silts of the Arenazzolo Formation. Following the scenario of Clauzon and Suc for the Messinian salinity crisis (see above), a hiatus 370 kyr long exists between the Arenazzolo Formation and the lowermost Zanclean Trubi Formation (Clauzon et al., 1996). A palynological study has been undertaken on 32 samples from clays interbedded with the gypsum, in the clays of the Lago Mare facies, and in the silts of the Arenazzolo Formation.

The early Zanclean in the Caltanissetta basin is represented by the Capo Rossello section, corresponding to the Trubi formation. The pollen data have been collected by Suc and Bessais (Suc and Bessais, 1990; Suc et al., 1995a), and the corresponding climatic reconstruction has already been published (Fauquette et al., 1999).

Hence, so far as the five sections of the Caltanissetta basin are representative of the Messinian succession and the Early Pliocene, with the pre-evaporitic Messinian clays and diatomites (the Tripoli Formation) at Capodarso, the Lower Evaporites at Racalmuto and Realmonte mines, the Upper Evaporites at Eraclea Minoa and finally the Lower Pliocene at Capo Rossello, it is possible to describe the vegetation evolution from the Lower Messinian to the Early Pliocene, keeping in mind that some deficiencies in the pollen record exist (lack of pollen grains within evaporites, hiatus in sedimentation at the top of the Arenazzolo Formation).

The more important variations observed in the pollen diagrams (Fig. 3) are due to relevant variations in *Pinus* pollen percentages. *Pinus* excepted, the pollen spectra are dominated by herbs showing an open and xeric environment, at least on the littoral: arboreal taxa were certainly growing in the hinterland. Megathermic elements are regularly recorded, especially at Capodarso, but they progressively decrease from the Lower Messinian to the Zanclean (Suc and Bessais, 1990). Within these tropical elements is the mangrove taxon *Avicennia*. The last appearance of *Avicennia* is found at Eraclea Minoa, at 3.48 m. No pollen grains of this taxon have been found at Capo Rossello during the Early Pliocene.

2.7. The Eastern Paratethys region

A palynological study has been performed on Upper Miocene to Lower Pliocene sediments cored at DSDP Site 380A, in the southwestern Black Sea (Fig. 2) (Popescu, 2001, 2006-this volume). The borehole at site 380A penetrates a 19 m thick «Pebbly Breccia» including blocks of stromatolitic dolomite (Ross et al., 1978) which is considered to have formed in an intertidal to supratidal environment (Stoffers and Müller, 1978). This suggests, together with diatom data, that the Black Sea was very shallow at that time (Schrader, 1978). This sea-level drop of the Black Sea has been interpreted by Hsü and Giovanoli (1979) as the consequence in the Black Sea of the Messinian salinity crisis.

Pollen data show, through the whole section, a forested environment, dominated by subtropical taxa such as *Engelhardia*, *Myrica*, *Distylium* cf. *sinensis*, Taxodiaceae, Sapotaceae, etc. Mesothermic elements are also abundant. However, the herbaceous elements, and in particular steppe elements (mainly *Artemisia*), are better represented during the Pliocene than during the Late Miocene. Anyway, in this area, steppe elements begin to develop just before the hiatus («Pebbly breccia») that putatively corresponds to the Messinian salinity crisis. Consequently conditions seem to become drier from the end of the Messinian and during the Pliocene, even if it was initiated before the crisis.

3. Climate quantification

In the present study, climatic reconstructions have been made on the pollen data using the «Climatic Amplitude Method». This method was developed by Fauquette et al. (1998a,b) specifically to quantify the climate of periods for which there are, currently, no modern analogue of the pollen spectra. The basis of this method consists of transposing the climatic requirements of the maximum number of modern taxa to the fossil data.

This method relies on the relationship between the relative pollen abundance of each individual taxon and the climate. The most probable climate for a set of taxa corresponds to the climatic interval suitable for the maximum number of taxa. The climatic estimate is obtained as a climatic interval and a «most likely value», which corresponds to a weighted mean.

Five climatic parameters have been estimated in this study from the pollen data: the mean annual temperature (T_A), the mean annual precipitation (P_A), the temperature of the coldest and warmest months (T_C and T_W) and the available moisture (i.e. the ratio actual evapotranspiration on potential evapotranspiration, *E/PE*).

Plants were separated into three groups, looking at their modern distributions, as described in Fauquette et al. (1998a): ubiquitous plants, plants growing under warm conditions (low latitude/altitude taxa) and plants growing under cold conditions (high latitude/altitude taxa). As we want to estimate the climatic parameters for lower altitudes, the two first groups of plants only are used in the reconstruction process.

As in Fauquette et al. (1998a, 1999), the pollen of *Pinus* and non-identified Pinaceae (due to poor preservation) have been excluded from the pollen sum of the fossil spectra because they are over-represented in the marine, and even coastal, deposits due to their prolific production and overabundance from air and water transport (Heusser, 1988; Suc and Drivaliari, 1991; Cambon et al., 1997).

For most of the pollen sequences, climatic estimates have been calculated on the sum of the spectra and are reported on maps (Figs. 4, 7 and 9). For three of the sequences, long «key-sections» (i.e. Maccarone, Bou Regreg and Site 380A in the Black Sea), climatic estimates have been calculated for each pollen spectrum (or for the sum of 3–4 levels at the bottom of Bou

