24. Fine-Tuning the Land–Ocean Correlation for the Late Middle Pleistocene of Southern Europe

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ABSTRACT

A marine pollen record from the Portuguese margin provides the means of correlating vegetation changes in southern Europe with North Atlantic sea-surface temperature and the marine isotope stratigraphy for the interval 180 to 345 kyr (marine isotope stages 7, 8 and 9). It reveals close correspondence between the patterns and timing of forest expansion and contraction and changes in North Atlantic sea-surface temperatures, but pronounced offsets between marine isotopic warm stage boundaries and forested intervals. Our study confirms the previous tentative observation that the latter vary in length from one stage to another and also highlights floristic differences between sites resulting from local climatic, geological and biogeographical factors.

24.1 INTRODUCTION

The pattern of vegetation development in southern Europe during the last 450 kyr is well known from the long pollen records produced in sedimentary sequences from Greece (Wijmstra, 1969; Wijmstra and Smit, 1976), Italy (Follieri *et al.*, 1988) and France (Reille and de Beaulieu, 1995; Reille *et al.*, 1998, 2000) over the last 40 years. In contrast to the majority of sequences from northern Europe, these sites contain continuous records spanning multiple climatic cycles and thus provide an opportunity to study the response of vegetation at individual sites to different combinations of environmental boundary conditions. They reveal a pattern of alternating periods of forest and more open vegetation on timescales of 10^4 to 10^5 years which are clearly a response to the Milankovitch-driven global climatic changes recorded in marine isotope records of global ice volume (Imbrie *et al.*, 1984; Martinson *et al.*, 1987). However, dating uncertainties mean that it has not been possible to determine the precise relationship between changes preserved in marine and terrestrial records on timescales of 10^3 to 10^4 years. If vegetation feedbacks are to be incorporated effectively into climate models, it is essential to establish the exact nature of this relationship (e.g. Crowley and Baum, 1997). Previous correlations have had to assume synchroneity between vegetational shifts and some feature of the marine record. The correlation scheme of Tzedakis *et al.* (1997) aligned four long pollen records from southern Europe to the SPECMAP benthic δ^{18}O stack by assuming synchroneity between forest expansion and deglaciation, a necessary and reasonable assumption at the time. This study clarified the broad equivalence of terrestrial and marine signals, thus demonstrating that the marine isotope stratigraphy is a suitable framework within which to interpret terrestrial environmental records and suggested that the forested intervals, previously assumed to be of similar duration, in fact varied in length from one stage to another. We are now in a position to test the basis of the Tzedakis *et al.* (1997) correlation scheme using a pollen record generated recently in a marine sequence from the Portuguese margin. Combining high-resolution benthic and planktonic foraminiferal oxygen isotope data with pollen data, this sequence records the precise relationship between the marine isotope records of ice volume and sea-surface temperature, and vegetation development on land. Knowledge of this relationship enables fine-tuning of the correlation between the three key southern European pollen sequences which span the late Middle Pleistocene and the marine isotope stratigraphic scheme.

24.2 THE TERRESTRIAL RECORDS

Cores from maar craters in the volcanic region of the Velay, in the French Massif Central, at sites Lac du Bouchet (44°55′N, 3°47′E, 1200 m a.s.l.) and Praclaux (44°49′N, 3°50′E, 1000 m a.s.l.) (Fig. 24.1) have produced a composite sedimentary sequence spanning the period from ca. 450 kyr to the present (Reille and de Beaulieu, 1995; Reille *et al.*, 1995, 1998, 2000). The sequence records an alternation of forest and open landscapes over time on Milankovitch time scales. Forested intervals tend to follow a typical succession, with *Juniperus, Betula* and *Pinus* in the early phases, followed by *Quercus*, *Corylus*, *Carpinus* and other mesic deciduous forest taxa, then *Abies, Fagus* and *Picea* (montane taxa with greater moisture requirements) and finally a period of *Pinus*-dominated woodland. Between forested intervals, abundant *Artemisia*, Chenopodiaceae and Poaceae pollen indicate extensive steppe vegetation. Today mean annual precipitation reaches 1500 mm in this region. Winters are severe, with mean January temperatures of between 0 and 2°C, and summers relatively cool, with mean July temperatures of 16 to 18°C. This climatic regime accounts for the abundance of temperate/mesophilous taxa and presence of *Picea* (a tree of cool, wet and boreal climates) during past interglacial and interstadial episodes (Reille and de Beaulieu, 1995; Reille *et al.*, 1995, 1998, 2000).

In Italy, another ancient volcanic lake site, Valle di Castiglione situated 20 km east of Rome (41°53′N 12°45′E, 44 m a.s.l.), has

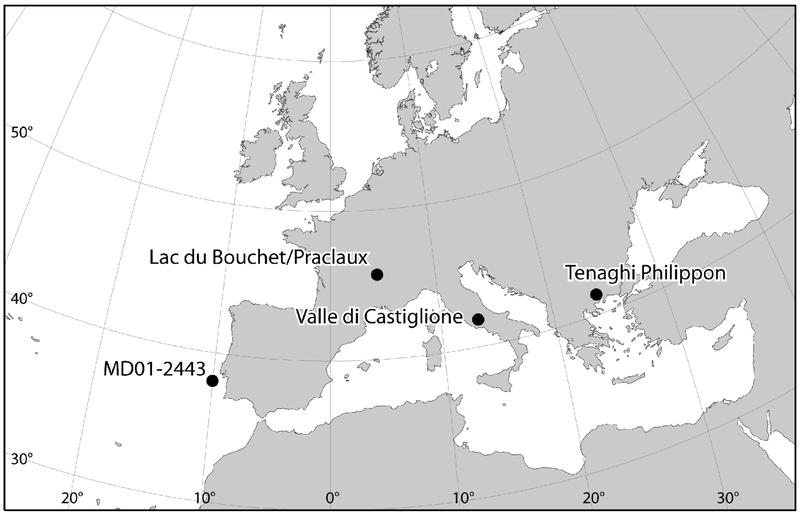

Fig. 24.1 Location of southern European pollen sites discussed in the text. Core MD01-2443 was retrieved at a depth of 2925 m, at 37°52.8′N, 10°10.57′W. Sites Lac du Bouchet (1200 m above sea level) and Praclaux (1000 m a.s.l.) are in the Velay region of the Massif Central, France, at 44°55′N 3°47′E and 44°49′N 3°50′E respectively (Reille and de Beaulieu 1995; Reille et al.*, 1998, 2000). The site of Valle di Castiglione (41 m a.s.l.) in Italy is at 41°53′N 12°45′E (Follieri* et al.*, 1988). The site of Tenaghi Philippon (40 m a.s.l.) in northern Greece is at 41°10′N 24°20′E (Wijmstra and Smit, 1976).*

