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Vegetation cycles in a disturbed sequence around the Cobb-Mountain subchron in Catalonia (Spain)

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Abstract

A 52 m-long lacustrine sequence has been recovered from the basin of Bòbila-Ordis, near Banyoles (N-E Spain). The presence of Early Biharian rodent teeth (Early Pleistocene) and of a c. 9 ka-long palaeomagnetic reversal (Cobb-Mountain subchron) suggests an age centred on 1.2 Ma, making this sequence one of the very few well-dated terrestrial sequences of that age in Europe. The first 22.5 m (with an interglacial character) are very homogenous owing to sedimentation affected by underwater springs. In the middle part of the sequence, palynological analyses, supported by sediment visual description, ostracod and mollusc assemblages, allow the reconstruction of one glacial-interglacial cycle, with vegetation succession. A second incomplete climatic cycle is recorded in the top part, within a shallower lake. These brief interruptions in the two climatic cycles are possibly linked to lake bank collapse caused by *Hippopotamus amphibius* or faulting linked to karst. The succession is likely to correlate to MIS 36-33. The Bòbila-Ordis lacustrine series (including two other nested lakes) covers altogether some sections of four glacial and four interglacial periods, not all contiguous.

Key words

Catalonia; lake sediment; Early Pleistocene; palynology; vegetation; *Hippopotamus*; underwater springs

Introduction

European Late Pliocene-Early Pleistocene continental lacustrine sequences are an archive rich in palaeoenvironmental information. Their scientific attraction has recently further increased, as it has appeared that the earliest humans had already reached Europe in the Early Pleistocene (Falguères 2003; Martínez-Navarro et al., 2005; Straus, 2001). It is however only in some rare cases that it is possible to attribute an absolute age to lacustrine sites of that age (Leroy, 2007; Leroy and Seret, 1992). In relation to establishing the duration of sequences, the recognition of progressive vegetation colonisation out of their glacial refugia and of their expansion throughout an interglacial period permits the detection of successive glacial-interglacial cycles (Leroy 2007; Leroy and Arpe 2007). The establishment of forcing by obliquity (41 ka) on vegetation change during the Gelasian and the Calabrian stages is fundamental to the approach (Ruddiman 2006, Leroy 2007).

This palynological study covers a part of the Early Pleistocene in N-E Catalonia, Spain. The sedimentation takes place in a large subsiding lacustrine complex at a time when regional volcanic activity was minimal. Dating is obtained by a unique combination of micromammal zone, cyclopalynostratigraphy and magnetic reversal zone (Cobb Mountain). The direct recognition of the obliquity forcing on the sediment and the palaeovegetation is however made more difficult by the presence of disturbances to the normal lake sedimentation which are also seen in the palynological diagram.

General setting

Modern setting

Lake Banyoles (42° 08' N; 2° 43' E; 173 m a. s. l.) (fig. 1a) is the relict of a much larger Plio-Pleistocene group of lakes: the Banyoles-Besalú lacustrine complex (Julià 1980). The karst in the underlying Eocene gypsum is very active as seen by the recent formation of new small lakes in villa gardens and frequent road collapse (Leroy 1997). The morphology of the lake corresponds to linked subcircular depressions with, in the centre of most, a deep and narrow channel (Canals et al. 1990). The hydrology of the present-day lake is characterized by endoreism and by twelve warm sublacustrine springs feeding the lake through the channels (Julià 1980). In some of the six main depressions, sediment suspensates over upward-flowing phreatic water are present providing them with artificial flat bottoms (Canals et al. 1990). The suspensates are made of various grain sizes (Sanz 1985) in which the sand fraction contains abundant Eocene fossils.

The mean annual air temperature measured at Banyoles town is 15.5 °C and the mean annual rainfall is 814 mm. The climate is characterized as humid Mediterranean, as there are hardly any dry summer months. Both Pliocene and present-day vegetation show a clear climatic limit at the latitude of Barcelona between dry Mediterranean climate in the south and more humid temperate climate in the north (Suc et al. 1995). The region of Banyoles is in the domain of the *Quercetum ilicis galloprovinciale* dominated by *Quercus ilex* and *Viburnum tinus* (Folch 1981, Bolós and Vigo 1984). More precisely the lakeshores belong to the *Quercetum galloprovinciale pistacietosum* (with a great abundance of *Pistacia*

lentiscus). A few kilometres to the west, the hills and mountains are already part of the *Quercetum mediterraneo-montanum*.

