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The Holocene 17,4 (2007) pp. 481–494

Palynological evidence for environmental and climatic change in the lower Guadiana valley, Portugal, during the last 13 000 years

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Received 22 August 2006; revised manuscript accepted 28 November 2006

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Abstract: Pollen analysis of a 48 m AMS radiocarbon-dated sediment sequence from the Guadiana estuary provides the first record of Lateglacial and Holocene vegetation history in the Algarve province of Portugal. This paper focuses on the record of terrestrial pollen taxa, which document a series of forest expansions and declines during the period 13 000 cal. BP to 1600 cal. BP and provide insights into climate evolution in southwestern Iberia. The main vegetation phases identified in the Guadiana valley are (1) Lateglacial interstadial (Allerød) forest with *Quercus* and *Pinus* under a temperate, moist, continental climate; (2) a Younger Dryas forest decline (*Quercus*) and expansion of pinewoods, xeric scrub and open ground habitats (with *Juniperus*, *Artemisia*, *Ephedra distachya* type, *Centaurea scabiosa* type) under arid and cold conditions; (3) an early Holocene forest/scrub/open-ground vegetation mosaic developing under a warm, dry and continental climate; (4) a maximum of *Quercus* forest and thermomediterranean evergreen taxa (*Olea*, *Phillyrea*, *Pistacia*) reflecting a warm, moist oceanic climate between *c.* 9000 cal. BP and *c.* 5000 cal. BP; and (5) the expansion of shrublands with Cistaceae and Ericaceae under a drier climatic regime and increasing anthropogenic activity since *c.* 5000 cal. BP. Holocene episodes of maximum climatic aridity are identified in the record of xerophytic taxa (*Juniperus*, *Artemisia*, *Ephedra distachya* type) centred around 10 200 cal. BP, 7800 cal. BP, 4800 cal. BP, 3100 cal. BP and 1700 cal. BP. Regional comparisons suggest a correlation of arid phases across southern Iberia and northwest Africa, which can be related to abrupt North Atlantic coolings (Bond events).

Key words: Pollen analysis, palaeoecology, Lateglacial, Holocene, Portugal, Iberian Peninsula, climate change, aridification events.

Introduction

Pollen analysis provides rich archives of regional palaeoecological information, critical to the understanding of Holocene environmental and climatic history at the regional to global scale. For the Iberian Peninsula, a landmass that presents strong regional contrasts in geology, flora, climate and glacial history, the abundance of palynological data varies greatly between regions. In the southwestern sector, the lack of natural, non-ephemeral lakes providing organic preservation has resulted in a relatively small number of well-dated Holocene pollen records. This scarcity of data is especially acute for the southernmost region of Portugal, the Algarve, where only pollen analysis of recent (past 1200 years) coastal deposits (Allen, 2003) and a Neolithic archaeological cave sequence (Straus *et al.*, 1993) has previously been undertaken. While recent research has rapidly advanced our knowledge of the history and characterization of sedimentary infills in the Guadiana and other estuaries of the southwestern Iberian Peninsula (Morales, 1997; Dabrio *et al.*, 2000; Lario *et al.*, 2001; Boski *et al.*, 2002; Alday *et al.*, 2006), the potential of these estuaries as sites of palynomorph preservation has not hitherto been exploited. This paper presents the findings of pollen analysis of a sediment sequence representing the infilling

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10.1177/0959683607077027

of the Guadiana palaeovalley since *c.* 13 000 cal. BP. In light of new pollen data, this paper seeks to address the topics of (a) vegetation history in southern Portugal, (b) regional climate change since the Lateglacial, and (c) the timing and characterization of abrupt Holocene arid events.

The modern landscape of the Algarve is heavily influenced by human action through forestry, pastoralism, fire, agriculture and urban development, so that few, if any, stands of natural forest exist to confirm the composition of the vegetation prior to human influence (Braun-Blanquet *et al.*, 1964; Capelo, 1996). The lack of continuous Holocene pollen records means that inferences regarding the past vegetation of the Algarve have generally been drawn from sites at considerable distance, notably in the Serra da Estrela of central Portugal (van der Knaap and van Leeuwen, 1995, 1997; van den Brink and Janssen, 1985) and the Sierra Nevada of southeast Spain (Pons and Reille, 1988) (Figure 1a). These montane sites, however, do not necessarily represent good analogues for the oceanic lowlands of the Algarve. A number of radiocarbon-dated pollen records are available from neighbouring regions, specifically from the Tagus valley (van Leeuwaarden and Janssen, 1985), the northern Alentejo littoral zone (Mateus 1989a; Queiroz 1989, 1999;