produced a long sedimentary sequence which spans the period from ca. 270 kyr to the present (Follieri *et al.*, 1988) (Fig. 24.1). It records periods of high biomass, often diverse forest alternating with periods characterised by a dominance of steppe vegetation and much lower biomass (Follieri *et al.*, 1988; Magri, 1989). Forest development typically follows a pattern similar to the succession in the Massif Central sequences, although Mediterranean tree taxa, including evergreen *Quercus*, *Olea*, *Phillyrea*, *Fraxinus* and *Zelkova*, were also present here. As in the Massif Central, forest intervals began and ended with a *Pinus* phase. The intervening open, herbaceous intervals were characterised by an abundance of *Artemisia*, Chenopodiaceae and Poaceae, indicating steppe vegetation. Today, mean annual precipitation at Valle di Castiglione is 800 mm, while mean temperatures are 7°C for January and 25 °C for July.

The chronologically longest Pleistocene sequence in southern Europe comes from the site of Tenaghi Phillippon (41°10′N 24°20′E, 40 m a.s.l.) in northern Greece (Wijmstra, 1969) (Fig. 24.1). The sequence of peats and clays is 280 m long and spans the last ca. 900 kyr (Wijmstra and Groenhart, 1983). The section between 43 and 68 m represents MIS 7 to 9 (Wijmstra and Smit, 1976). The sequence records periods of forest vegetation, dominated by deciduous *Quercus* and *Pinus*, alternating with periods of steppe vegetation, dominated by *Artemisia* and Chenopodiaceae (*ibid.*). Located on the landlocked Drama plain, the site experiences a continental climate with a mean January temperature of 3.4°C in January and 23.9°C in July. Mean annual precipitation for the area is 600 mm. The region's cool and dry climate probably accounts for the low abundance of moisture-requiring mesophilous taxa during previous warm stages and the relatively low abundance of Mediterranean taxa. A second terrestrial pollen sequence from Greece, the record from Ioannina, was also used in the Tzedakis *et al.* (1997) study, but as it is of lower resolution than the other southern European sequences it is not considered here. A new high-resolution record from Ioannina is in the process of being generated (Tzedakis *et al.*, 2002; Roucoux *et al.*, in preparation).

24.3 THE MARINE RECORD

Drilled in 2001 by the French research vessel Marion Dufresne, core MD01-2443 is one of several long deep-ocean sediment cores from the Portuguese margin that were collected with the aim of obtaining high-resolution deep-sea records combined with a terrestrial pollen signal of contemporaneous vegetation on the adjacent continent. The benthic foraminiferal $\delta^{18}O$ record in this core shows the classic succession of climatic cycles representing the accumulation and wasting of continental ice masses through marine isotope stages (MIS) 7, 8, 9 and the start of MIS 6 (Tzedakis *et al.*, 2004a). The planktonic foraminiferal $\delta^{18}O$ record at this site is thought to be dominated by sea-surface temperature (Cayre *et al.*, 1999; de Abreu, 2000; de Abreu *et al.*, 2003), an inference supported by its close correspondence with temperature estimates based on planktonic foraminiferal faunal analyses (de Abreu, unpublished data). Abundance of the polar foraminifera *Neogloboquadrina pachyderma* (sinistral) is plotted in Fig. 24.3; it indicates the extent of polar water influence at the core site. There is some temporal offset between the benthic and planktonic $\delta^{18}O$ curves, which is particularly pronounced at the deglaciations MIS 10/9 and MIS 8/7. The early shift in benthic $\delta^{18}O$ values may be partly due to changes in deep-water temperatures and $\delta^{18}O$, reflecting changes in deep-water hydrography as shown for Termination I by Skinner and Shackleton (2005).

The timescale for MD01-2443 (Tzedakis *et al.*, 2004a) was developed by aligning the benthic $\delta^{18}O$ record to the Antarctic Vostok deuterium (D/H) record (Petit *et al.*, 1999) (Fig. 24.2). This is based on the implications of the study by Shackleton *et al.* (2000) which