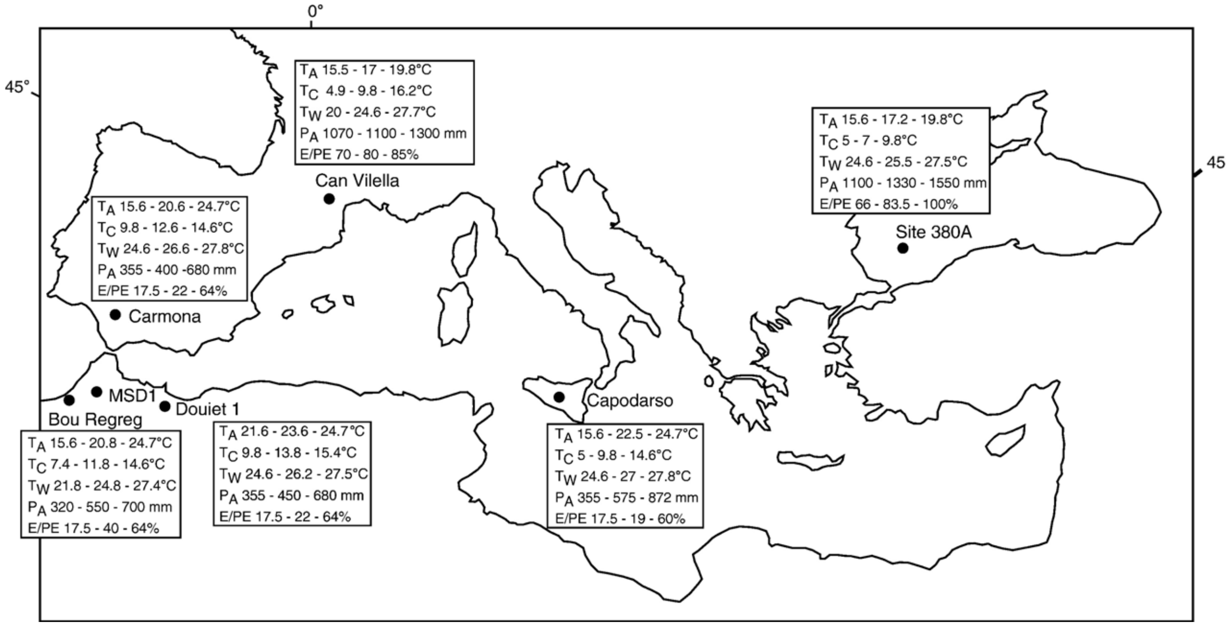

Fig. 4. Climatic quantification results based on pollen data from the period preceding the Messinian salinity crisis (early Messinian). T_A: mean annual temperature, T_C: mean temperature of the coldest month, T_W: mean temperature of the warmest month, P_A: mean annual precipitation, *E*/PE: ratio

Regreg sequence where pollen spectra are particularly poor) and are given on graphs (Figs. 5, 6 and 8).

3.1. The climate before the Messinian salinity crisis (Figs. 4–6)

In the western Mediterranean region, the climate before the crisis is documented in North Africa (at Douiet 1, MSD 1 sites), Sicily (at Capodarso), Spain (at Can Vilella), along the Atlantic coast (at Carmona and Bou Regreg) and in the Black Sea area.

The climatic reconstruction for this period shows a warm and dry climate in southwestern Spain, North Africa and Sicily. Mean annual temperatures (T_A) were between 15.0–15.5 and 24.7 °C with a most likely value (MLV) ranging between 20.5 and 22.5 °C. Only the Douiet 1 and MSD 1 sites show higher values (21.6 to 24.7 °C with a MLV around 23.7 °C). Temperatures of the coldest (T_C) and warmest (T_W) months are similar for all the sites (T_C between ~8 and 14.6–15.4 °C with most likely values around 11–14 °C, and T_W between 22 and 27.8 °C with most likely values around 25–26.5 °C). Mean annual precipitation is very low everywhere, even at Carmona along the Atlantic coast (between ~350 and 700 mm with most likely values around 400–500 mm). The lower part of Bou Regreg sequence displays important variations in the most likely value (Fig. 5) due to the presence or absence of such taxa as *Quercus* deciduous type, and *Carya*. However, estimated intervals do not show variations. The ratio *E/PE* (corresponding to the available moisture) shows low values, comprising between 17.5% and 60–64%, with a MLV around 20%.

At Can Vilella, in Cerdanya, the climate was warm and humid. T_A was around 15 to 19.8 °C with a MLV of 17 °C, T_C between 5 and 12.5 °C with MLV of 9 °C, and T_W between 23.5 and 27.7 °C with a MLV of 25.5 °C. Mean annual precipitation was high, ranging between