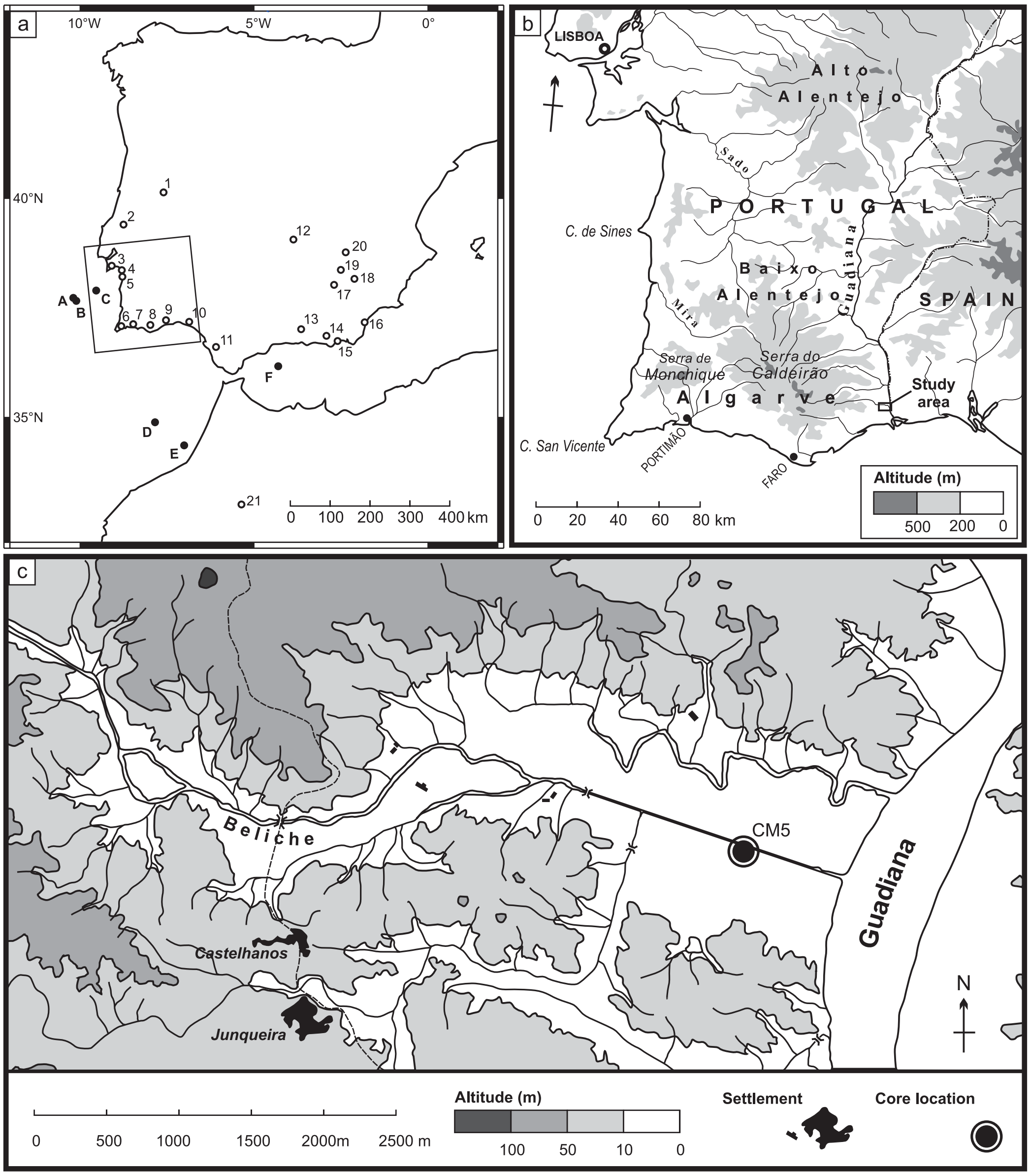

Figure 1 (a) The Iberian peninsula and northwest Africa, showing the location of the study site and other Holocene pollen studies cited in the text. Terrestrial sites: 1, Serra da Estrela (van den Brink and Janssen, 1985; van der Knaap and van Leeuwen, 1995, 1997); 2, Alpiarça (van Leeuwaarden and Janssen, 1985); 3, Lagoa de Albufeira (Queiroz, 1989; Queiroz and Mateus, 1994), Lagoa de Golfo (Queiroz, 1999); 4, Lagoa Travessa (Mateus, 1989a); 5, Lagoa de Melides (Queiroz and Mateus, 1994), Lagoa Santo André (Santos and Sánchez Goñi, 2003); 6, Boca do Rio (Allen, 2003); 7, Boina-Arade Estuary (Fletcher, 2005); 8, Goldra cave (Straus *et al.*, 1993); 9, Beliche-Guadiana (this study); 10, Laguna de las Madres (Stevenson, 1985; Stevenson and Harrison, 1992); 11, Laguna de Medina (Reed *et al.*, 2001); 12, Las Tablas de Daimiel (Dorado Valiño *et al.*, 2002); 13, Padul (Pons and Reille, 1988); 14, Sierra de Gádor (Carrión *et al.*, 2003); 15, 16, San Rafael/Roquetas, Antas (Pantaléon-Cano *et al.*, 2003); 17, Cañada de la Cruz (Carrión *et al.*, 2001b); 18, El Sabinar (Carrión *et al.*, 2004); 19, Siles (Carrión, 2002); 20, Villaverde (Carrión *et al.*, 2001a); 21, Tigalmamine (Lamb and van der Kars, 1995). Marine pollen records: A, SU-8118 (Turon *et al.*, 2003); B, 8057B (Hooghiemstra *et al.*, 1992); C, SO75–6KL (Boessenkool *et al.*, 2001); D, M15669–1 (Hooghiemstra *et al.*, 1992); E, KS 7807 (Marret and Turon, 1994); F, ODP Site 976 (Combourieu Nebout *et al.*, 1999, 2002). (b) Location of the study area in southern Portugal. (c) Location of the CM5 borehole on the Beliche floodplain

Queiroz and Mateus, 1994; Santos and Sánchez Goñi, 2003), and the Huelva area of southwest Spain (Stevenson, 1985, 1988; Stevenson and Harrison, 1992) (Figure 1a). These records (chiefly of mid to late Holocene age) identify significant vegetation events, notably the expansion in southern Portugal of semi-natural heathlands and shrublands at the expense of forest vegetation between 5000 and 3000 cal. BP, and the late-Holocene development of managed woodland and viticulture in southwestern Spain. However, in the absence of comparable records from the Algarve, inter-regional comparisons remain speculative and long-term perspectives on vegetation history for southwestern Iberia poorly developed in general.

The scarcity of continuous Holocene pollen records in southwestern Iberia means that the evolution of regional climate over the Holocene has not been fully explored. Marine pollen records from the SW Portuguese Atlantic margin (Hooghiemstra *et al.*, 1992; Lézine and Denèfle, 1997; Boessenkool *et al.*, 2001; Turon *et al.*, 2003) register a broad regional pollen signal from southwestern Iberia that may be directly compared with marine isotopic and biotic proxy data. These studies illustrate a clear vegetation response to rapid climate changes during the last glacial and deglaciation periods, a phenomenon also documented for southeastern Spain in the Alborán Sea pollen records (Combourieu Nebout *et al.*, 1999, 2002). However, the temporal and taxonomic resolution of published studies is generally low for the Holocene. In contrast, recent research in southeast Spain suggests three main climatic phases during the Holocene, with a generally dry early Holocene, a mid-Holocene moisture maximum, and a return to drier conditions after *c.* 5200 cal. BP (Carrión, 2002). Additional pollen data, in particular for the early Holocene period, have been required to demonstrate whether this climate sequence applies also to southwestern Iberia. Lake records from southern Spain (Reed *et al.*, 2001; Carrión, 2002) and Morocco (Lamb and van der Kaars, 1995) also provide evidence of abrupt aridification phases during the Holocene. However, data have been lacking to confirm the impact and timing of arid events in southwestern Iberia.

Physical setting

The study site is located in the lower Guadiana basin, in the Algarve province of Portugal near the eastern border with Spain (Figure 1b). The CM5 borehole (37°16' N, 7°27' W) is located near the confluence of the Guadiana and a tributary, the Beliche river, *c.* 600 m west of the main channel of the Guadiana, and *c.* 10 km inland from the coast (Figure 1c). The borehole is located in a saltmarsh within the upper altitudinal range of the intertidal zone of the Guadiana, and is inundated during spring high tides. The surrounding territory is characteristic of the hilly Algarve interior or *Serras* (Mabberley and Placito, 1993). The local Palaeozoic geology (Zona Sul Portuguesa) consists of intensely folded and lightly metamorphosed Carboniferous turbidites and greywackes arranged in flysch facies, or 'metasediments' (Chester and James, 1995). The landscape is characterized by polycyclic relief, intense erosion, steep slopes and deep incision of the region's rivers.

The climate of the Algarve is of mediterranean-type, with hot, dry summers with at least two months of drought, and mild winters during which the majority of rain falls. The Guadiana valley lowlands are classified as thermomediterranean (oceanic influence, mild winters) and dry (mean annual precipitation (P) below 500 mm) while inland areas at higher altitudes are mesomediterranean (continental influence, cool winters) and subhumid (P 600–1000 mm) to humid (P 1000–1500 mm), with the valley of the Guadiana permitting the extension of thermomediterranean conditions about 50 km into the hinterland (Rivas-Martínez *et al.*, 1990; Capelo, 1996). With high insolation and high potential evapotranspiration, the severity of summer drought poses the main limiting factor on vegetation development.

The history of agricultural, pastoral and agroforestry activities means that evidence for the extent and composition of natural forest vegetation in the Guadiana basin is scarce. The drier parts of the Guadiana basin (dry to subhumid ombrotypes) are considered the domain of *Quercus rotundifolia* (syn. *Quercus ilex* ssp. *ballota*) accompanied by the wild olive (*Olea europea* var. *sylvestris*), and the wetter areas (subhumid to humid) the domain of *Quercus suber* (Capelo, 1996). Semi-deciduous species of oak also occur in relict stands in humid upland sites in the western Algarve, including *Quercus faginea* and *Q. canariensis* (Malato-Beliz, 1982; Simonson, 1994). In the Guadiana basin, extensive lowland and upland areas are dominated by shrublands of variously sclerophyllous, armoured (thorny, spiny, prickly) and aromatic plants. Shrub communities range from tall thickets of up to 4 m in height (Portuguese, *matagais*), to dense scrub of intermediate height less than 2 m (*matos*) to open, dwarf-shrublands lower than knee-height (*charnecas*). While thickets may represent a permanent community of xerophytic forest margins on incipient soils, in general the density and stature of these communities decreases with the intensity of anthropic pressures (Capelo, 1996). Important plants of the shrub communities include *Quercus coccifera*, *Pistacia lentiscus*, *Juniperus phoenicea*, *Phillyrea* spp., *Myrtus communis* and several species from the families Cistaceae, Ericaceae, Fabaceae and Lamiaceae, among others.

The modern surroundings of the CM5 core site display a mosaic of agricultural, pastoral and semi-natural environments. Grasses (family Poaceae) including *Spartina maritima* occupy the lowest marsh, giving way to upper marshes with shrubby halophytic plants of the Chenopodiaceae family (*Arthrocnemum* and *Limoniastrum* spp.) and areas of sterile (non-vegetated) marsh with evaporative salt crusts. West of the borehole location and towards the floodplain margins, a transitional saline/freshwater zone subject to grazing displays a vegetation with *Suaeda vera*, *Juncus* sp., grasses and a wide range of herbaceous plants (*Rumex*, *Plantago* and numerous Asteraceae spp.). Patches of riparian woodland with *Fraxinus angustifolia* and *Tamarix africana* occur near the fluvial channels. Orchards of carob (*Ceratonia siliqua*) underplanted with winter arable crops occupy the hillslopes to the south of the borehole, while to the north, a *matos* vegetation with *Cistus ladanifer* and *C. monspeliensis*, *Phillyrea angustifolia*, *Genista* sp. and *Lavandula stoechas* occurs on the hillslopes.

Methods

The recovery of the 6" diameter CM5 core by WIRTH Bo drilling rig is described in Boski *et al.* (2007). Samples for pollen analysis were taken from the central (inner) part of the core and kept in cold storage prior to further treatment. A total of 51 samples were prepared for pollen analysis, representing an average temporal resolution of 230 years. Pollen preparation followed a standard procedure using hot HF hydrofluoric acid (Faegri *et al.*, 1989), adding a known quantity of *Lycopodium* spores prior to the preparation to permit the calculation of absolute pollen concentrations (Stockmarr, 1971). Residues were mounted in silicone oil, and slides counted on a Leica DMLB transmitted-light microscope at ×400 magnification, with routine use of ×1000 magnification for the observation of critical morphological features. Total counts were large (average count, 2200 pollen and spores) to ensure that taxa from both local and regional vegetation were well represented and that, in particular, a significant subset (generally >200 grains) representing forest and shrub communities was counted.