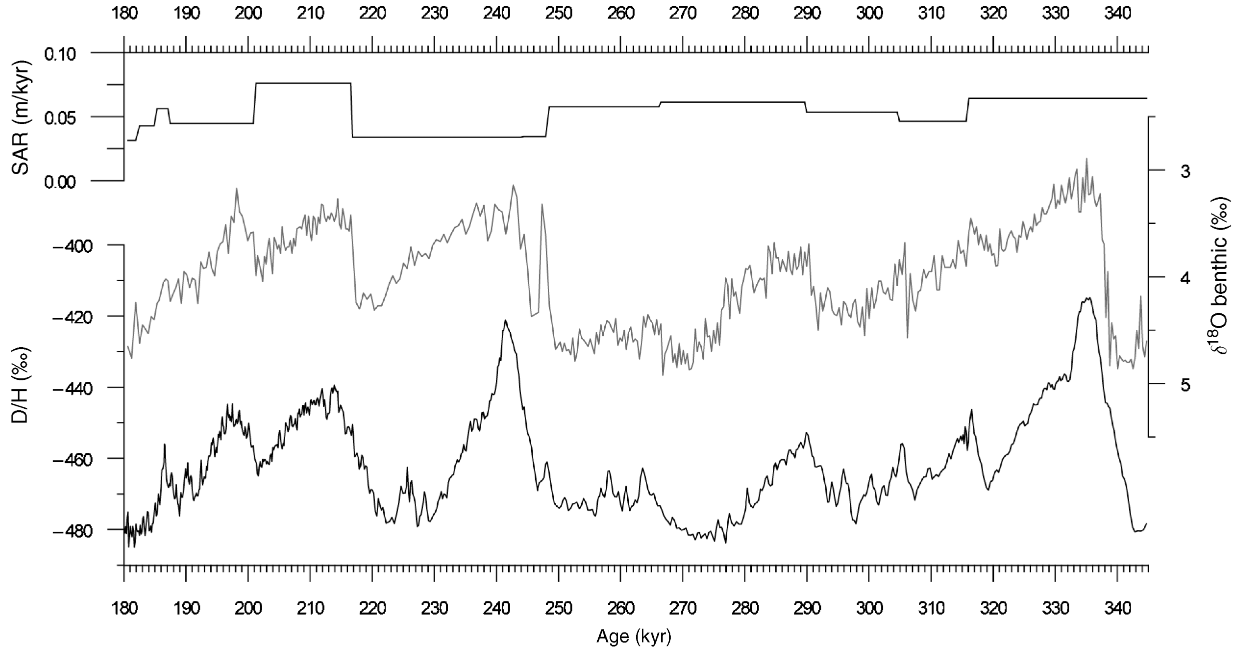

Fig. 24.2 Development of the age model for MD01-2443. Age control was established by alignment of the MD01-2443 benthic foraminiferal oxygen isotope record (δ^{18}*O ‰) to the Vostok deuterium record (D/H ‰) (Petit* et al.*, 1999; Parrenin, personal communication). Inflections of the sediment accumulation rate (SAR) curve indicate positions of the tie-points.*

showed strong similarity between the benthic δ^{18}O record off Portugal and Antarctic temperatures. The implication that shifts in benthic δ^{18}O are synchronous with shifts in Antarctic temperature allows the use of chronologies developed for the Antarctic ice cores to generate an age model for MD01-2443. The Vostok timescale used here has been developed by F. Parrenin (personal communication) through alignment with the EPICA Dome C record (EPICA Community Members, 2004) and is considered an improvement on the Vostok glaciological timescale (GT4) of Petit *et al.* (1999). This is because ice at the Vostok site originates upstream, where accumulation rates are poorly constrained, whereas ice at Dome C accumulates *in situ*, which facilitates derivation of a timescale based on an ice flow model. Figure 24.2 shows the alignment of the MD01-2443 record to Vostok D/H and the resulting sediment accumulation rates (SAR). Inflections of the SAR curve show the location of the control points, which were chosen at the midpoints of transitions between MIS.

Pollen analysis in MD01-2443 (see Tzedakis *et al.*, 2004a for methodology) reveals phases of deciduous *Quercus*-dominated forest, ericaceous heathland and open steppe, but the temperate forest succession that typifies the terrestrial sequences is not present. Instead, forests were dominated by deciduous *Quercus* throughout, with small amounts of *Corylus, Alnus*, evergreen *Quercus* and *Olea* at times of maximum forest extent, followed by expansion of ericaceous heath as forest contracted (Fig. 24.3). This may be due to an absence of local refugia of temperate trees during glaciations combined with a tendency in Portugal for rapid soil leaching and acidification (a consequence of widespread granitic bedrock and relatively high precipitation). Today, mean annual precipitation ranges from 600 mm in the lowlands of the lower reaches of the river Tagus to 2000 mm in the mountains nearby. Mean temperatures are between 10 and 12°C in January and between 20 and 24°C in July.