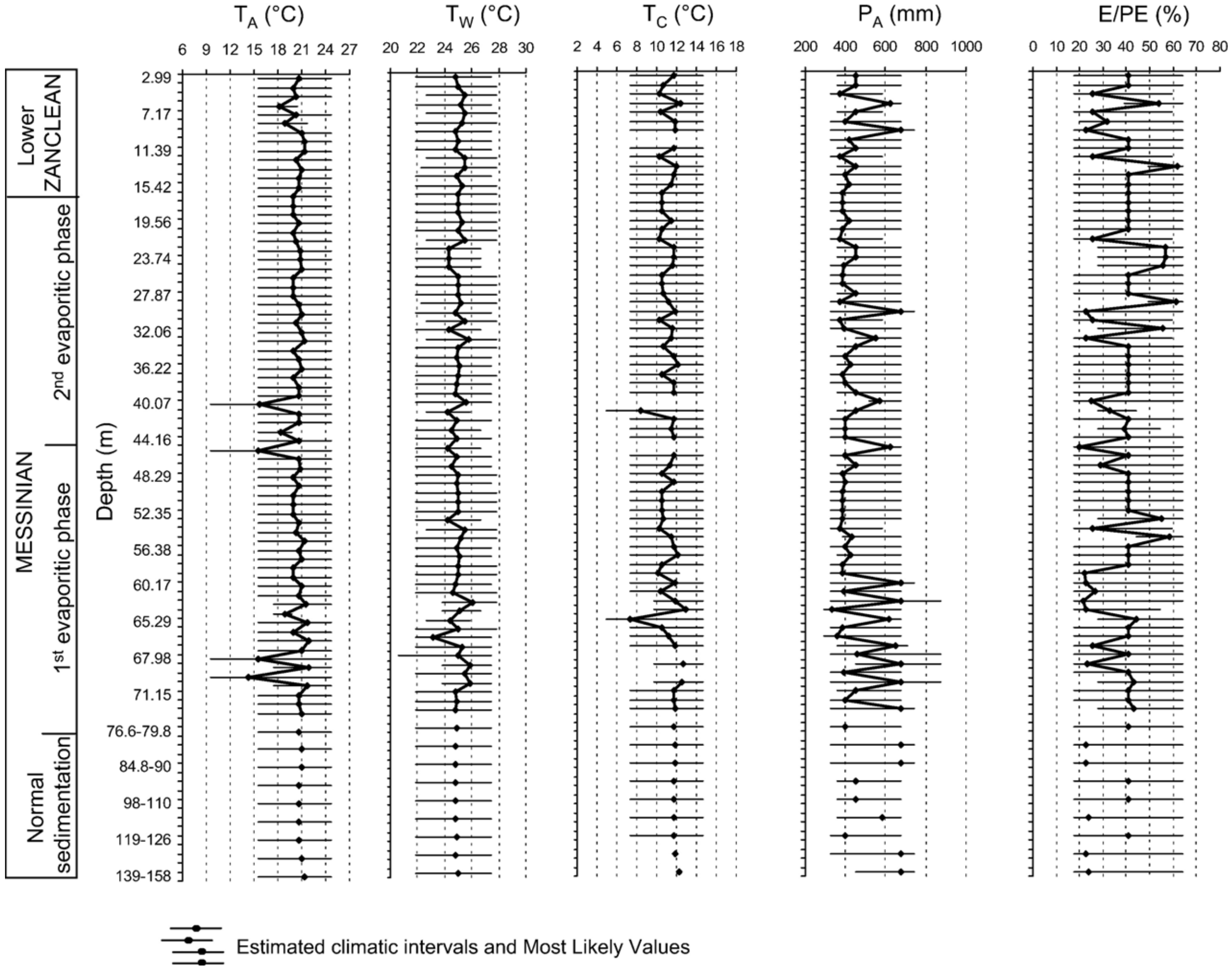

Fig. 5. Climatic quantification results based on pollen data from Bou Regreg for the entire Messinian.

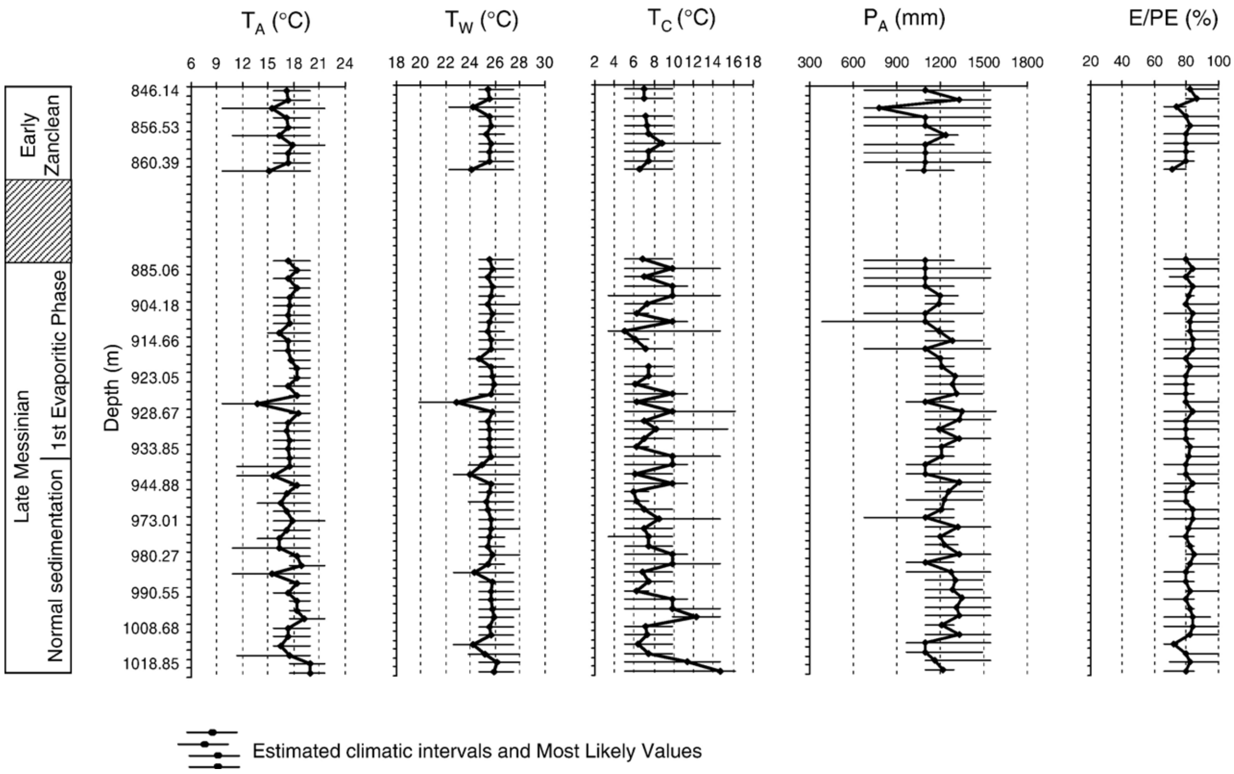

Fig. 6. Climatic quantification results based on pollen data from Site 380A covering the periods just before the Messinian salinity crisis, during the first evaporitic phase and the early Pliocene.

1000 and 1350 mm with a most likely value of 1150 mm. The ratio *E*/PE was between 66% and 84% with a MLV of 72.5%.

The climate before the Messinian salinity crisis is also documented in the Black Sea area (DSDP Site 380A) (Figs. 4 and 6). There the climate was warm and humid at the beginning of the Messinian. On Fig. 4 are reported values corresponding to a mean climate for this period. Mean annual temperatures were between 15.6 and 19.8 °C with MLV around 17.3 °C (sometimes higher at the beginning of the sequence), temperatures of the coldest month ranged between 5 and 9.8 °C, with a most likely value around 7 °C, temperatures of the warmest month ranged between 24.6 and 27.5 °C with a MLV around 25.5 °C. Mean annual precipitation was between ~1100 and 1550 mm with a MLV around 1200–1300 mm. The available moisture was important, between 66% and 100% with a most likely value of 83.5%. Looking in more detail at Fig. 6, annual precipitation, mean annual temperatures and temperatures of the coldest month show oscillations around the mean values, depending on the presence or absence of megathermic elements in the spectra.