Identifications were made with the aid of: (a) the Cambridge University reference collection, (b) reference pollen for 35 additional species collected in the field area, (c) pollen atlases (Valdés *et al.*, 1987; Reille, 1992), and (d) published studies on Mediterranean and/or southwest European pollen and spore groups. For the genus *Quercus*, identification criteria of Sáenz de Rivas (1973) were observed, differentiating between *Q.* deciduous type (which for the Mediterranean flora of Iberia includes grains of *Q. faginea*, *Q. canariensis, Q. pyrenaica* and *Q. fruticosa*), *Q. suber* type (grains of *Q. suber*) and *Q.* evergreen type (which includes grains of *Q. coccifera* and *Q. rotundifolia*). Fossil grains that could not be ascribed with confidence to one of the *Quercus* subtypes were assigned to *Quercus* undiff. Identifications within the families Ericaceae and Cistaceae were made following Mateus (1989b) and Queiroz (1999), respectively. Where the condition of fossil grains did not permit identification beyond the family level, grains were identified to Ericaceae or Cistaceae undiff.

Diagrams showing both pollen percentage and concentration values are presented. Pollen percentages are based on a main sum of terrestrial pollen excluding Cyperaceae and Asteraceae (Lactuceae). Frequencies of Cyperaceae, Asteraceae (Lactuceae), aquatics, fern spores, indeterminate pollen grains and non-pollen microfossils such as dinoflagellates are calculated relative to the main sum plus the individual sum for each taxon.

Lithostratigraphy

Five lithostratigraphic zones (Figure 2) and their environmental interpretations based on sedimentological and faunal analyses have been proposed for core CM5 by Boski *et al.* (2007). The core records a general transition from fluvial to estuarine environment reflecting the postglacial evolution of the Guadiana estuary, while a marginal location sheltered from the influence of the main Guadiana channel explains the preservation of a deep sequence of predominantly fine-grained (silty) sediments not disturbed by high-energy erosion or deposition events. Lowermost Unit I (5080–4856 cm) contains reddened sands and gravels (shales, greywackes and quartz). Similar basal deposits have been identified throughout the terminal segment of the Guadiana palaeovalley, and are considered to reflect a phase of fluvial deposition prior to the last glacial maximum sea-level lowstand (Boski *et al.*, 2002; Lobo *et al.*, 2003). Coarse-grained and highly oxidized, this zone is unsuitable for pollen analysis. Unit II (4856–4080 cm) is composed of laminated silts and sands, and represents a transitional fluvial-estuarine environment. The lower part (below 4570 cm) is predominantly silty, with intercalations of fine sands, loading structures, pockets of clay and small lenses of organic material. The upper part (above 4570 cm) is predominantly sandy, displaying flaser bedding structures with rhythmic interlaminations of compact silts. Unit III (4080–2450 cm) contains fine compact silts with dispersed fragments of carbonized plant material, small lenses of charcoal and centimetre-scale peaty layers of organic material. Unit IV (2450–420 cm) is composed of very dark grey silts and sandy

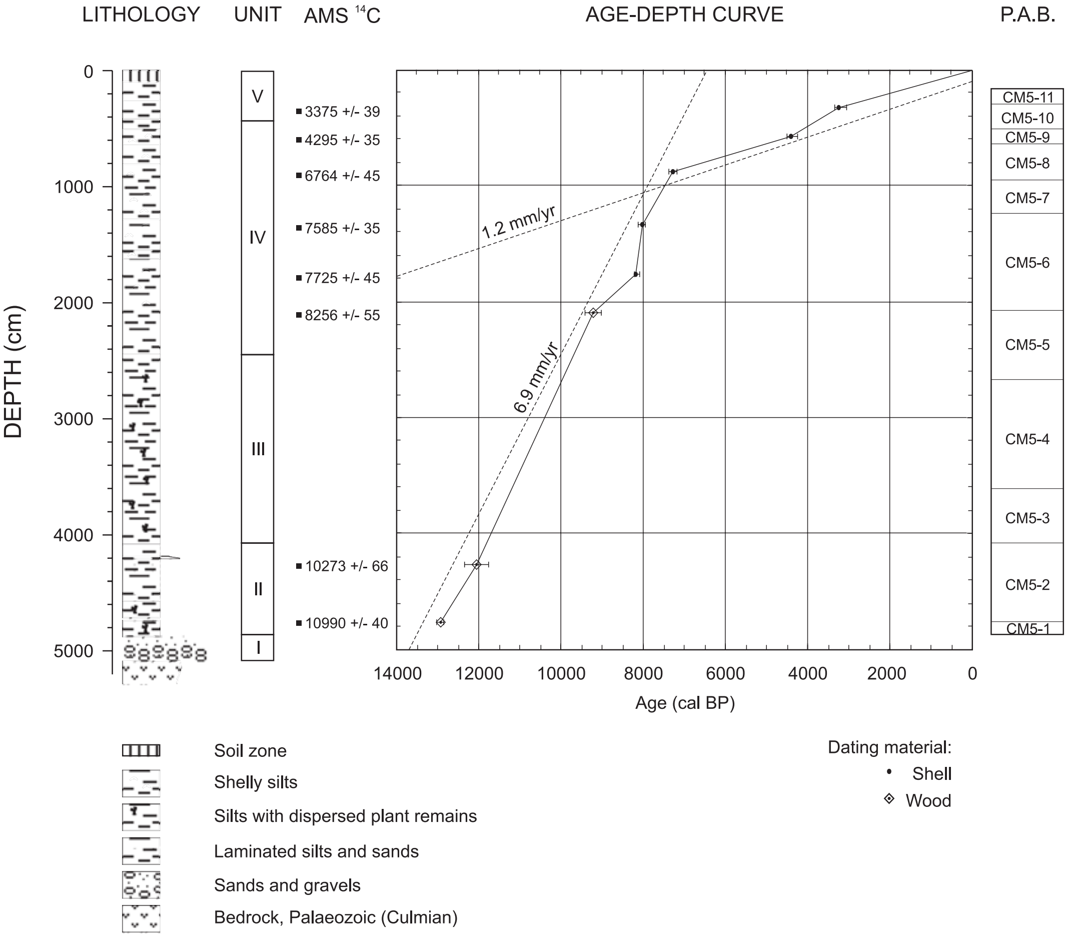

Figure 2 Lithostratigraphy, radiocarbon dates, age–depth plot for calibrated radiocarbon dates with 2 sigma confidence intervals, and pollen assemblage biozones (P.A.B.) for core CM5

silts with shell fragments, intact shells (bivalves and gastropods) and dispersed organic material. Lithological and faunal analyses suggest that Unit III represents an upper intertidal environment (salt marsh), and Unit IV a lower (mudflat) environment. Unit V (420–0 cm) contains compact silts with reduced shell fauna, traces of halophyte rootlets and nodular zones of oxidation, and corresponds with the final stages of infilling of the estuary. Oxidation and disturbance of the upper 160 cm prohibits pollen analysis above this depth.

Chronology

Nine AMS radiocarbon dates have been obtained for core CM5 (Table 1) on wood and shell samples. Wood represents an unambiguous source of terrestrial organic matter and is not subject to reservoir effects, although taphonomic factors related to storage and reworking in the fluvial system may produce dates which are erroneously old (Brown and Pasternack, 2004). In contrast, dates on biogenic carbonate are subject to reservoir effects related to (a) the global marine reservoir effect (~400 years), (b) regional offsets ($\triangle R$) related to variability in rates of coastal upwelling, and (c) local variations in the estuarine environment caused by the mixing of marine and river water of different radiocarbon ages (Stuiver and Braziunas, 1993; Heier-Nielsen *et al*., 1995; Stuiver *et al*., 1998). In this study, shell samples have been calibrated using the global average marine reservoir correction ($\triangle R = 0$), for the following reasons. First, where recorded, near-zero $\delta^{13}C$ values indicate a marine source of carbon (Colman *et al*., 2002). Second, while a strong, upwelling-related offset has been identified for the southern Portuguese margin ($\triangle R = 235 \pm 35$ ^{14}C yr) (Soares, 1993), the same study also identified considerable variability between locations including a $\triangle R$ value of 5 ± 70 ^{14}C yr at Vila Real de San Antonio at the mouth of the Guadiana and a general reduction in $\triangle R$ prior to 2000 ^{14}C yr. However, it is recognized that variation in reservoir effects during the time period may introduce uncertainty on the order of several centuries, meaning that the error range associated with the available shell dates may be considerably greater than that derived simply from the laboratory supplied analytical error.