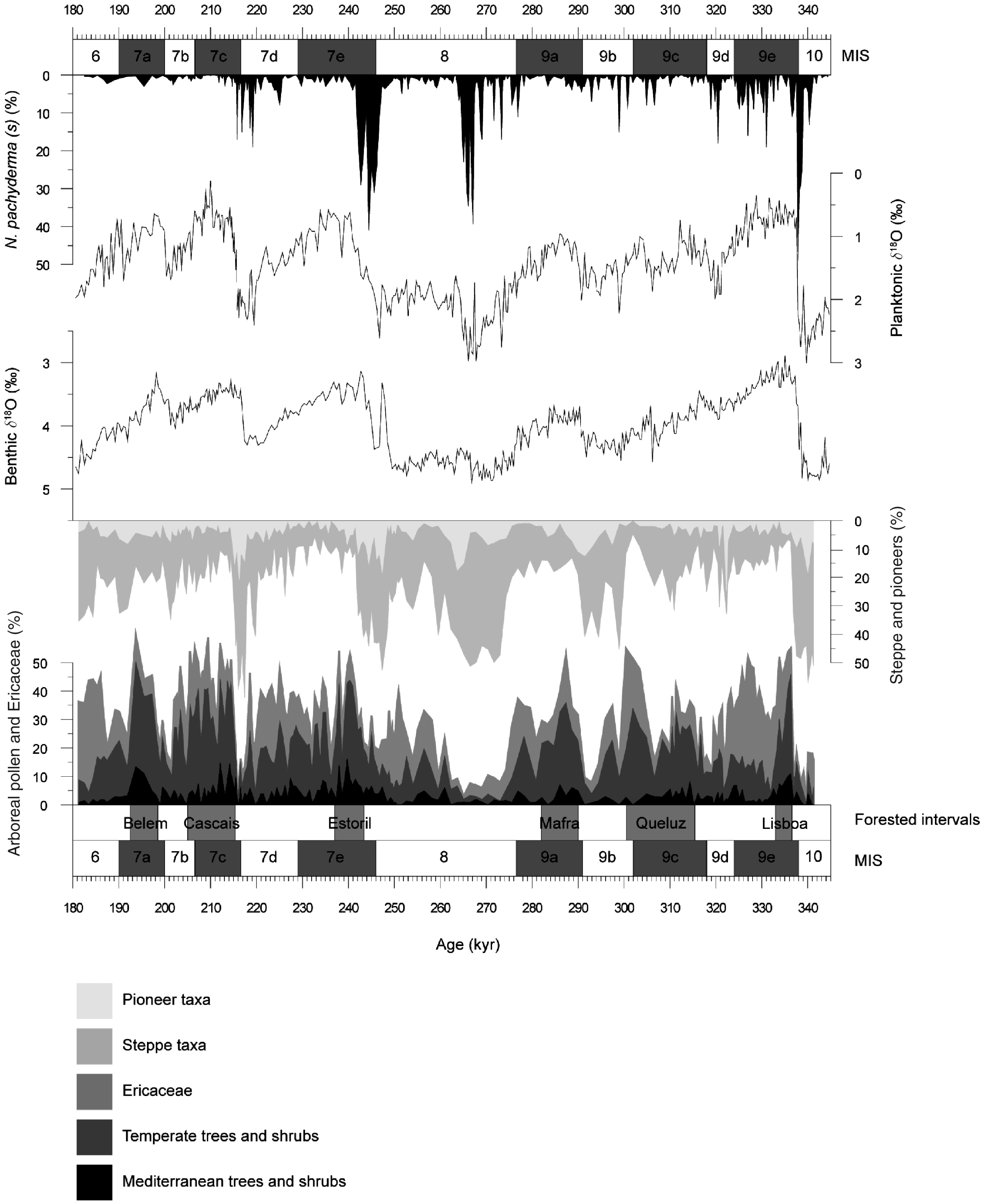

Fig. 24.3 Pollen percentage data, benthic and planktonic oxygen isotopic data (Tzedakis et al.*, 2004a), and* Neogloboquadrina pachyderma *(sinistral) as a percentage of total planktonic foraminifera, for core MD01-2443. Pollen data are cumulative percentages: Mediterranean trees and shrubs; temperate or Eurosiberian trees and shrubs; Ericaceae; steppe taxa; pioneer taxa; other herbs (see legend). Forested intervals, where arboreal pollen percentages rise above 20%, are indicated in grey and labelled with their local stage name. Marine isotope stages (MIS) are also labelled and the isotopically defined temperate intervals are indicated in dark grey.*

24.4 CORRELATION

Our correlation of the terrestrial sequences with the marine pollen record is based on two key assumptions: firstly, that climatic events originating in the North Atlantic are translated rapidly across southern Europe, since atmospheric circulation patterns result in dominantly westerly air flow over the region; and secondly, that vegetation responses to North Atlantic climatic warming were also rapid and effectively synchronous across southern Europe. Deciduous *Quercus* populations persisted at all of the southern European pollen sites through cold intervals (both glacial and stadial), thus ruling out the possibility of a migrational lag at the start of warm periods. The responsiveness of deciduous *Quercus* to millennial scale climatic oscillation during MIS 3 across the region (Allen *et al.*, 1999; Sánchez Goñi *et al.*, 2000, 2002; Tzedakis *et al.*, 2004b; Roucoux *et al.*, 2005) supports this conclusion.

We correlate the terrestrial sequences with the marine pollen record using the midpoints of increases in arboreal pollen (AP) percentages, which represent the expansion of forest in response to climatic warming and increased moisture availability, as tie-points. We assume a constant SAR between tie-points. A systematic definition of the beginning and end of forested intervals is clearly desirable. The value of 50% AP, or 40% AP excluding *Pinus*; has been used in terrestrial pollen sequences to define stage boundaries (Zagwijn, 1989). However, in the marine pollen record, a lower value is more appropriate because of the over-representation of herbaceous taxa in the marine pollen spectra (Roucoux, 2000; Tzedakis *et al.*, 2004a). Even during peak interglacial conditions, maximum temperate tree values in MD01-2443 are ca. 50% compared with 80 to 90% in terrestrial records. Comparison with terrestrial Holocene sequences (van der Knaap and van Leeuwen, 1995, 1997; Roucoux, 2000) suggests that an appropriate AP value to represent the development of closed forest cover in the marine pollen record is 20% excluding *Pinus*; which is strongly over-represented in marine records (Heusser and Balsam, 1977; Tzedakis *et al.*, 2004a). This value also coincides with the midpoint of the increases in AP in most instances. Forested intervals in MD01-2443 have been assigned local stratigraphic names (Table 24.1; Fig. 24.3).

The correlation scheme for the three terrestrial pollen sequences and the marine isotope stratigraphy, established via correlation with the MD01-2443 pollen record, is

Table 24.1: Correlation scheme for temperate stages in the terrestrial and marine pollen sequences and the marine isotope stratigraphy.

Marine stratigraphic nomenclature	Chronology in MD01-2443 (ka)		Local stratigraphic nomenclature			
MIS	MIS lower boundaries	Onset of forest intervals	MD01-2443 (see Figure 3)	Bouchet / Praclaux	Valle di Castiglione	Tenaghi Philippon
7a	200	198.5	Belem	Bouchet 3	Roma 3	H2–3 Symvolon
7c	216.8	215.3	Cascais	Bouchet 2	Roma 2	H1 Symvolon
7e (TIII)	246	243.2	Estoril	Bouchet 1	Roma 1	Strymon
9a	291	290	Mafra	Amargiers	n/a	Kavalla
9c	318	315.5	Queluz	Ussel	n/a	Krimenes
9e (TIV)	338	336.6	Lisboa	Landos	n/a	Litochoris

Ages are given for the lower boundaries of the warm marine isotope stages, as identified in MD01-2443, and for the onset of forested intervals in this core (see Figure 2 and Tzedakis et al., 2004a for basis of chronology). Local stratigraphic names are assigned to forest intervals in MD01-2443 (see Figure 3). Local stage names for temperate intervals in the terrestrial sequences are from Reille *et al.* (2000), Follieri *et al.* (1988) and Wijmstra (1969).

shown in Table 24.1. When plotted on the same timescale (Fig. 24.4), it is clear that the four pollen sequences show very similar patterns of forest expansion and contraction. There follows a description of the relationship between conditions in the North Atlantic, the marine isotope stratigraphy and vegetation development in southwest Portugal based on the record in MD01-2443, together with a description of the vegetation changes taking place contemporaneously, according to our correlation, across southern Europe (Fig. 24.4).