3.2. The climate during the Messinian salinity crisis (Figs. 7 and 8)

The climate during the first desiccation phase of the Messinian salinity crisis in the Mediterranean region is documented for Sicily (Racalmuto and Realmonte mines, Eraclea Minoa), at Carmona, Tarragona, Andalucia, Habibas, Bou Regreg, in the Po Valley, at Borgo Tossignano, Monticino 88 and in the Black Sea area. The end of the Messinian salinity crisis is documented at Torre Sterpi, in the Po Valley and Maccarone, and along the Adriatic coast (Figs. 3 and 7).

At Racalmuto, Realmonte, Eraclea Minoa, Carmona, Andalucia, Tarragona, Habibas and Bou Regreg, the climate during the first desiccation phase was warm and dry, with the same climatic amplitudes as before the crisis. The site of Tarragona, located more to the north, shows slightly higher values of mean annual precipitation (between ~700 and 900 mm with a MLV around 800 mm) and of *E*/PE with values between 17.5% and 99% (most likely values of 58%).

In the Po Valley, the climate during both first and second evaporitic phases was warm and humid with mean annual temperatures between 15.5 and 19.8 °C

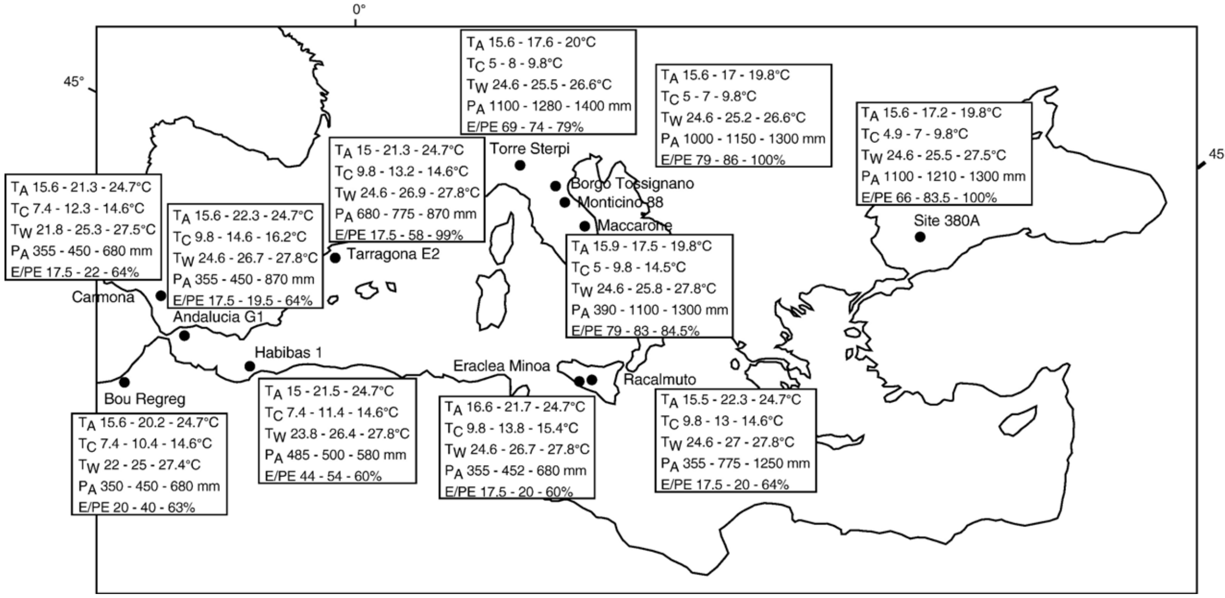

Fig. 7. Climatic quantification results based on pollen data corresponding to the Messinian salinity crisis (1st evaporitic phase: Andalucia, Habibas 1, Tarragona E2, Carmona, Monticino 88, Borgo Tossignano, Eraclea Minoa, Racalmuto, Realmonte mines, Site 380A; 2nd evaporitic phase: Maccarone, Torre Sterpi).

(MLV around 17 °C), mean temperatures of the coldest month between 5.0 and 9.8 °C (MLV around 6.5–7.5 °C), and mean temperatures of the warmest month between 24.6 and 27–28 °C (MLV around 25 °C). Mean annual precipitation was around 1000 and 1300 mm (MLV around 1100–1200 mm), and the available moisture was between 80% and 100% (MLV around 86%).

At Maccarone, one of the «key-site», we present the climatic evolution along the sequence which covers the period from around 5.5 to the Early Pliocene (Fig. 8). Mean annual temperatures were between about 16 and 20 °C for most spectra but up to 23–24.5 °C for some, with most likely values oscillating between 17 and 20 °C (only 1 spectrum shows a lower MLV around 15 °C). Estimated temperatures of the coldest month show significant changes during the first part of the sequence. These temperatures are between 5 and 15 °C or 5 and 10 °C or also 10 and 15 °C. Most likely values are mostly between 7 and 12 °C but up to 15 °C for two samples. On the other hand, during the second part of the sequence, temperatures of the coldest month are more stable, between 5 and 10 °C for most of the spectra, with a MLV of around 7 to 10 °C. Temperatures of the warmest month are relatively stable along the first part of the sequence, between 24.5 and 28 °C with a most likely value oscillating between 25 and 27 °C. Mean annual precipitation is less stable along the sequence. The first part of the sequence is characterised by both large intervals from around 400 to 1300 mm and a MLV of 1100 mm and smaller intervals from 1100 to 1300 mm whereas the second part of the Messinian stage is characterised by more precise ranges from 700 to 1300 mm with a most likely value around 800 to 1200 mm.

In the Black Sea region, the estimated climate is the same as during the previous period, warm and humid, but with lower values of mean annual precipitation (650 to 1300 mm with MLV ~1100 mm) at the very end of the Messinian part of the sequence (Fig. 6).

3.3. The climate after the Messinian salinity crisis, at 5.33 Ma (Figs. 8 and 9)

For some sites (Tarragona, Andalucia, Habibas, Capo Rossello), the climate has already been reconstructed (Fauquette et al., 1999). Values are given again in Fig. 9.