With the exception of one date (depth 1085 cm, KIA 15213), which is rejected, the dates present a systematic series of increasing age with depth. Linear interpolation between the median calibrated ages (using a core-top age of 0 cal. BP, and extrapolation below the lowest data point) is used to derive an age–depth model for the estimation of calendar ages for sample depths and pollen zone boundaries. The age–depth profile for core CM5 indicates high sediment accumulation rates during the Lateglacial and early to mid Holocene (prior to *c.* 7300 cal. BP) with long-term average sedimentation of 6.9 mm/yr, and reduced sediment accumulation rates after *c.* 7300 cal. BP (long-term average sedimentation, 1.2 mm/yr) (Figure 2). This two-fold sedimentation history is consistent with a regional trend in the Gulf of Cadiz related to eustatic sea-level, namely for rapid estuarine sedimentation during the postglacial transgressive sea-level rise, and reduced sedimentation after 7000–6500 cal. BP during the sea-level deceleration and subsequent high-stand phase (Dabrio *et al*., 2000; Boski *et al*., 2002; Lario *et al*., 2002).

Results

In general, pollen and spores are well-preserved in the CM5 core at high concentrations (10^4 to 10^5 grains/cc). Overall, the diversity of pollen and spore types is high (>100 recorded taxa), including both anemophilous (eg, *Quercus* types, *Pinus*) and entomophilous (eg, Cistaceae types) taxa. The diversity of taxa reflects pollen contributions from a range of dry ground and wetland habitats and suggests recruitment of pollen to the site by both local (gravity), fluvial and aerial processes. While the abundance of certain taxa in the record (eg, Cyperaceae, *Isoetes*) most likely reflects a local origin from marsh vegetation, a well-represented subset of pollen types derived from dry ground habitats indicates the recruitment of pollen from a wider area within the hydrographic basin of the Guadiana. While the potential pollen source area for dry ground or regional pollen types is ultimately very large, the influence of local tributary inputs (notably the Beliche river) and short to medium distance airborne sources (up to several kilometres) probably results in a pollen content that primarily reflects a smaller region surrounding the core site (Brush and Brush, 1994; Chmura *et al.* 1999). For this reason, the composition of the CM5 dry ground pollen assemblage is considered to be indicative of vegetation in the lower Guadiana basin, ie, lowland areas surrounding the modern estuary and the hilly hinterland of the Algarve *Serras*.

While the CM5 record documents changes in both wetland and dry ground vegetation, this article focuses on palynological

Table 1 Radiocarbon data for core CM5

Core	Depth (cm)	Material[a]	Laboratory number	$\delta^{13}C$ (‰, PDB)	^{14}C age (yr BP)	Cal age, 2σ (yr BP)[b]	Median age[c]	Calibration method[d]
CM5	333	Shell (*Sp*)	IGNS[NZA-21412]	-2.9 ± 0.2	3375 ± 39	3130–3350	3250	M
CM5[c]	579	Shell (*V*)	KIA 15211	n/a	4295 ± 35	4300–4520	4420	M
CM5	890	Shell (*Cg*)	IGNS[NZA-21413]	0.2 ± 0.2	6764 ± 45	7200–7400	7300	M
CM5	1085	Shell (*C*)	KIA 15213	n/a	4095 ± 30	4020–4260	4140	M
CM5	1345	Shell (*V*)	KIA15212	n/a	7585 ± 35	7960–8140	8040	M
CM5[e]	1775	Shell (*C*)	KIA15210	n/a	7725 ± 45	8060–8310	8200	M
CM5	2095	Wood	IGNS[NZA-21414]	-25.3 ± 0.2	8256 ± 55	9030–9420	9240	T
CM5	4270	Wood	IGNS[NZA-21415]	-25.5 ± 0.2	$10\,273 \pm 66$	11 770–12 370	12 050	T
CM5[e]	4767	Wood	Beta-137110	-25.7	$10\,990 \pm 40$	12 860–13 030	12 920	T

[a] Shell i.d., *Sp*, *Scrobicularia plana*; *V*, *Venerupis* sp.; *Cg*, *Cerastoderma glaucum*; *C, Cerastoderma* sp.

[b] Calibrated ages for the 95.4% confidence interval, rounded to the nearest 10 years.

[c] Calendar age estimate based on the median probability of the probability distribution.

[d] Calibration with CALIB 5.0, using: M, Marine04 (Hughen *et al.*, 2004), $\Delta R = 0$; T, IntCal04 (Reimer *et al.*, 2004).

[e] Previously published in González-Vila *et al.* (2003).

information that pertains to vegetation of dry ground habitats and is therefore likely to be of regional significance. This focus on the record of dry ground environments is supported by the observation in modern surface sediments that the distribution of dry ground pollen types tends to be fairly uniform across different tidal subenvironments that may themselves be characterized by very different local vegetation and local pollen signals (Clark and Patterson, 1985; Roe and van den Plassche, 2005). There remain, however, a number of complicating factors inherent in the study of estuarine pollen assemblages, namely: (a) over-representation of local vegetation types in the pollen spectra and ecological ambiguity of common pollen types, (b) poorly constrained pollen source areas, related to a multiplicity of pollen transport pathways (eg, fluvial, tidal, aerial), (c) contribution of reworked palynomorphs from inwashed soils and sediments, compounded by recycling and redistribution by tidal currents, and (d) variable pollen preservation, related to bacterial activity and oxidation, transport history, and wet/dry cycles at the sediment/water interface (Clark and Patterson, 1985; Campbell, 1991; Chmura, 1994; Campbell and Campbell, 1994). These factors demand cautious interpretation of this estuarine pollen record and, in future, the confirmation of results from further cores and study sites.

Pollen analysis results are shown in Figures 3, 4 and 5 and summarized in Table 2. Eleven pollen assemblage biozones (numbered from base to top, and referred to using the core prefix, CM5-) are distinguished in the record, which mainly reflect a dynamic between arboreal and shrub taxa with several phases of forest expansion and contraction during the last 13 000 years. Although total pollen concentration shows strong variation related to sedimentological differences between lithological zones, trends in the concentration curves for the main taxa generally support the interpretations based on the pollen percentage diagram (Figure 4). The oldest pollen spectra suggest extensive forestation of the Guadiana valley during the Lateglacial interstadial (CM5-1), with subsequent phases of forest development identified during the initial Holocene (CM5-3) and early to mid Holocene (CM5-6, CM5-8). Periods of forest decline occur during the Younger Dryas (CM5-2), the early Holocene (CM5-4, CM5-7) and the late Holocene (CM5-9, CM5-10, CM5-11). Forest declines are associated with expansions of shrub and open-ground vegetation, which vary in composition between the different phases, with distinct records for the sclerophylls (*Olea*, *Phillyrea*, *Pistacia*), the lower-stature shrubs of heathland and scrub (Ericaceae, Cistaceae) and arid-tolerant (xerophytic) shrubs (*Juniperus*, *Ephedra distachya* type).

Maximum frequencies of xerophytic taxa (*Artemisia*, *Juniperus*, *Ephedra distachya* type) occur during the Younger Dryas (CM5-2). Although these pollen types are poorly represented during the Holocene, a series of distinct, minor peaks in abundance are recorded, occurring around 10 200 cal. BP, 7800 cal. BP, 4900 cal. BP, 3100 cal. BP and 1700 cal. BP (Figures 5, 6). These Holocene peaks do not suggest a widespread expansion of steppic or semi-arid environments in the Guadiana valley; rather, they probably reflect either (a) localized expansions of vegetation communities of the driest micro-climatic and edaphic conditions (sandy soils in the littoral lowlands; steep, rocky slopes in the uplands), and/or (b) an extra-regional signal from the continental interior. The xerophyte peaks are associated with phases of forest decline (zones CM5-4, -7, -9, -10, -11) and correspond with increases in the relative proportion of evergreen *Quercus* pollen (Figure 5). The Holocene xerophyte record is considered an important additional line of evidence for periodic arid climate conditions.