24.4.1 MIS 9

At the start of MIS 9, MD01-2443 records the shift to lighter δ^{18}O values approximately 1000 years earlier in the benthic record than in the planktonic, probably caused in part by changes in deep-water hydrography (Skinner and Shackleton, 2005). The associated forest expansion in southwest Portugal occurs ca. 1000 years later than the planktonic shift. Faunal planktonic foraminiferal assemblages (Fig. 24.3) indicate that this was probably due to the continued presence of polar water masses offshore; forest expanded abruptly as soon as polar waters retreated at 336 kyr.

A similarly abrupt forest expansion is recorded in the Tenaghi Philippon (Wijmstra and Smit, 1976) and Praclaux (Reille *et al.*, 2000) sequences. At all three sites, forest is dominated by deciduous *Quercus* in the earliest phase (337–333 kyr). The end of the *Quercus* phase marked the end of the forested interval in Portugal since *Quercus* populations did not recover and ericaceous heath expanded instead. This means that the forest interval was short, at only 3.6 kyr, compared with the duration of MIS 9e (14 kyr). At the terrestrial sites, there was a transient reduction in tree populations at ca. 333 kyr which, in contrast to the pattern recorded in MD01-2443, was followed by a recovery: at Praclaux, *Quercus* was replaced by *Carpinus* (Reille *et al.*, 2000) and at Tenaghi Philippon, *Quercus* populations recovered (Wijmstra and Smit, 1976). Ericaceae extent in Portugal reached a peak at 327 kyr, which coincides with the timing of *Fagus* and *Abies* expansion in France and Greece. Thus, the forested interval recorded in the French and Greek sequences appear to last somewhat longer (with durations of ca. 11 and 13 kyr respectively) than in Portugal and thus correspond more closely with the planktonic δ^{18}O plateau of MIS 9e. This may of course be an artefact of varying sedimentation rate, but the fact that the duration corresponds closely with the isotopic plateau combined with the continued abundance of Ericaceae, which suggests relatively warm conditions in Portugal, supports this conclusion.

Falling sea-surface temperatures and increasing global ice volume from 327 kyr coincide with shrinking ericaceous heathland in Portugal and contraction of forest populations recorded at Lac du Bouchet (Reille *et al.*, 2000) and Tenaghi Philippon (Wijmstra and Smit, 1976). Relatively large tree populations, dominated by *Pinus*, persisted in the Massif Central through MIS 9d, and the degree of steppe population expansion was minor compared with the other stadial and glacial intervals. *Pinus* populations were more strongly reduced at Tenaghi Philippon, suggesting greater aridity in northern Greece than in France at this time.

Both marine and terrestrial sites record moderate temperate forest extent during MIS 9c, dominated by deciduous *Quercus* with much smaller proportions of other temperate trees than during MIS 9e. At all four sites, the pattern of forest expansion and contraction corresponds to the pattern of planktonic δ^{18}O values in MD01-2443. Planktonic δ^{18}O records two clear warm intervals with a cooler phase in between, while the pollen records show two corresponding intervals of increased forest extent. This indicates that Atlantic influence on the climate in France and Greece was as strong as that experienced in southwest Portugal. Between 305 and 299 kyr, ericaceous heath was extensive in Portugal, while *Picea* was abundant at Lac du Bouchet (Reille *et al.*, 2000), both suggesting high precipitation levels and low temperatures.