As for the previous interval, the climate was warm and dry in the southwestern Mediterranean region but warm and humid at Maccarone and in the Black Sea region. At Maccarone, along the Adriatic Sea, the climate was exactly as at Stirone in the western part of the Po Valley (Fauquette and Bertini, 2003). However, looking at the detailed climatic reconstruction at Maccarone (Fig. 8), mean annual temperatures and in particular mean temperature of the coldest month show

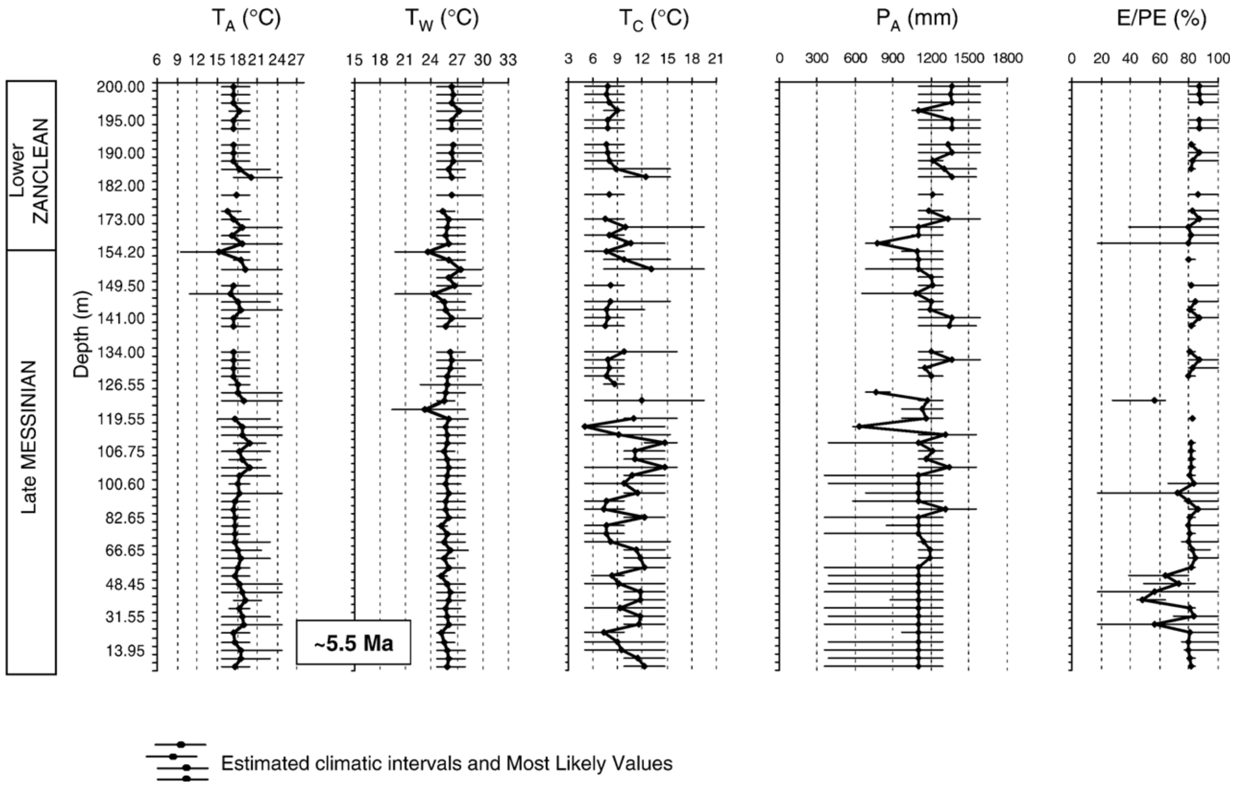

Fig. 8. Climatic quantification results based on pollen data from Maccarone covering the end of the Messinian salinity crisis (from around 5.5 Ma) and the lower Zanclean.

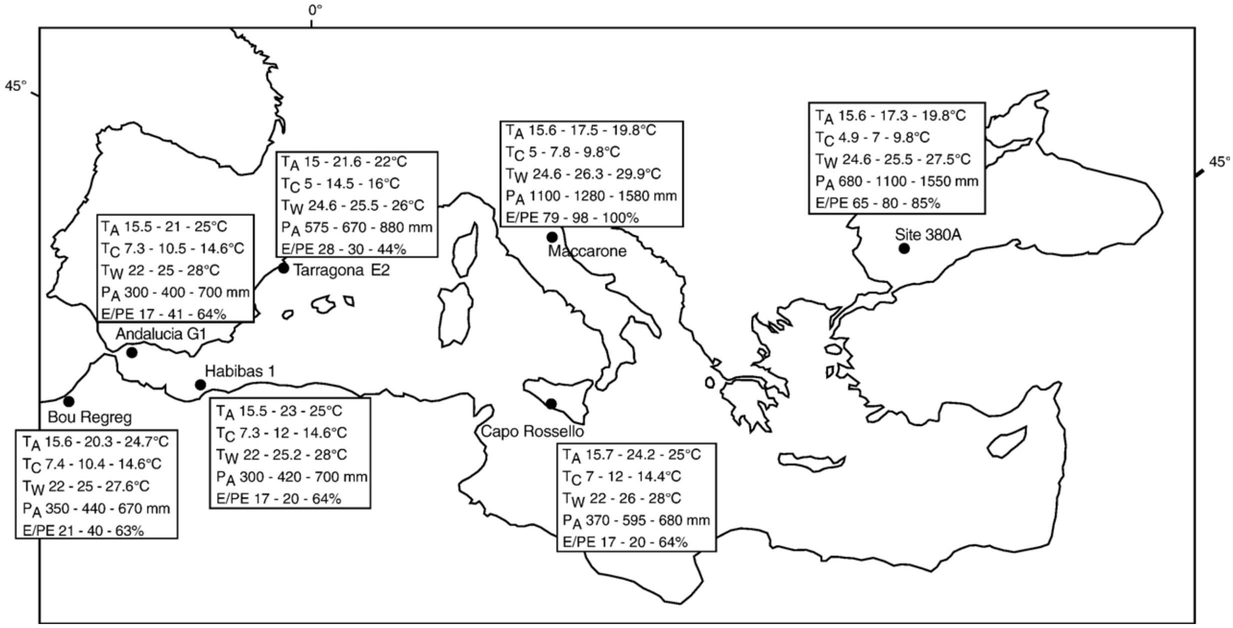

Fig. 9. Climatic quantification results based on pollen data corresponding to the period after the Messinian salinity crisis, i.e. the Early Pliocene.

lower values (except for 2 spectra) which never again exceed 20 and 10 °C respectively. During this period mean annual precipitation shows higher values than during the previous part of the sequence, ranging between 1100 and 1600 mm. Similarly, Fig. 6 shows for the Black Sea region larger ranges of mean annual precipitation than during the previous period, from around 680 to 1550 mm, due to larger amounts of herbs in the spectra. Temperatures of the coldest month never again exceed 10 °C (except for one spectrum), in contrast to the Messinian part.