Discussion

Vegetation and climate history of the lower Guadiana valley

Lateglacial (13 000 cal. BP–11 790 cal. BP)

The CM5 pollen record provides insights into both vegetation change and regional climatic trends since 13 000 cal. BP. Evidence for *Quercus* forest in the Guadiana valley (CM5-1) during the Lateglacial interstadial (Allerød chronozone) is consistent with pollen records from the Sierra Nevada (Pons and Reille, 1988) and marine sediments of the SW Portuguese margin and Alborán Sea (Hooghiemstra *et al.*, 1992; Combourieu Nebout *et al.*, 1999, 2002; Boessenkool *et al.*, 2001; Turon *et al.*, 2003), suggesting a widespread presence of oak forest across southern Iberia. A contrasting situation is observed on the northern littoral of the Alentejo, where a dominant signal of pinewoods is recorded for the Lateglacial period (Quieroz, 1999; Santos and Sánchez Goñi, 2003). The evidence for established *Quercus* forest during the Lateglacial interstadial suggests a temperate, moist regime in the Guadiana lowlands, although the absence of the typical thermomediterranean sclerophyllous taxa (*Olea*, *Phillyrea*, *Pistacia*) suggests a continental seasonality with relatively cold winters.

A decline of *Quercus* forest and an expansion of pinewoods and xerophytic vegetation after *c.* 12 900 cal. BP (CM5-2) is contemporary with the Younger Dryas (YD) climate event as recorded in the Greenland oxygen isotope records. Increases in xerophytic taxa in the CM5 record may reflect enhanced long-distance transport of steppic pollen from the continental Iberian interior, although extra-regional sources are not considered solely responsible. The strong representation of *Juniperus* pollen, for example, may represent a formerly greater extension of xerophytic scrub vegetation similar to the vegetation community with *Juniperus phoenicea* ssp. *turbinata* that occurs today in the lower Guadiana basin in conditions of strong exposure and extreme aridity on steep slopes (Capelo, 1996). While strongly reduced from Lateglacial interstadial levels, significant frequencies of *Quercus* pollen attest to the persistence of forest stands in favourable microclimatic locations. A high proportion of deciduous *Quercus* and low proportions of *Q. suber* and evergreen types suggest that cold temperatures and severe frosts may have exerted a strong control over forest composition during the YD (Figure 5). The CM5 pollen record suggests that changes in atmospheric circulation during the YD were expressed in southern Portugal by cold and strongly arid climatic conditions. These conditions are consistent with geomorphological indications of intense aridity and strong winds in the Alentejo and Algarve coastal zone (formation of mass-wasting deposits and aeolian sand-bodies (Dias *et al.*, 2000)), and may explain, for example, the YD pollinic hiatus at the Santo André lagoon (Santos and Sánchez Goñi, 2003). Comparable reductions in forest cover and expansions in xerophytic or steppic taxa are readily identified in terrestrial records from southern Iberia (Pons and Reille, 1988; Quieroz, 1999; Giralt *et al.*, 1999; Dorado Valiño *et al.*, 2002) and marine pollen records from both the Atlantic and Mediterranean margins, where forest declines may be directly correlated with abrupt changes in SST during the YD (Boessenkool *et al.*, 2001; Turon *et al.*, 2003; Combourieu Nebout *et al.*, 2002).

Early to mid Holocene (11 790 cal. BP–4920 cal. BP)

Expansion of forest and thermophyllous taxa in CM5-3 suggests warming and increased precipitation at the onset of the Holocene. However, following this initial Holocene phase, renewed expansion of scrub and open-ground taxa point to an

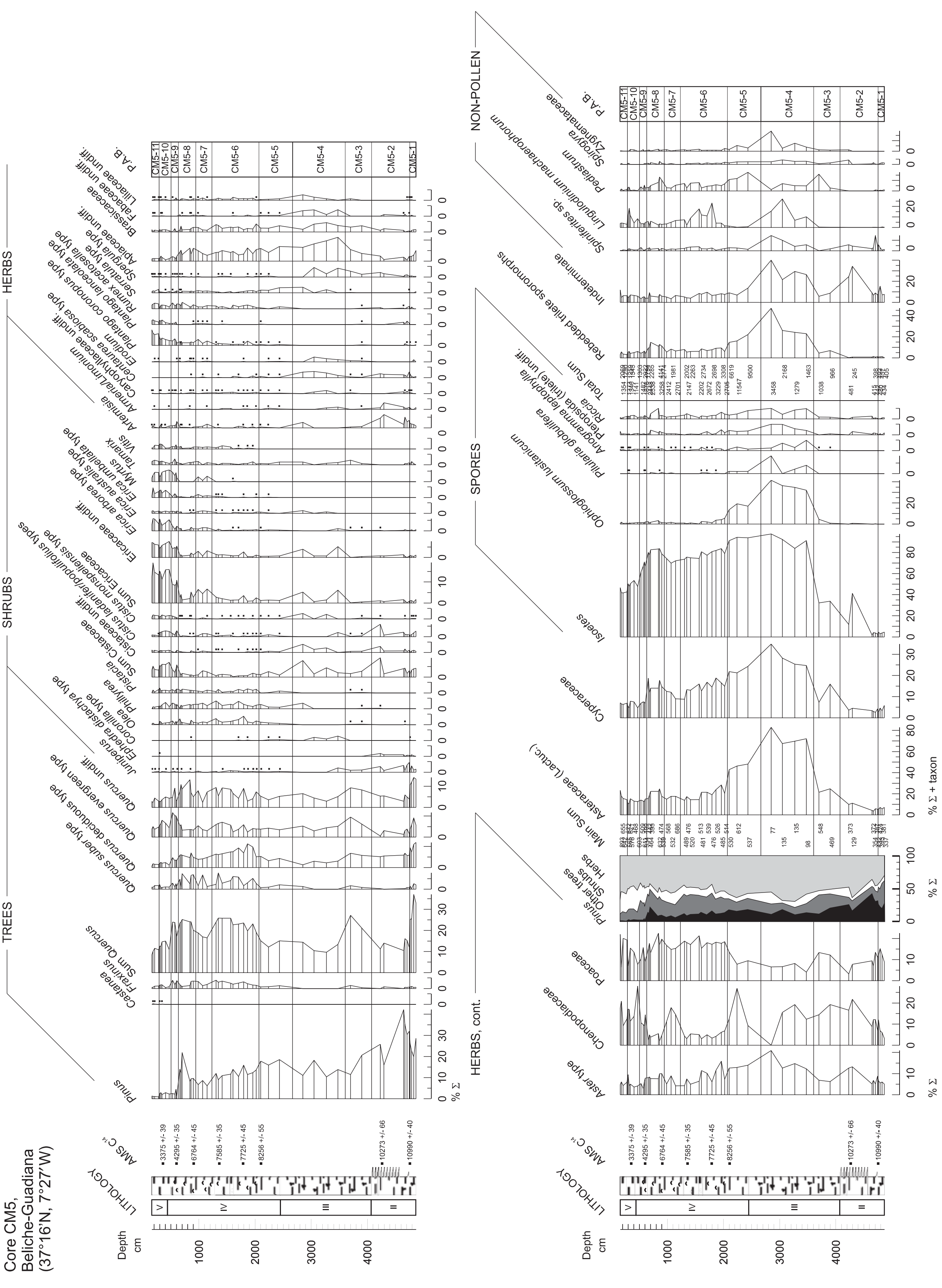

Figure 3 Percentage pollen diagram for core CM5, plotted against depth (including all taxa occurring at frequencies >1%)