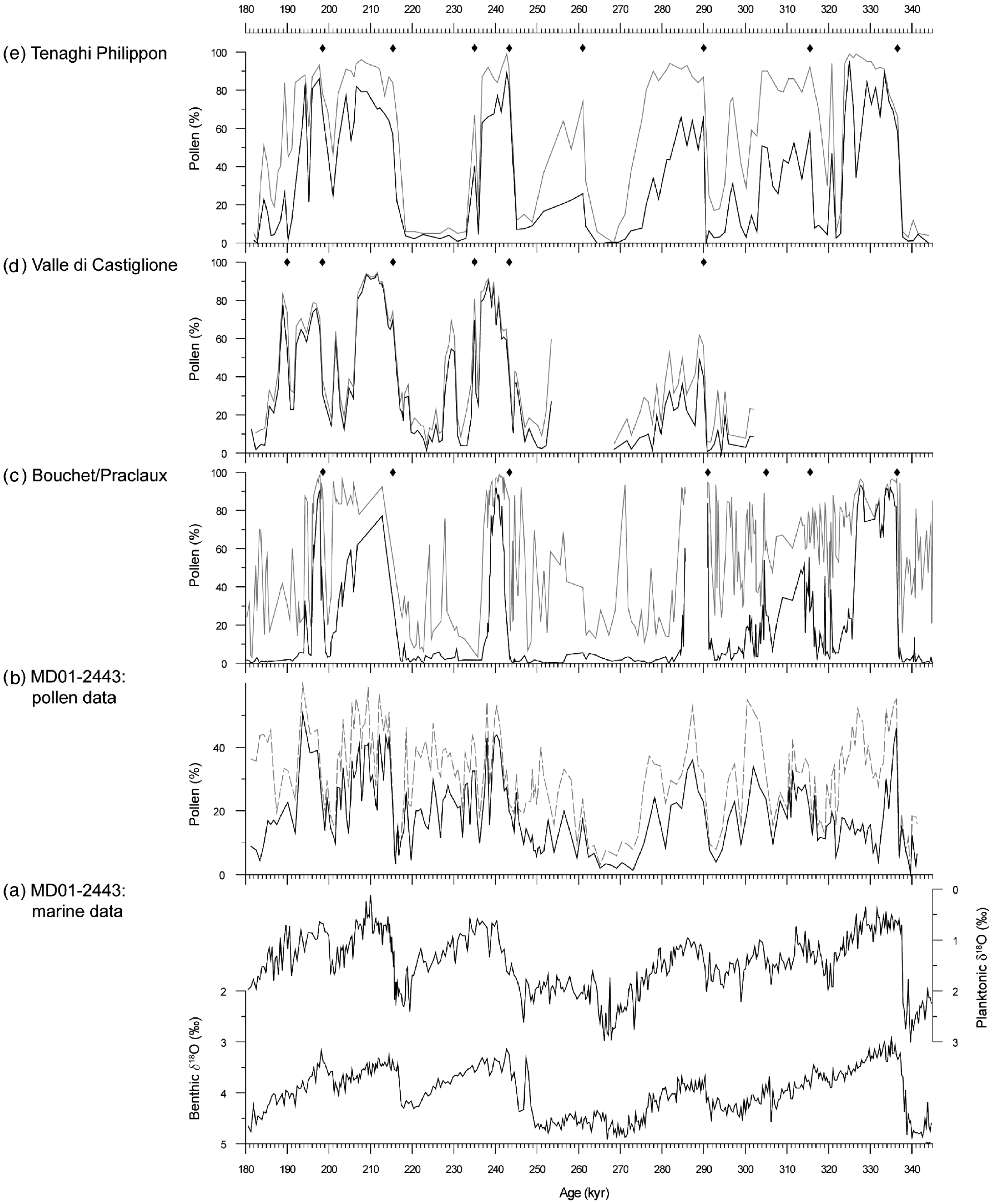

Fig. 24.4 Comparison of southern European pollen records and the Portuguese margin pollen record for the interval 180 to 345 kyr. (a) Benthic and planktonic foraminiferal isotope ratios in MD01-2443; (b) Cumulative percentages of AP excluding Pinus *(black) and Ericaceae (grey) in MD01-2443; (c) AP excluding (black) and including (grey)* Pinus *in the composite Lac du Bouchet/Praclaux sequence (after Reille* et al.*, 2000); (d) same in Valle di Castiglione (after Follieri* et al.*, 1988); (e) same in Tenaghi Philippon (after Wijmstra and Smit, 1976). Terrestrial sequences are aligned to the marine sequence using the midpoint of rapid increases in AP (excluding* Pinus*) as tie-points (positions indicated by a diamond). All are plotted on the Antarctic ice-core-derived timescale (see Fig. 24.2 and Tzedakis* et al.*, 2004a).*

In MD01-2443, MIS 9b records a pronounced tree population collapse in southwest Portugal coincident with a moderate and brief incursion of polar water offshore and a large accumulation of continental ice (more clearly recorded in other North Atlantic sequences; e.g. McManus *et al.*, 1999; Shackleton 2000; Desprat *et al.*, this volume). Sequences from both Tenaghi Phillipon and Praclaux also record very small residual temperate tree populations indicating cold, dry conditions across southern Europe (Wijmstra and Smit, 1976; Reille *et al.*, 2000; Tzedakis *et al.*, 2003).

Forest expansion in southwest Portugal at the start of MIS 9a again corresponds closely with planktonic δ^{18}O, and the offset with the marine isotope stage boundary is small. Temperate tree populations were intermediate in extent between those of 9c and 9e. At MD01-2443, Valle di Castiglione and Tenaghi Philippon, *Quercus* dominates, while at Lac du Bouchet *Carpinus* and *Picea* also contribute significantly to the vegetation (Wijmstra and Smit, 1976; Follieri *et al.*, 1988; Reille *et al.*, 2000). A gradual contraction of forest towards MIS 8 is recorded at all sites except Lac du Bouchet where temperate tree populations appear to collapse suddenly, although the pattern at this site may be distorted by hiatuses in the sequence (Reille *et al.*, 1998). Increasing ice volume and decreasing sea-surface temperatures coincide with a decline in heath and forest populations after 276 kyr in southwest Portugal, and with a decline of *Pinus* and temperate tree populations at the other sites, indicating widespread cooling and drying.

24.4.2 MIS 8

During MIS 8, the MD01-2443 benthic δ^{18}O record indicates greatest ice volume near the beginning of the stage, a pattern contrary to that of the last two glaciations (e.g. McManus *et al.*, 1999; Shackleton, 2000). Likewise, the planktonic δ^{18}O record shows lowest sea-surface temperatures in the early part of the stage with warmer conditions in the latter half, although there is a short renewal of low temperatures just before the start of MIS 7e. The Portuguese vegetation reflects this climatic pattern, with the most extensive steppe populations and smallest tree populations near the beginning (276.6–264 kyr), and larger tree populations towards the end (264–252 kyr). The terrestrial sequences similarly show the smallest tree populations during the early part of MIS 8. Tree population expansion during the latter part of MIS 8 is experienced at all sites, characterised by deciduous *Quercus* (with Ericaceae) at MD01-2443, *Pinus* at Lac du Bouchet (Reille *et al.*, 2000), *Betula*, deciduous *Quercus*, *Corylus* and *Pinus* at Valle di Castiglione (Follieri *et al.*, 1988) and deciduous *Quercus* and *Pinus* at Tenaghi Philippon (Wijmstra and Smit, 1976). It may be that conditions were only warm and/or wet enough to allow the expansion of temperate trees at the most southerly sites, while further north, in France, only *Pinus* could expand. All the sites record a return to open vegetation at the end of MIS 8 (252–246 kyr).

24.4.3 MIS 7

The Portuguese forest expansion associated with MIS 7e coincides closely with the increasingly light values of planktonic δ^{18}O. There is, however, a delay between forest onset and the MIS 7e boundary which, as in Termination IV, may be smaller than it appears if changes in deep-water hydrography are contained in the benthic δ^{18}O record. The forested interval of MIS 7e in southwest Portugal is much shorter (6.2 kyr) than the marine isotopic warm stage (17 kyr), ending midway through the plateau in planktonic δ^{18}O (which is between 233.5 and 241 kyr) in a similar way to the forested interval of MIS 9e, but with the important difference that in MIS 7e heath expands more gradually and does not dominate the vegetation until much later on in the stage. The three terrestrial sites also show a short forested interval during MIS 7e.

The shortest is in France where a deciduous *Quercus* and *Corylus* phase is followed by a *Carpinus* phase ending at 239 kyr (Reille *et al.*, 2000). The collapse of mesophilous forest populations in France coincides with the first major decline of *Quercus* populations in southwest Portugal. At Tenaghi Philippon, temperate forests were dominated by *Quercus* throughout (Wijmstra and Smit, 1976), while at Valle di Castiglione a complete forest succession is recorded (Follieri *et al.*, 1988). Tree populations at these two sites appear to have persisted for slightly longer (by 1.3 kyr according to our correlation with MD01-2443) than those in southwest Portugal or the Massif Central, corresponding more closely to the plateau in benthic and planktonic δ^{18}O, but still ending well before the marine isotopic warm stage (Fig. 24.4).