4. Discussion

A first examination of the synthetic pollen diagrams in Fig. 3 reveals a high regional variability according to geographic location and conditions (latitude, longitude, proximity of highlands, oceanic influence, etc.). Whatever the period, herb frequency increases southward in contrast to tree frequency. This indicates that open and probably dry environments existed in the southern Mediterranean region prior to, during and after the salinity crisis. Trees (including high altitude elements) developed in areas close to mountains such as in the Po Valley (Alps and Apennines), in Cerdanya (Pyrenees) and in Black Sea (Plateau of Anatolia). Nevertheless, the influence of relief appears insufficient to explain high values of thermophilous trees in lands surrounding the Black Sea. The location of this region in southeastern Europe, where the Asian monsoon extended some control, needs also to be considered (Popescu et al., 2006-this volume). Indeed, strengthening of the Asian monsoon over the Eastern Mediterranean region during the late Miocene–earliest Pliocene has been discussed by Griffin (2002).

To the south, herb assemblages are dominated by Poaceae, Asteraceae, *Plantago*, *Erodium* and some very characteristic plants such as *Lygeum*, *Nitraria*, *Calligonum* and *Neurada*. *Lygeum* today characterises the southern Mediterranean region under a thermo-mediterranean climate (from semi-arid to arid conditions, with mean annual precipitation from around 500 to 100 mm, and under high annual temperatures from around 16 to 26°C; Fauquette et al., 1998b). *Nitraria*, *Calligonum* and *Neurada* are found today only in North Africa, in the Sahara, under hyper-arid conditions, with mean annual precipitation under 150 mm. Mediterranean xerophytes are frequent in a latitudinal strip extending from Tarragona to Sicily. In the Nile delta area, the abundance of herbs has a different significance because assemblages are dominated by Cyperaceae and Poaceae which evoke a savannah landscape in the northeastern Africa realm. The development at so high a latitude of such a vegetation, which requires relatively humid and warm conditions, is also supported by the abundance of megathermic (i.e. tropical elements in the Naf 1 pollen diagram; Poumot and Suc, 1984) taxa. Such a vegetational structure in the southeastern Mediterranean region is in agreement with the hypothesis of Griffin (2002) who proposes an increase of moisture over this area during the salinity crisis but appears to contradict the modelling of climate and vegetation (Fluteau et al., 2003; François et al., 2006-this volume). Perhaps the climatic contrast between central and southeastern Mediterranean regions has many subtle touches, the latter region being less altered by an increase in dryness than the former.

Obviously, most of the variations observed in the pollen diagrams are constrained by fluctuations in the quantity of *Pinus* (Fig. 3). In fact, *Pinus* pollen grains are very effectively transported by air and water, so that variations in percentages indicate variations in the position of the coastline (i.e. eustatic variations). When the littoral zone is far from the sedimentation point, *Pinus* is largely over-represented and inversely, when the littoral zone is close to the site of deposition, *Pinus* is less important compared with the other taxa. Pollen diagrams for Bou Regreg, Carmona, Monticino 88, Maccarone, Capodarso, and Eraclea Minoa demonstrate this effect well. In any case, excluding *Pinus* from the pollen sum results in pollen sequences of almost homogeneous composition, supporting the idea that no relevant climatic change occurred in the Mediterranean region between 6.7 and 5.0 Ma, i.e. just before, during and just after the salinity crisis. This is in good agreement with Münch et al. (2003) who see no climatic variations between 6.9 and 6.0 Ma from the study of coral reefs. Interpreting such pollen diagrams initially in terms of coastline variations (i.e. eustasy fluctuations) is in good agreement with variability in the amounts of halophytes (plants living in saline environments along the shoreline). Pollen of these plants generally increase as *Pinus* percentages decrease (at Capodarso, Eraclea Minoa, in the Messinian part of Site 380A, for example). Interpretation of the pollen diagram of DSDP Site 380A is more complicated because a climatic signal overprints the «eustatic» one. This has been clearly evidenced by Popescu (2006-this volume) for the early Pliocene part of the section where the expected earliest Zanclean age of sediments overlying the breccia has been confirmed using European climatostratigraphic relationships. Just below the breccia, desiccation of the Black Sea is supported by large amounts of halophytes between 935 and 900 m depth interpreted as a moderate lowering of sea level, probably related to the first step of the salinity crisis (Fig. 3). This is in agreement with the reverse curve of *Pinus*, the greater percentages of which reveal more distal conditions (i.e. probably a higher sea-level). The increase in *Pinus* above 900 m depth could be related to the sea-level rise that corresponds to the Sicilian Upper Evaporites (isotopic stage TG 15) (for more details, see Popescu, this volume).

It is well established that the inverse relationship between *Pinus* and halophytes reflects the distance of the pollen locality to the paleo-coastline (Suc et al., 1995c). But there is some uncertainty about whether to interpret some herbs as halophytes. For example, *Artemisia* may have an edaphic (halophytic) or a climatic significance. This question affects Site 380A. For the Pliocene, large amounts of, and variations in *Artemisia* are clearly linked to climate evolution (Popescu, 2006-this volume). The development of *Artemisia* at the end of the Miocene might have double significance: proximity of the shoreline because of the Messinian sea-level drop and/or increasing dryness in the regional climate (Fluteau et al., 2003; François et al., 2006-this volume). So, the decreasing mean annual precipitation observed on Fig. 6 at the end of the Messinian may be an artefact, or not.