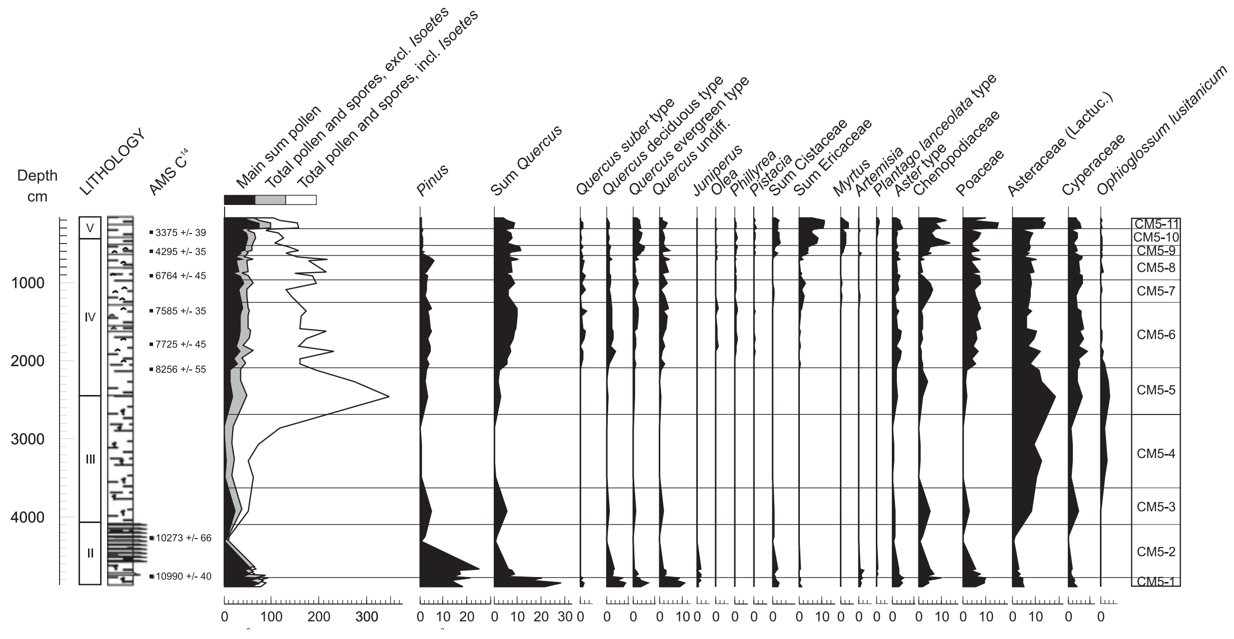

Figure 4 Pollen concentration diagram for common taxa in core CM5

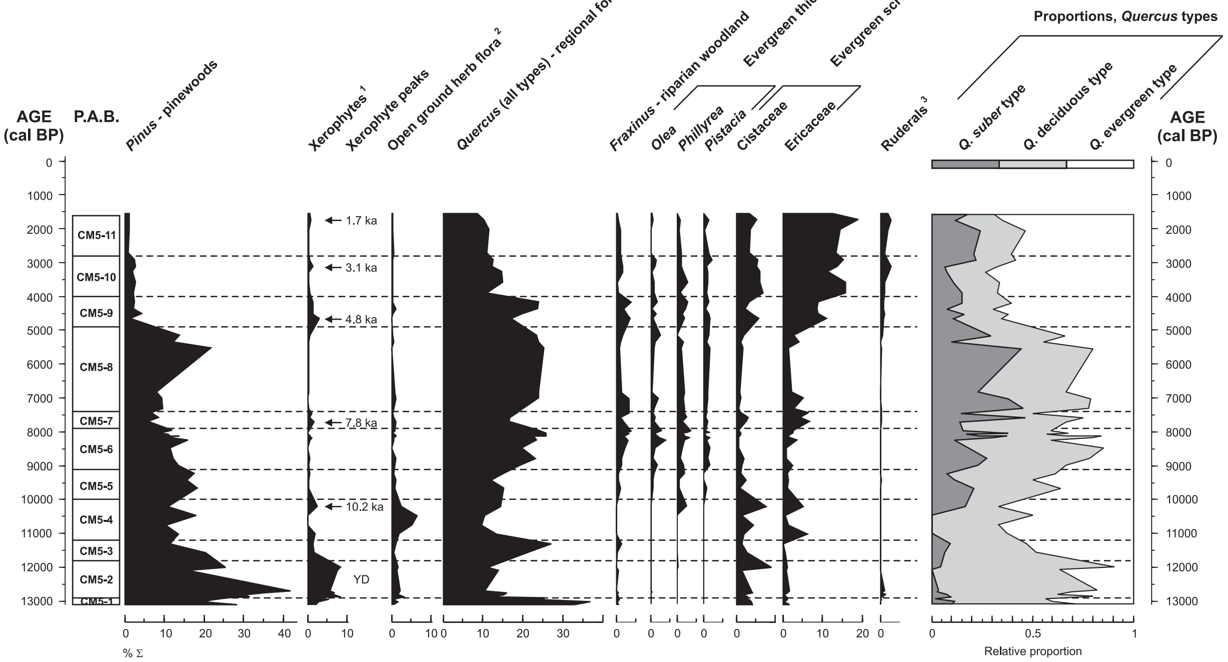

Figure 5 Percentage pollen diagram for ecologically significant dry ground pollen taxa, plotted against age. Summary groups include: 1, Xerophytes: *Artemisia*, *Juniperus*, *Ephedra distachya* type; 2, open ground herb flora: Caryophyllaceae undiff., *Centaurea nigra* type, *Centaurea scabiosa* type, *Echium*, *Erodium*, *Serratula* type; 3, ruderals: *Anthemis* type, *Fumaria officinalis* type, *Galium* type, *Jasione montana* type, *Plantago lanceolata* type, *Scabiosa colombaria* type, *Tuberaria guttata* type, *Valerianella*

early Holocene open vegetation mosaic of forest, evergreen scrub and grassland developing under generally dry conditions. Increased proportions of evergreen *Quercus* pollen further suggest that moisture availability became a critical factor on forest composition at this time. Changes in the shrub flora across zones CM5-4 to CM5-5 suggest an early Holocene trend towards warmer conditions with reduced continentality (lower incidence of winter frosts) with the decline of *Juniperus* after *c.* 11 000 cal. BP and the main expansion of thermomediterranean sclerophyllous taxa (*Olea*, *Phillyrea*, *Pistacia*) after *c.* 9950 cal. BP. This picture accords with wider evidence from other southern Iberian pollen records for a warm and rather dry early Holocene, with xerothermic forest prevalent in the Serra da Estrela (van der Knaap and van Leeuwen, 1995), an arboreal decline and steppe expansion in the upper Guadiana basin (Dorado Valiño *et al.*, 2002), a dominance of *Pinus* and xerophytes in the Segura montane zone of inland SE Spain (Carrión *et al.*, 2001a; Carrión, 2002) and steppe vegetation in the coastal lowlands of Almería, SE Spain (Pantaléon-Cano *et al.*, 2003).

Table 2 Description and interpretation of pollen assemblage biozones

P.A.B.	Depth (cm)	Age (cal. BP)	Description: dry ground pollen characteristics	Interpretation: vegetation events and climate trends
CM5-11	290–160	2830–1560	Decreases in *Pinus*, all *Quercus* types, *Olea* and *Phillyrea*; peak values for Ericaceae and *Plantago lanceolata* type; presence of *Castanea*	Forest minimum with further decline of pinewoods, *Quercus* forest and evergreen thickets; expansion of upland heath scrub (Ericaceae) and open ground habitats. Climate warm and dry
CM5-10	500–290	4040–2830	Decreases in all *Quercus* types and *Fraxinus;* peak values for Cistaceae, increase in Ericaceae, Myrtus and *Plantago lanceolata* type; presence of *Castanea;* peak values for *Vitis*	Major decline of *Quercus* forestand riparian wood lands; major expansion of lowland (Cistus) scrub vegetation; increase in anthropogenic activities. Climate warm and dry
CM5-9	633–500	≡4920–4040	Abrupt reduction in *Pinus*; decreases in *Quercus suber* and deciduous types; strong increase in *Quercus* evergreen type; increases in Cistaceae, Ericaceae, *Myrtus*, *Plantago lanceolata* type	Decline of pinewoods; decline of subhumid *Quercus* forest; shift in *Quercus* forest composition and/or expansion of *Q. coccifera* scrub, expansion of ever green shrublands (*matos*). Shift towards drier climatic regime
CM5-8	943–633	7390–4920	Increase in *Pinus*, *Quercus suber* and deciduous types; reduced frequencies of shrub taxa (Cistaceae, Ericaceae *Myrtus*)	Extensive forest cover with subhumid forest (*Quercus suber*); expansion of pinewoods. Climate warm, moist, oceanic
CM5-7	1225–943	7850–7390	Reduced frequencies of *Quercus*; moderate increases in Cistaceae, Ericaceae *Myrtus* and *P. lanceolata* type	Short-lived *Quercus* forest decline accompanied by expansion of shrublands. Arid interval
CM5-6	2060–1225	9130–7850	Increases in *Quercus* (notably *Quercus* deciduous and *Quercus suber* types) and *Fraxinus*; peak values for *Olea*, *Phillyrea* and *Pistacia;* declining frequencies of *Pinus* across the zone	Extensive forest cover with expansions of subhumid forest (*Quercus suber*), riparian woodlands and ever green thickets. Climate warm, moist, oceanic
CM5-5	2643–2060	≡9950–9130	*Pinus* and *Quercus* types stable; continuous curves for *Olea*, *Phillyrea* and *Pistacia;* reduced frequencies of Cistaceae, Ericaceae, Fabaceae, Caryophyllaceae undiff., *Centaurea scabiosa* type, *Erodium*, *Spergula* type	Expansion of thermomediterranean vegetation (evergreen thickets, woodlands), replacing more open shrub and grassland formations. Climate warm, dry, reduced continentality
CM5-4	3588–2643	11 170–9950	Reduced frequencies of *Quercus* pollen (in particular *Quercus* deciduous type); increases in Cistaceae, Ericaceae, *Coronilla* type (Fabaceae), Caryophyllaceae, *Centaurea scabiosa* type, *Erodium*; decline of *Juniperus*	Early Holocene *Quercus* forest decline; expansion of evergreen shrublands (*matos*) and open-ground environments. Climate warm, dry, continental
CM5-3	4066–3588	11 790–11 170	Increases in *Quercus* pollen (notably *Quercus* evergreen type); sporadic occurrences of *Olea*, *Phillyrea*, *Pistacia;* decreases in *Artemisia* and *Centaurea scabiosa* type	Initial Holocene *Quercus* forest expansion; modest development of thermomediterranean forest fringe (evergreen thickets); contraction of open ground environments. Increased temperature and humidity; reduced continentality
CM5-2	4754–4066	12 900–11 790	Peak frequencies for *Pinus*; reduction in all *Quercus* pollen types; increases in *Juniperus*, *Ephedra distachya* type, *Artemisia*, *Centaurea scabiosa* type and *Plantago lanceolata* type	*Quercus* forest decline; expansion of pinewoods, xeric scrub and open-ground environments (Younger Dryas). Increased aridity and continentality
CM5-1	4865–4754	13 090–12 900	Strong representation of *Pinus*, *Quercus* deciduous, *suber* and evergreen types	Extensive forestation by *Quercus* and *Pinus* (Allerød forest maximum). Climate temperate, moist, continental