The ensuing period of small (but oscillating) tree populations and expanding ericaceous heath in southwest Portugal coincided with falling sea-surface temperatures in the North Atlantic and a gradual increase in global ice volume towards the end of MIS 7e. This period saw brief expansions of tree populations at Valle di Castiglione (*Quercus* and *Fagus*) and Lac du Bouchet (*Pinus*) (Follieri *et al.*, 1988; Reille *et al.*, 2000), but the record from Tenaghi Philippon does not register such oscillations.

The pronounced contraction of tree populations and expansion of steppe vegetation in southwest Portugal coinciding with MIS 7d indicates cold and dry conditions on land, similar to those of the preceding glaciation (MIS 8). Temperatures offshore, which had been decreasing gradually since the peak of the preceding temperate stage, reached glacial levels and polar water masses extended southwards to this latitude (Fig. 24.3). Records from Antarctica and the North Atlantic show that MIS 7d was an extremely cold stadial event (Ruddiman and McIntyre, 1982; McManus *et al.*, 1999; Petit *et al.*, 1999), the low global temperatures and large ice volume resulting from high eccentricity, low obliquity and high precession which combined to give low June insolation in the Northern hemisphere at this time (Berger, 1978). Across southern Europe, all three terrestrial sequences record strong reductions in the extent of mesophilous tree populations and expansion of steppe vegetation (Wijmstra and Smit, 1976; Follieri *et al.*, 1988; Tzedakis *et al.*, 1997; Reille *et al.*, 1998, 2000).

During MIS 7c, forest expansion continued to track planktonic δ^{18}O closely in southwest Portugal but lagged benthic δ^{18}O producing an offset between the MIS boundary and the forested phase. MIS 7c saw the longest forested interval of MIS 7 (at 10.3 kyr), which reflects the long duration of warm sea-surface temperatures (Tzedakis *et al.*, 2004a). The three terrestrial sequences also record a long forested interval coincident with MIS 7c, which was the most floristically diverse of the temperate stages considered here (Follieri *et al.*, 1988; Tzedakis *et al.*, 2003). The initial deciduous *Quercus* peak in southwest Portugal coincided with the *Quercus* peaks at the other sites. Then, while in Portugal *Quercus* continued to dominate and Ericaceae populations were expanding, the other sites record a succession with *Carpinus* followed by *Abies*. At Valle di Castiglione, this was followed by a major expansion of *Fagus* (Follieri *et al.*, 1988) and at Lac du Bouchet by moderate expansions of *Fagus* and *Picea* (Reille *et al.*, 2000). Heath in Portugal contracted after 206 kyr which coincided with falling sea-surface temperatures and increasing global ice volume. An increase in the rate of tree population decline in the terrestrial sequences which, in our correlation scheme, appears contemporaneous with this, suggests cooling and/or drying across southern Europe at this time.

During MIS 7b, Atlantic sea-surface temperatures declined only slightly (McManus *et al.*, 1999). In MD01-2443, polar foraminifera remain rare through this interval (Fig. 24.3), while sea-level reconstructions indicate only minor accumulation of ice (Shackleton, 2000). Of all the stadial events of this sequence, this period has the least polar water influence at the latitude of southern

Portugal. Among the pollen sites, only the sequence from Lac du Bouchet shows a very pronounced tree population contraction to glacial levels, perhaps reflecting its relatively northerly position (Reille *et al.*, 2000).

Tree populations closely tracked temperatures offshore throughout MIS 7a. This warm interval is represented by a tree population expansion which, although short-lived, is more pronounced than in either of the previous MIS 7 warm stages. A similarly large expansion in response to MIS 7a warming is recorded at the terrestrial sites (Reille *et al.*, 2000; Wijmstra and Smit, 1976; Tzedakis *et al.*, 2003). This is unexpected since in Antarctica this was the coolest of the MIS 7 temperate stages (Petit *et al.*, 1999), insolation was low relative to MIS 7c (Berger, 1978), and ice volume was similar to MIS 7c and MIS 7e (Shackleton, 2000). A possible explanation for this apparent discrepancy is the persistence of relatively large tree populations through the preceding stadial MIS 7b. Beginning from a larger starting population, forest expansion at the subsequent warming could lead to a large-scale tree population expansion even in response to a relatively minor warming (Reille *et al.*, 2000). The peak in deciduous *Quercus* populations in Portugal associated with MIS 7a corresponds to a complete forest succession at Lac du Bouchet and Valle di Castiglione (Follieri *et al.*, 1988; Reille *et al.*, 2000), while at Tenaghi Philippon forest remained dominated by *Quercus* (Wijmstra and Smit, 1976). Although all the sites register oscillations in tree populations as they shrank towards the transition to MIS 6, they appear to have remained extensive in Valle di Castiglione and Tenaghi Philippon for longer than in Portugal or the Massif Central.

24.4.4 MIS 6

The first 10 kyr of MIS 6 are recorded here. MD01–2443 records falling sea-surface temperatures and increasing global ice volume coincident with shrinking forests and heathland, and the expansion of steppe in southwest Portugal. All three terrestrial sites record expansion of steppe vegetation, indicating the onset of extremely cold and dry conditions across southern Europe (Wijmstra and Smit, 1976; Follieri *et al.*, 1988; Reille *et al.*, 2000).