Climatic quantification from pollen data does not show obvious climatic change due to the desiccation of the Mediterranean Sea, especially in the dry southwestern Mediterranean area. Sicily, southern Spain and also North Africa, where the vegetation was subdesertic, are certainly not the best regions to detect climatic variation, especially if small in amplitude. Indeed, a slight change in temperature is certainly not sufficient to modify this type of open vegetation. On the contrary, a small increase in precipitation is sufficient to modify the vegetation in these regions. But there are no real changes in the vegetation composition, or associated changes in precipitation, observed at time of the Messinian salinity crisis (many herbaceous plants and subdesertic plants have been recorded continuously).

We have emphasised the presence in some pollen spectra (Sicily: Capodarso and Eraclea Minoa; North Africa: Douiet 1 and MSD1; Black Sea: Site 380A) of *Avicennia*, a mangrove taxon. Even at very low quantities, the occurrence of *Avicennia* pollen grains indicates the presence of mangrove close to the sampled site, as the taxon is under-represented in the modern pollen floras (Blasco and Caratini, 1973; Lézine, 1996). But it seems that in Sicily and North Africa during the Messinian, the mangrove communities were impoverished compared with modern tropical mangroves. Such impoverished mangroves are found today in the northern part of the Red Sea area, extending as far as 30°N, i.e. considerably beyond the tropical zone where fully developed mangroves are growing. In fact during Messinian time, the North African, Sicilian and northern Turkish mangroves were certainly highly discontinuous, at their northern limit of distribution, and thus decidedly fragile.

In these regions, *Avicennia* ceases to be recorded in the Lower Zanclean, except in the Black Sea which represents its last appearance in the Mediterranean region (at about 4.7 Ma) owing to the suitable wet and warm climatic conditions in the area (Popescu, 2006-this volume). In fact, the flooding of the Mediterranean makes the sampled sites more distal so that *Avicennia*, whose pollen grains are weakly transported, is less likely to be recorded. In spite of this bias, some Zanclean *Avicennia* pollen have been recorded at Site 380A when the Black Sea was full and the site far from the coastline. It should be mentioned that no pollen of *Avicennia* has been found in the earliest Zanclean coastal localities studied from the southern Mediterranean region (Spain, Morocco, Algeria, Tunisia, Egypt, Israel, Turkey, Syria: Suc et al., 1995b, 1999; Drivaliari, 1993; M. Abdelmalek, pers. com.; Suc, unpublished data; Feddi, unpublished data). Accordingly, we feel that the disappearance of *Avicennia* took place before the earliest Zanclean. The disappearance of *Avicennia* was probably due to severe ecological stress, such as the expansion of hypersaline waters during the desiccation of the Mediterranean, rather than to a climatic deterioration. In Sicily, the disappearance of this taxon occurs between the uppermost Messinian at Eraclea Minoa and the lowermost Zanclean at Capo Rossello. If no gap in sedimentation exists between these two deposits (following Krijgsman's scenario; Fig. 1), there is no climatic deterioration to explain such a crucial disappearance. In contrast, the extinction of *Avicennia* along the southern Mediterranean shorelines could be easily explained by the desiccation, the Caltanissetta basin and other deeper areas becoming very dry and salty. These areas would then have been inhospitable to mangrove which had not survived in refugia within the Mediterranean realm and could not have returned. This argument is used to support the scenario of Clauzon et al. (1996).

Because the causes of this taxon's disappearance are still under discussion, it has not been taken into account in the climate estimates, although it is a good ecological and climatic marker. However, the climate reconstructed without *Avicennia* is consistent with modern climatic conditions prevailing in the northern part of the Red Sea (high temperatures and very low precipitation). And, as today in the northern part of the Red Sea (Kassas, 1957), the southern Mediterranean vegetation, prior to the complete desiccation of the sea, was composed of an impoverished mangrove zone, an open subdesertic vegetation zone, and a less open vegetation zone of mainly evergreen and mixed mesophilous taxa at higher elevations.

The lower half of the Maccarone section is characterised by the presence, among a large representation of herbaceous plants, of pollen grains of *Lygeum* (up to 7.6%), a Poaceae found today in North Africa, southern Italy, Sicily, southern Spain and Crete, under a thermo-mediterranean semi-arid to arid climate. Thus, this plant indicates very dry conditions in contradiction with the abundance of subtropical plants requiring humidity. This seems to indicate more humid conditions at the foothill and on the slopes of the uplifting Apennines and drier conditions in littoral areas. This hypothesis is reinforced by *Lygeum*'s unique morphology (a relatively big and heavy pollen grain) and, consequently, its weak affinity for transport, so that its presence in the sediments indicates that the plant was living in littoral areas.

Such a composite pollen spectra with plants coming from two different vegetation types lead to very broad climatic estimates, particularly with respect to mean annual precipitation.

It is pertinent to ask whether *Lygeum* was already present at Maccarone before the Messinian salinity crisis. In other words, is the presence of *Lygeum* at so high a latitude (at about 4–5° more than its modern habitat) directly related to the crisis or not? The first possibility is that *Lygeum* was present at Maccarone before the crisis and that a geographic and climatic threshold already existed between Monticino/Borgo Tossignano and Maccarone. The second possibility is that *Lygeum* was not present at Maccarone before the crisis because the harsh ecological conditions imposed by the crisis (expanding saline environments) led to the migration of *Lygeum* with other herbaceous companions from south (Sicily, Calabria) to north, where ecological conditions were more suitable. The apparent absence of *Lygeum* in the pollen record of Moscosi, a thin deposit underlying the Maccarone section, constitutes an argument in favour of the migration to the North of *Lygeum* during the salinity crisis. In any case, the possible migration of subdesertic herbs to the north is considered by Clauzon et al. (2005) as a reliable argument (in addition to the radiometric age of the Maccarone ash) for proposing that the Adriatic–Po realm became a perched basin still supplied by freshwater runoff from the surrounding mountains when the Mediterranean Sea was desiccated.