It is recognized that the early Holocene in the CM5 record is also associated with the expansion of an oligotrophic marsh flora (*Isoetes*, *Cyperaceae*, *Ophioglossum lusitanicum, Pilularia globulifera*), reflecting major changes in the estuarine environment and greatly increased (though perhaps seasonal or episodic) moisture availability. However, this moisture availability is considered to have been driven predominantly by local hydrographic conditions related to rapid sea-level transgression rather than regional climatic factors. This local phenomenon may have been rather typical of other drowned valleys across the region, since increased transport of wetland pollen and spores (notably *Isoetes*) into the marine realm is recorded for the early Holocene in marine cores from the Portuguese and North African margins (Hooghiemstra *et al*., 1992; Marret and Turon, 1994; Boessenkool *et al*., 2001; Turon *et al*., 2003). The marked increase in Asteraceae (Lactuceae) at this time is of ambiguous significance, reflecting either (a) species of the marsh flora, (b) species of dry-ground open vegetation (accompanying *Centaurea scabiosa* type and *Erodium*) or (c) an inwashed soil component relating to the resilient morphology of the fenestrate Asteraceae (Havinga, 1984).

Forest expansion and maximum development of sclerophyllous taxa from *c.* 9130 cal. BP suggest a shift towards a warm, oceanic climate with mild winters and increased precipitation, which prevailed in general until *c.* 4920 cal. BP. In particular, increased proportions of *Q. suber* and deciduous *Quercus* within the record of oak pollen (Figure 5), support the inference of increased precipitation, because of the preference of *Q. suber* and the semi-evergreen oaks (*Q. faginea*, *Q. canariensis* = *Q*. deciduous type pollen) for subhumid to humid conditions (Polunin and Smythies, 1973; Capelo, 1996). A similar shift towards a wetter climate at around 9000 cal. BP is detected in a transition from xerothermic to mesothermic forest in the Serra da Estrela (van der Knaap and van Leeuwen, 1995), forest expansion in the upper Guadiana basin (Dorado Valiño *et al.*, 2002), the rise of *Q. suber* at Padul (Pons and Reille, 1988), and a shift from steppe to maquis vegetation in the arid lowlands of SE Spain (Pantaléon-Cano *et al.*, 2003). A shift to a wetter climate may also underlie the initiation of the Laguna de Medina lake record in SW Spain at this time (Reed *et al.*, 2001). The general prevalence of optimal conditions for forest development in the Guadiana valley until around 5000 cal. BP is consistent with pollen evidence for a mid-Holocene mesophytic forest maximum from the Arade basin of the western Algarve (Fletcher, 2005), the Alentejo littoral (Mateus, 1989a; Quieroz, 1999) and the Segura and Gádor mountains of SE Spain (Carrión, 2002; Carrión *et al.*, 2001a, 2001b, 2003, 2004), and includes the period of maximum Holocene lake levels at Laguna de Medina between *c.* 7200 cal. BP and 5500 cal. BP (Reed *et al.*, 2001).

This early to mid Holocene forest phase is interrupted by a short-lived but marked event of forest decline and shrubland expansion (CM5-7, *c.* 7850–7390 cal. BP). This forest decline is associated with aridity indicators, namely a shift towards increased proportions of evergreen *Quercus* and a series of local peaks in xerophyte taxa (Figure 5), and is considered the expression of an arid climate episode. A contemporary arid event is detected in lacustrine records in southern Spain and Morocco (Figure 6), as well as in the northern Sahara, where lake dessication events interrupt the main Holocene lacustrine phase (Gasse, 2002). An aridification phase at this time is also inferred from evergreen:deciduous pollen ratios at numerous sites in the western Mediterranean (Jalut *et al.*, 2000). These records point to an arid interval of wider regional significance beginning at ~8 ka cal. BP. This interval may be related to the strongest Holocene Greenland δ^{18}O isotope excursion (8.2 ka event) and global evidence for rapid climate change at this time (Alley *et al.*, 1997; Mayewski *et al.*, 2004). The evidence for an arid episode in the Guadiana valley is consistent with the proposed tripartite latitudinal division of climate conditions during the 8.2 ka event (Magny *et al.*, 2003), namely that southern and northern European latitudes were characterized by drier conditions while central latitudes experienced wetter conditions.

Late Holocene (4920 cal. BP–1600 cal. BP)

Zones CM5-9, CM5-10 and CM5-11 record a series of declines in arboreal populations and a progressive expansion of shrublands, characterized in particular by Cistaceae and Ericaceae. The shift in *Quercus* proportions to predominance of evergreen *Quercus* suggests a generally drier climatic regime after *c.* 5000 cal. BP, with three late-Holocene peaks in xerophyte taxa suggesting episodes of marked aridity at 4800 cal. BP, 3100 cal. BP and 1700 cal. BP (Figures 5, 6). While this aridification trend may have driven forward or exacerbated the progressive decline of the regional forest, human influence is also considered significant during this period, and climatic changes around 5000 cal. BP appear to have been coincident with the earliest indications of human pressure on the forest environment. The decline of *Pinus* in zone CM5-9 is not readily explained by a shift to a drier climate, and may represent the localized clearance of pinewoods during the Copper Age,