Geological setting and past investigations

The Banyoles-Besalú lacustrine complex (which is part of the Neogene basin of the Empordà) is now dislocated and collapsed due to tectono-karstic activity over the last few millions of years (Julià 1980, Pérez-Obiol and Julià 1994). The hills west of the lake are part of the Eocene relief of the Garrotxa. The normal fault of Albanyà, here with a NNE- SSW orientation, borders the east of the lake (Julià 1980). A wealth of palaeoenvironmental information has been derived from the region. Abundant large mammals and fossil leaves dating to the Late Pliocene and Early Pleistocene have been found in the lacustrine bedrock and in sinkholes in the Incarcà quarry at Crespià (Roiron 1992, Galobart *et al.* 1996). A recent 30,000 year-long pollen diagram has been obtained from the lakeshores at La Draga (Pérez-Obiol and Julià 1994).

Drilling in Early Pleistocene deposits in the 1980s has provided a series of long lacustrine sequences at Tres Pins and at Bòbila-Ordis, two sites a few hundred meters from each other on the hills a couple of kilometres north of the modern lake (Leroy 1990, Leroy 1997, local map in Leroy *et al.* 2001).

For more than 40 years, extensive palynological studies have been performed on several sequences exposed and drilled in the brickyard of Bòbila-Ordis (190 m a. s. l.) altogether adding to more than 127 m. The existence of at least three palaeolakes separated by normal faults has been revealed (location map of these sites in Leroy 1997 and Leroy *et al.* 2001). They are named as follows: lake 1 for the oldest, lake 2 for the middle one and lake 3 for the most recent of them (fig. 1b). Multidisciplinary studies such as sedimentology, pollen, mammal fauna (macro and

microfauna), ostracods, gastropods, magnetic susceptibility and palaeomagnetism have contributed to reveal the age of the palaeoclimatic changes as belonging to the second half of the Early Pleistocene (hence part of the Calabrian Stage).

Lake 3 sediments are exploited for brick production and have been investigated in outcrops (17 m in thickness) (Elhaï 1966; Geurts 1977; Julià 1977, Julià 1980; Julià and Suc 1980) as well as from three borings (BO I, BO II and BO III, maximum depth 29 m) in the floor of the quarry (Leroy 1987, Leroy 1990) (fig. 1b). The sediment of the cores and of the outcrops is very homogenous and dominated by a black carbonate mud, becoming a yellow sand only towards the top of the outcrop. A relatively rich mammal fauna has been found over the years (Agustí *et al.* 1987), as well as a part of a bird (Mayr and Gregor 1999). The small mammal fauna is composed of a first lower molar of *Mimomys savini* and a first lower molar of *Allophaiomys burgondiae* (Agustí in Leroy *et al.* 1991). The large mammal fauna includes *Cervus philisi*, *Hippopotamus antiquus* and *Equus stenonis* (Julià 1980). Bòbila-Ordís' *H. antiquus* identification has been subsequently revised to *H. incognitus* Faure (Faure, 1985) and to *H. amphibius* (Galobart *et al.* 1996). This fauna agrees with a Late Biharian age suggested by rodent finds, the Biharian being a micromammal zone at c. 2.0-0.7 Ma ago (Agustí *et al.* 1999). Pollen diagrams indicate a warm temperate deciduous forest dominated by *Carpinus*, *Quercus* and *Ulmus-Zelkova* (Leroy, 1987). Pollen from the upper part of the outcrop indicates that the forest is followed by a steppe vegetation rich in Asteraceae Cichorioideae (Julià and Suc 1980).

Lake 2 is known from a 13 m outcrop (BOC III and IV) (Leroy 1988, Leroy 1990) (fig. 1b). The sediment is mostly aleuritic. The pollen spectra correspond to a well-developed steppe vegetation rich in Asteraceae Cichorioideae interrupted by a

short interstadial period. Only a tooth of *Microtus* sp. has been found in this unit (Leroy et al. 2001).

The detailed results of the palynological study of lake 1 (BO IV) are presented here for the first time (fig. 1b). A summary palaeoclimatic interpretation based on an arboreal pollen/non arboreal pollen (AP/NAP) curve of 146 palynological samples as well as the dating and palaeomagnetism have been previously published by Løvlie and Leroy (1995).

Lake 1: the succession of BO IV

Drilling

The BO IV drillhole is located on the limestone plateau overlooking the quarry (fig. 1b). The Sedidril 500 (Leroy and Colman 2001) was used to obtain a 5210 cm long core in 1988. The system is rotary and uses a piston to retrieve continuous core sections in a liner (10 cm in diameter) each 100 cm long plus a 15 cm-long head. The bottom of the lacustrine succession has not been reached. The top 631 cm were not sampled, as this unit was known in outcrop (limestone on fig. 1b) as being barren of palynomorphs (Leroy 1990). Only one core section was disturbed: at 2065-2020 cm, probably not by drilling but by in-situ phenomena.