24.5 DISCUSSION

The most important conclusion of the Tzedakis *et al.* (1997) correlation scheme is supported by our study, namely that there is broad correspondence between marine isotopically defined warm intervals (periods of low ice volume) and forested intervals on land. However, with the details afforded by the marine pollen record, this relationship can be seen to be complex. Vegetation and climate in southwest Portugal are more strongly influenced by North Atlantic sea-surface temperatures than by global ice volume, which makes sense *a priori* given that today terrestrial climate in southern Europe is largely determined by North Atlantic conditions. Furthermore, the relationship between benthic δ^{18}O and global ice volume at any one site may be complicated by the influence of hydrography on deep-water temperatures and δ^{18}O (Skinner and Shackleton, 2005). As a result of these various factors, forest expansion is often not synchronous with the deglaciation at the end of marine isotopic cold stages. For instance, at Termination IV the continued presence of polar water offshore caused tree population expansion to be delayed relative to the deglaciation; as soon as temperate waters arrived, temperate tree populations expanded immediately. There are two instances (the midwarm stage forest declines during MIS 7e and MIS 9e) when abrupt tree population changes cannot be accounted for entirely by conditions in the North Atlantic, nor indeed by shifts in global ice volume, since the changes taking place do not seem large enough to account for collapse of tree populations. An alternative suggestion has been made for the cause of these forest declines by Tzedakis *et al.* (2004a) who observed that maximum forest extent coincides with the period of maximum air temperatures and greenhouse gas concentrations (methane and carbon dioxide) in the Vostok ice core record (Petit *et al.*, 1999). The ensuing forest collapse coincides with a rapid decrease in temperature and greenhouse gas concentrations. This correspondence suggests that the vegetation changes recorded for southwest Portugal are reflecting an abrupt, global scale shift in atmospheric and climatic conditions which is not registered in the planktonic or benthic δ^{18}O curves. Thus, land–ocean correlations based on the actual relationship between vegetation and the benthic oxygen isotope record established *in situ* in a combined marine pollen record represent an improvement over the assumption of synchroneity that has underlain previous attempts. In addition, this correlation has enabled the assignment of a reliable age model to the terrestrial sequences, which provides a more accurate general chronological framework of vegetation changes than hitherto possible. However, the assumption of linear SARs between control points means that deviations from real age of specific events are possible.

The patterns of vegetation change shown in the marine and terrestrial sequences share many similarities in their approximate duration and in the amplitude of changes in forest extent recorded. However, there are strong differences in the precise nature of the vegetation responses, i.e. the patterns of succession and taxa involved, between sites. These give rise to slight differences in the length of forest intervals between sites for many of the temperate periods, suggesting that we should not assume that periods of interglacial conditions necessarily result in forest vegetation everywhere, for the whole of their duration. Clearly, climate is modified by geography and topography, which in turn account for differences in vegetation response between sites. To take one example, the MD01-2443 pollen record shows that in Portugal heathland expanded (perhaps as a consequence of soil degradation) as each warm stage progressed, while terrestrial sequences show that elsewhere in southern Europe forests continued to thrive. As another example, during cold intervals, drier sites, like Tenaghi Philippon, experienced more pronounced tree population contraction than more oceanic sites. When warming was very minor, for example, during the second half of MIS 8, the southerly sites saw expansion of temperate tree populations, while further north, in the Massif Central, only *Pinus* populations, being tolerant of cold and drought, could expand. Thus, there is no fundamental reason to expect the nature or duration of any forest interval associated with an interglacial to be the same everywhere in Europe. Peculiarities of geography, geology and biogeographical history result in a variable relationship between global climatic state and local vegetation.

There are limitations to the conclusions we can draw about the relative timing of vegetation change, changes in sea-surface conditions and the positioning of MIS boundaries from the correlation presented here. Firstly, changes in deep-water hydrography contained in the δ^{18}O of benthic foraminifera may distort the true phase relationship between the onset of the marine and terrestrial stages at Terminations. Secondly, our correlation assumes that the tree population response to warming was synchronous across southern Europe. Given the differences in the precise nature of the vegetation response and in forest duration between sites it may be that the underlying causes (differences in soils, local climate and biogeography for example) could cause differences in timing of forest expansion at the beginning of warm intervals as well. However, there are reasons to think otherwise. At all of the sites, deciduous *Quercus* expands first in response to warming; this taxon is known to have persisted at each of the sites throughout cold intervals; thus there is no reason to expect any migrational lag in its response to climatic warming. This argument is supported by the demonstrable sensitivity of *Quercus* populations to millennial scale climatic fluctuations during MIS 3 (Allen *et al.*, 1999; Sánchez Goñi *et al.*, 2000, 2002; Roucoux *et al.*, 2001; Tzedakis *et al.*, 2004b) and by the fact that deciduous *Quercus* responded rapidly to warming at the start of the Holocene (e.g. Willis, 1994; Lawson *et al.*, 2004). A consideration of the shape of the planktonic δ^{18}O curve offers further support: the rapid rise in sea-surface temperature at the start of each warm period contrasts with the more gradual cooling towards the end. Even if local factors mean that the threshold between forest and non-forest vegetation corresponds to different sea-surface temperatures from site to site, the crossing of the various thresholds will occur closer together in time during a rapid change in SST than during a more gradual change. Hence, the vegetation response to rapid climatic warming at the start of interglacials is likely to be approximately synchronous across southern Europe, even allowing for variation in local conditions.

24.6 CONCLUSIONS

The correlation of marine and terrestrial pollen records presented here confirms the broad correspondence between terrestrial forested, or temperate, intervals and marine isotopically defined warm intervals on orbital timescales across southern Europe. Closer inspection of the land–ocean relationship, at the millennial scale, reveals offsets between the MIS boundaries and the shifts in forest extent on land that define the terrestrial temperate stages. The main factors contributing to these offsets are probably (1) the overriding effect of North Atlantic sea-surface temperature in determining the timing of forest expansion, and (2) the effect of decreases in global temperature and greenhouse gas concentration, recorded early in MIS 7e and 9e in the Vostok ice core to which the premature end of forested intervals in southern Europe may be related. In addition, hydrographic effects on benthic δ^{18}O may lead to apparent earlier deglaciations (Terminations) and thus artificially stretch the offset between the MIS and terrestrial stage boundaries. Comparison between the pollen records reveals that forested intervals may vary considerably in length from one stage to the next, but differences in the length of forested intervals between sites are generally small. These differences in the length of forested intervals along with floristic differences result from local climatic, geological and biogeographical factors such as the effects of altitude and latitude on temperature, of distance from the sea and topography on precipitation levels, of the propensity of soils to become leached, and of the proximity of sites to glacial refugia for temperate trees.

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