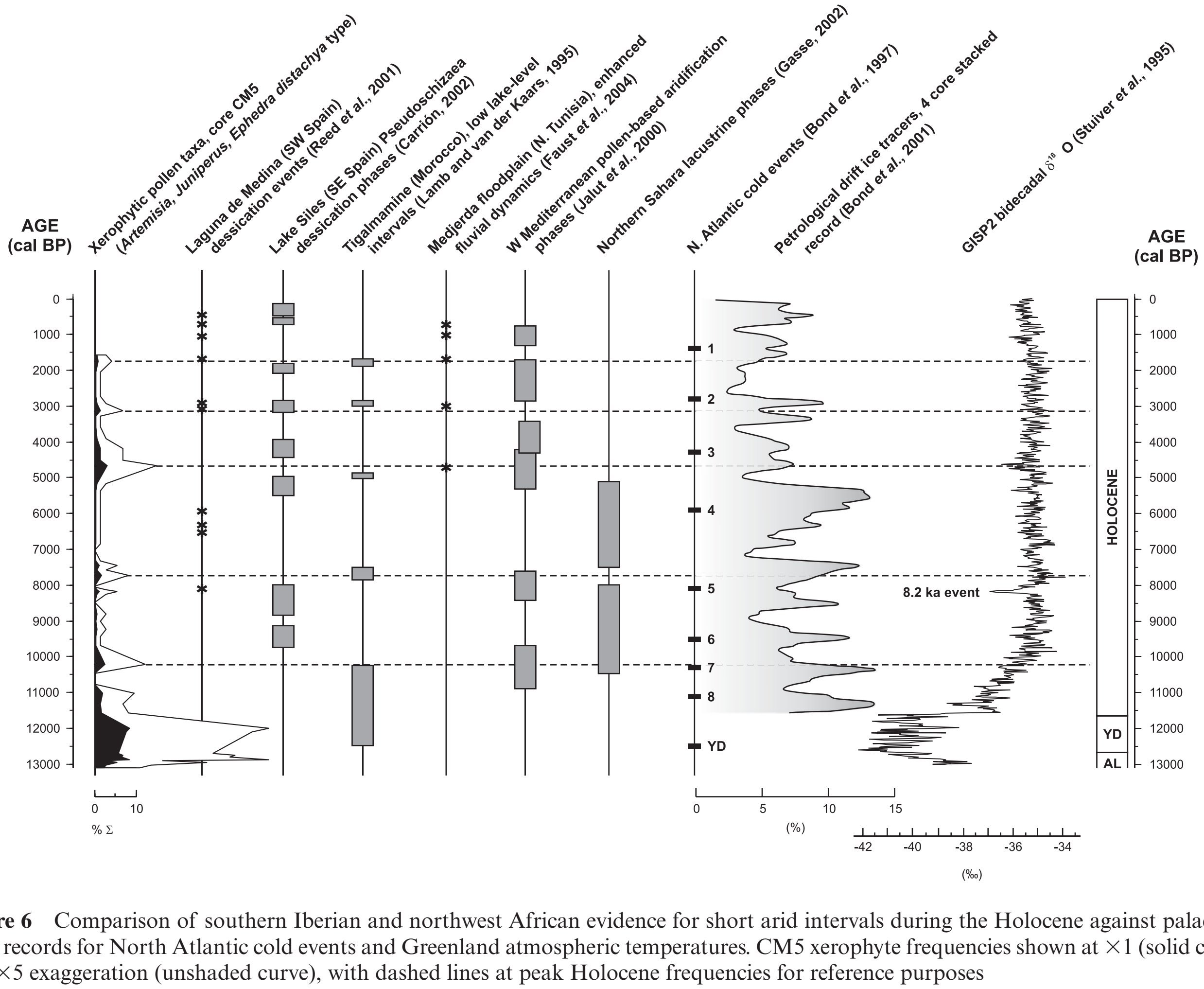

Figure 6 Comparison of southern Iberian and northwest African evidence for short arid intervals during the Holocene against palaeoclimate records for North Atlantic cold events and Greenland atmospheric temperatures. CM5 xerophyte frequencies shown at ×1 (solid curve) and ×5 exaggeration (unshaded curve), with dashed lines at peak Holocene frequencies for reference purposes

which began at *c.* 5200 cal. BP and saw the expansion of human activity into the hinterland of southern Portugal (Straus, 1989; Kalb, 1989).

Human influence on the landscape became increasingly important after *c.* 4000 cal. BP. A marked decline in both *Quercus* forest and riparian woodlands at *c.* 4040 cal. BP (CM5-10) is not accompanied by clear indications of increased aridity, and suggests an extension of deforestation activities into the upland valleys. This clearance precedes the appearance of *Castanea* (sweet chestnut), most probably an introduced species of southeastern European origin, in the pollen spectra from *c.* 3300 cal. BP (CM5-10). These vegetation events attest to the emergence of a semi-forested, cultural landscape during the Bronze Age. A further decline of pinewoods, *Quercus* forest and sclerophyllous thickets with *Olea* after *c.* 2830 cal. BP (CM5-11) attests to an intensification of human impact on woodland resources and a strongly anthropogenic landscape during the protohistoric periods (Iron Age, Roman). Across these periods, the progressive expansion of *matos* or scrub vegetation with fire-adapted members of the Cistaceae and Ericaceae families attests to an increased prevalence of fire in the landscape, reflecting the intensification of human influence and perhaps promoted by prevailing dry climatic conditions.

In the wider perspective, the decline of subhumid *Quercus* forest in the Guadiana valley corresponds with a regional chronological horizon at *c.* 5000 cal. BP of major environmental and climatic change, with mesophytic forest declines and expansions of evergreen taxa and/or xerophytic vegetation widely recorded at southern Iberia sites (Carrión *et al.*, 2001a, 2003, 2004; Carrión, 2002; Dorado Valiño *et al.*, 2002; Santos and Sánchez Goñi, 2003; Pantaléon-Cano *et al.*, 2003). Lake shallowing at Laguna de Medina (Reed *et al.*, 2001) and an increased prevalence of dessication phases at Lake Siles (Carrión, 2002) point to the onset of a more arid climate regime across southern Iberia at this time, part of a wider pattern of aridification in the western Mediterranean and north Africa (Magny *et al.*, 2002; Jalut *et al.*, 2000; Gasse, 2002; deMenocal *et al.*, 2000) occurring in the context of rapid global climate change at the Hypsithermal/Neoglacial transition (Mayewski *et al.*, 2004; Magny *et al.*, 2006).

Holocene aridification events

A series of submillennial arid episodes are detected in the CM5 xerophyte record, centred at around 10 200 cal. BP, 7800 cal. BP, 4800 cal. BP, 3100 cal. BP and 1700 cal. BP. With the exception of the 7800 cal. BP episode (discussed above), which interrupts the early- to mid-Holocene moisture maximum, these episodes appear to represent aridity maxima during the drier parts of the Holocene. Lake records at Laguna de Medina (Reed *et al.*, 2001), Siles (Carrión, 2002) and Tigalmamine in Morocco (Lamb and van der Kaars, 1995)) also provide evidence of submillennial arid intervals resulting in low lake levels or dessication events. While no two sites record exactly the same sequence of events, comparison of the records (Figure 6) suggests that several of the events were of wider regional impact in southern Iberia and north Africa, notably those occurring at around 1.7 ka cal. BP, 3.0 ka cal. BP, 5.0 ka cal. BP and 8.0 ka cal. BP. A further correlation is noted with the centennial-scale alluvial record of the Medjerda floodplain in northern Tunisia, where a late-Holocene series of 'event-like' episodes of enhanced fluvial dynamics have been detected, reflecting reduced vegetation cover and increased erosion during arid climate episodes (Faust *et al.*, 2004).

The correlation of arid intervals in the CM5 pollen, Tigalmamine lacustrine and Tunisian alluvial records highlights a strong climate linkage between southwestern Europe and Mediterranean north Africa. As precipitation in these regions is derived largely from Atlantic cyclonic activity, the origin and pacing of short arid intervals may be anticipated to reflect variation in the North Atlantic ocean–atmosphere climate system, notably as detected by Bond *et al.* (1997). Indeed, the timing of these regional arid episodes reveals a periodicity resembling the Bond cyclicity of ~1470 ± 500 years, and a reasonable correlation with specific episodes of North Atlantic cooling and ice-rafting, namely Bond events 1, 2, 3 and 5 (Figure 6). This correlation supports the view that North Atlantic cooling events during the Holocene were associated with dry atmospheric conditions in the Mediterranean zones of southern Iberia and north Africa, as previously demonstrated for the more marked cold events (Dansgaard/Oeschger stadials and Heinrich events) of the last glacial period (Combourieu Nebout *et al.*, 2002; Sánchez Goñi *et al.*, 2002). However, further research is required to understand in detail the chronological and climatological relationships between Holocene North Atlantic climate variability and short-term aridification events in this region, and to determine whether longer-term climatic trends or anthropogenic impacts underlie the apparently greater sensitivity of environmental systems to abrupt events during the last 5000 years.

Conclusion

Core CM5 provides a palynological record of dynamic vegetation changes in the lower Guadiana basin for the period from *c.*13 000 to *c.*1600 cal. BP. Reconstruction of the climate history of the region based on changes in the pollen spectra indicate (1) a moist, temperate Lateglacial interstadial (Allerød chronozone) from the base of the record at *c.* 13 090 cal. BP to *c.* 12 900 cal. BP, (2) an arid, cold, continental Younger Dryas phase between *c.* 12 900 cal. BP and *c.* 11 790 cal. BP, (3) a warm, dry early Holocene phase between *c.* 11 790 cal. BP and *c.* 9000 cal. BP, (4) generally warm, moist, oceanic conditions from *c.* 9000 cal. BP to *c.* 5000 cal. BP, and (5) a return to warm, dry conditions after *c.* 5000 cal. BP. This sequence is consistent with records from the Serra da Estrela, the upper Guadiana basin and southeast Spain, indicating a broadly parallel climatic development across southern Iberia since the Lateglacial. In addition to the principal record of forest/shrubland dynamics, the record of xerophytic taxa indicates a series of Holocene episodes of increased aridity. Despite chronological uncertainties involved in the correlation of brief events between terrestrial sites, several parallels are noted with arid events in records from southern Iberia and north Africa. North Atlantic sea-surface coolings and associated atmospheric reorganization provide the most likely explanation for the wider regional expression of these short-lived arid events.

Acknowledgements

This research was funded through a Natural Environment Research Council studentship for WJF (NERC/S/A/2001/06109), with the support of Trinity College and the Department of Geography, University of Cambridge. WJF gratefully acknowledges the support of his supervisor, Harriet Allen, and the advice and technical assistance of Phil Gibbard, Charles Turner, Steve Boreham and Chris Rolfe of the Quaternary Palaeoenvironments Group in Cambridge, and the assistance of Paolo Santana at CIMA. The authors thank Maria Fernanda Sánchez Goñi for helpful comments on the paper. This paper is Université Bordeaux 1, UMR-CNRS 5805 EPOC contribution no. 1623.

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