Lithology

The visual lithological description (partially published in Leroy 1990; Løvlie and Leroy 1995; Julià *in*: Leroy et al. 2001) indicates that the beige to dark coloured sediment consists of fine to coarse-grained calcium carbonate (25-95%) mostly

formed by Charophyte vegetative structures (fig. 1b). Fossil wood remains and other organic constituents have been sulphurised.

At 5210-2815 cm, the sediment is a dark grey clayey silt with some thin horizons rich in Characeae, ostracods or yellow sands, becoming more micritic upwards. At 2815-2390 cm, coarse yellow layers alternates with black clays at a cm-scale. At 2390-2000 cm, the sediment is very disturbed, with soft and hard sub-rounded stones at 2294-2254 cm, with several microfaults (including a larger fault at 2150-2140 cm), and with a very disturbed zone at 2065-2020 cm. It is suggested that this zone (2390-2000 cm) is bounded by discontinuities in connection with the dissolution of the underlying Eocene sediment leading to bank collapse, erosion and sediment mixing (Julià 1980). A silty clay rich in Characeae and gastropods at 2000-1658 cm is succeeded by a bedded zone (greenish clayey silt and yellow silt) up to 1315 cm. The sediment is at first fine with alternation of beige and green beds, and then becomes coarser, more oxidised and rich in gastropod remains. Afterwards, the lamination progressively fades out and is replaced by coarser carbonates consisting predominantly of Charophyte thalli. At 1263-985 cm depth, the coarser and lighter carbonates, sometimes indurated, contain abundant gastropods (including some pure shell layers) and sand layers. The presence of roots, oxidation features and edaphic carbonate nodular precipitation suggest a period of sub-aerial exposure. At 985-630 cm, the sediment is finer with some beds of organic matter. Traces of emersion and pedogenesis are still present. The top of the sequence (not sampled by the corer) has penetrated through the limestone forming the plateau above the quarry (fig. 1b).

Malacology and Ostracodology

Figure 2 provides the summary interpretation of the mollusc diagram (53 samples grouped into five main zones) prepared by Magnin (Magnin 1991; Magnin *in* Leroy et al. 1997 and Leroy et al. 2001).

Forty samples have been analysed for their content in ostracod valves by Coen (see Coen *in* Leroy 1990 and Leroy *et al.* 1997, 2001) (fig. 2 and 3). From the bottom of the sequence up to 2040 cm, the regular occurrence of *Metacypris cordata* indicates a true freshwater environment (fig. 3). The most common accompanying taxa are *Candona neglecta*, *C. compressa*, *Ilyocypris gibba* and *I. cf. getica*. Of these, *Ilyocypris gibba* is known to reproduce parthenogenetically throughout northern and middle Europe. Males are rare and only known from Spain (this is actually the case in the present lake) and some other places in the Mediterranean area. A few males are also present in the sequence around 2400-2300 cm. Lower and higher, only females occur and the environment thus seems to be less favourable. At 5160-4145 cm, *Candona* is only represented by larvae, except at 4840 cm, a level that is a thin white horizon very shell-rich and containing adults. At 3700-3200 cm, the sediment is very poor in shells. At 3200-2040 cm, the assemblages become more diverse. At 2790 cm, *Metacypris* temporarily regresses whereas the concentration of *Candona* and *Ilyocypris* reaches a maximum. At 2320 cm, Eocene foraminifera are present as well as marine ostracods (*Pterygocythereis*). The following two samples are uncharacteristically sterile in ostracods (2240 and 2140 cm). Above 2000 cm depth, *M. cordata* is no longer present. *Cyprideis torosa* enters at 1650 cm and becomes the most common species at 1210-1100 cm. *Cyprideis* valves become tuberculated, a phenomenon typical of brackish waters, and then disappear. Because the eggs are unable to sustain desiccation, it is suggested that there is no longer a permanent body of water in the uppermost part of

the sequence. *C. compressa*/*C. marchica* become more abundant than *C. neglecta* indicating a more littoral environment. At 1000 cm, *Heterocypris salina* with such species as *Cypricercus obliquus*, *Cypris pubera* (all valves are broken suggesting wave action) and *Eucypris pigra* indicate temporary emersion only. Both *C. torosa* and *H. salina* further indicate brackish water. At 890-650 cm, only forms of temporary waters such as *Candona* and *Cyclocypris* survive.