Approximately 120 m above the base of the Maccarone section, the strong and sudden decrease in tropical, subtropical, and warm-temperate elements and herbaceous plants, including *Lygeum* (correlated to a decrease in temperatures of the coldest month and, less importantly, to a decrease in mean annual temperatures), viewed against the increase in Pinaceae may be interpreted as a significant paleoenvironmental change. Such a break represents a suddenly increasing distance of the site from the coastline, and has been related to a eustatic/tectonic event by Bertini (1994a, 2002) and Roveri et al. (2001), but to the massive marine transgression in the area by Clauzon et al. (2005). Our understanding of the Maccarone pollen flora may be supported by the data of Vidal et al. (2002) who indicate that the second phase of evaporite deposition should occur during a period of global warming. So, the drastic vegetational changes recorded at Maccarone after 5.5 Ma may not be due to a cooling but rather to regional environmental changes. In fact Maccarone is certainly not a «key-site» for understanding the climate during the Messinian salinity crisis. The pressure of environmental change is so severe that it is difficult to distinguish the relative effects of the climate and/or of the supposed flooding.

The Messinian salinity crisis is a phenomenon in the Mediterranean region, and its influence certainly extends beyond the Mediterranean region, but it is difficult to extricate all the mechanisms involved. Generally, the Messinian salinity crisis is thought to be linked to a eustatic control (Kastens, 1992; Zhang and Scott, 1996), but the timing of the isotope events compared with the chronology of the crisis suggests that global sea-level variations are not alone responsible for the beginning or the end of the crisis (Hodell et al., 2001; Vidal et al., 2002). In the same way, the climatic evolution in the western Mediterranean area shows that the climate is not the direct cause of the Mediterranean desiccation, as the Mediterranean region was subjected long before the crisis to continuously high evaporation (this study; Suc and Bessais, 1990; Bertini, 1994a,b; Bertini et al., 1998; Warny and Wrenn, 2002; Warny et al., 2003). It, therefore, now seems clear that the main factor leading to this event is the closure of the Rifian corridor after that of the Betic corridor, isolating the Mediterranean Sea from the Atlantic Ocean (Clauzon et al., 1996; Krijgsman et al., 1999a,b).

Of course, other mechanisms, all more or less interdependent, are also involved in this event, such as global climate evolution, global eustasy, sea temperatures, ocean circulation, and ice volume variation (Antarctic and Arctic). Knowing that the Mediterranean Sea is supplied mainly by Atlantic waters, closure of the passage from the Atlantic to the Mediterranean, associated with a known global sea-level drop (Vidal et al., 2002), led to evaporation being more important than filling and, as a consequence, to the desiccation of the basin. On the other hand, it has been proposed that the abrupt regional sea-level rise that reflooded the Mediterranean Sea may have been related to accelerated ice volume reduction caused by a thinning of the Antarctic ice sheet (Warny et al., 2003), and that this facilitated erosion within the Gibraltar Strait and thus its opening (Blanc, 2002).

5. Conclusions

An intensive pollen review allows us to present this first regional synthesis for the period including the Messinian salinity crisis. Two main contrasting areas are evident with respect to the vegetation cover: a southern Mediterranean area characterised by dominant open vegetation growing under dry and warm conditions, and a northern Mediterranean area inhabited by forest assemblages (humid and warm conditions) especially close to upland areas. Few changes are recorded in the pollen diagrams, these being mostly linked to variability in *Pinus* percentages controlled by variations in distance of site from the shoreline, i.e. to eustatic variations. This suggests that no significant climatic change occurred during the studied period, an inference confirmed by climate quantification. Some megathermic elements disappear from the Mediterranean realm at the Messinian–Zanclean transition: the most impressive concerns the mangrove element *Avicennia*. Our observations suggest that its regional extinction was caused by its inability to survive in increasingly saline coastal environments as the Mediterranean Sea was desiccating. A noticeable expansion of herbs (including subdesertic elements such as *Lygeum*) to the north occurred between 5.5 and about 5.4 Ma, i.e. when the Mediterranean Sea had become desiccated. This migration might be related to increasingly harsh conditions in the desiccated areas without the need to invoke a climatic change towards drier conditions some 4–5° northward in latitude. It is probable that migration of plants was induced by a striking increase in dryness over the central Mediterranean. For example, subdesertic herbs could have moved to the north and tropical–subtropical elements to the southeast without climatic conditions in these areas changing significantly as a response to the desiccation of the Mediterranean. So, the proposed increase in moisture in the southeastern Mediterranean might have been lower than that deduced from the regional geomorphological response to the salinity crisis.

From this study we are able to answer the two questions asked in the introduction: (1) has the climate played a role in triggering the Messinian salinity crisis? and (2) has the Messinian salinity crisis changed the climate in the Mediterranean region?

Regarding the first question, climate was not the direct cause of the Messinian salinity crisis. This is also evident from the δ^{18}O records. Indeed, the Mediterranean region was submitted to continuously high evaporation long before the crisis, especially in the south. Given that the Mediterranean Sea is supplied mainly by Atlantic waters, a closure of the passage from the Atlantic to the Mediterranean led to evaporation unrestored by entry of oceanic waters, i.e. to a negative regional hydrological budget.

Regarding the second question, the Messinian salinity crisis seems not to have changed the climate in the Mediterranean region, in particular in the southwestern area, where the climate was very dry and warm before, during and after the event. Some other climatic variations (weak decrease in precipitation at the beginning of the crisis in the Black Sea region, increasing precipitation and decreasing temperatures at the end of the Messinian at Maccarone) may be related to artefacts. Indeed, some vegetation changes are more due to environmental variations (sea-level change) than to climatic changes. This result seem to be confirmed by model simulations (Fluteau et al., 2003) that show no or little changes in the Mediterranean region and in the Rifian area (Atlantic side). On the other hand, these authors show that the Messinian salinity crisis seems to influence deeply the summer monsoon in Asia (shift to the West, temperature decrease over India) and Africa (weakening of precipitation). But the lack of data avoids to validate these results.

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well as results of the climatic quantification have been placed on the Medias-France website in the «Cenozoic Pollen and Climatic values database» (C.P.C., for further information contact S. Fauquette, curator of the database) which is being developed within the framework of the EEDEN Programme. E. Bessais (deceased) generated some of the pollen spectra in the Andalucia G1 and Tarragona E2 sections.

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