Palynology of the BO IV sequence

Methods

A total of 196 samples is presented here, including a first batch of 146 samples analysed more than 15 years ago (Leroy 1990) and fifty additional samples taken especially above 23 m depth in order to precisely identify some steps of vegetation development. The first batch used density separation (Dricot and Leroy 1989) and the more recent batch HF instead. The density technique seems to result in slightly higher Pinaceae values. The sampling resolution is of < 60 cm below 2980 cm, of < 35 cm at 2944-1070 cm and < 15 cm above 1068 cm. Twenty seven samples were very poor or did not contain any palynomorphs (fig. 2). They have been omitted in the statistical analysis but they nevertheless carry some environmental information used in the interpretation.

Psimpoll 4.10 has been used for plotting the data as well as for the statistical analysis (Bennett 2003) (fig. 4 to 6). More than 150 taxa have been identified. The terrestrial taxa (AP and NAP) form the sum (usually > 300) used for percentage calculation. The aquatic taxa, the spores, the reworked, indeterminated and

undeterminable pollen and spores (excluded from the sum used in the percentages) have been plotted at the end of the detailed diagrams as well as some other microfossils providing information on reworking, water depth (such as spores of Zygnemataceae) and contamination by Eocene marine sediment (Dinoflagellate cysts). The aquatics include *Thelypteris* cf. *palustris*, as it is a fern growing in swamps (Leroy 1987). The concentration in numbers of palynomorphs per g of dry sediment has been calculated for the first batch of 146 samples using a combination of volumes and weights (Leroy 1990). The same laboratory and equipment were not available for later samples. The concentration of the additional samples was then estimated using the *Lycopodium* tablet method and is given in number of palynomorphs per ml. Figure 2 provides a graph where the two sets of values are plotted on the same axes. Unexpectedly, no major difference seems to arise from the use of the two different methods and units. A zonation has been created on the basis of the 17 most frequent taxa (fig. 2) and has been obtained by CONISS after square-root transformation and exclusion of the sterile samples. The dissimilarity coefficient is Edwards and Cavalli-Sforza's chord distance (Cavalli-Sforza and Edwards, 1967).

Results

pz1: 5210-2937 cm (47 samples and one sterile)

After the Pinaceae pollen, the dominant AP are: *Carya* (on average 15%), *Quercus* (c. 11%), *Picea* (c. 6% and two 'whole diagram' maxima at 13%) and *Ulmus-Zelkova* (c. 3%) (fig. 4). *Abies* pollen percentages also form a continuous curve, reach twice maximal values for the diagram (>4%) and decrease towards the top. *Fagus* values reach a maximum of 3.5% in an isolated peak at 4176 cm. *Tilia* pollen grains come to a diagram maximum at 1.1%. Ericaceae are continuously present as well as *Parrotia* cf. *persica* for which a clear increase of the mean values

(> 3%) occurs above 3117 cm and a maximum is reached at 9%. A progressive increase of *Pterocarya* is observed. The herbs are poorly represented with the exception of Poaceae and *Artemisia*. Cyperaceae have continuous curves. *Cladium* cf. *mariscus* (diagram maximum at 2.4%), psilate monolete spores (diagram maximum at 3.1%) and *Thelypteris* cf. *palustris* are sub-continuous. They all decrease progressively towards the top. It is noteworthy to underline the very regular occurrences of *Pteris* (except in the last meters of this zone) and dinocysts (diagram maximum at 5.2%).

pz2: 2937-2807 cm (9 samples)

Owing to a relative decline of the dominant AP taxa, the diversity of other AP increases with the better marked presence of *Betula* and *Corylus* (fig. 5). *Carpinus* percentages rise. *Parrotia* values remain high as it already was at the end of the previous zone. Amongst the NAP, *Artemisia* and Poaceae slightly expand.

pz3: 2807-2760 cm (5 samples)

It is only in this zone that *Betula* values pass the threshold of 2%. *Eucommia* (> 1.5%), *Artemisia* (13.4%) and Poaceae (25.4%) values are maximal. This zone is characterized by the most distinct drop in AP of the whole diagram in favour of Asteroideae, *Artemisia*, Cyperaceae, Poaceae, *Plantago*, *Thalictrum*, Rosaceae and *Sanguisorba* cf. *minor*. *Thelypteris* and psilate monolete spores also increase.

pz4: 2760-2415.5 cm (15 samples)

Pinaceae values are generally low. Only some AP recover fast: *Ulmus-Zelkova* (with a distinct maximum of 22% followed by a progressive decline) and *Quercus* that will later reach a maximum at the end of the zone. *Carya* re-increase is

lightly delayed. *Carpinus*, *Parrotia* and *Pterocarya* reach high values at the end of this zone. *Artemisia* and Poaceae progressively decline to the centre of the zone and re-increase towards the zone last third. *Nymphaea* (2.0%) forms a single peak.

pz5: 2415.5-2299.5 cm (6 samples)

This zone is characterised by a re-increase of Pinaceae and Ericaceae. *Quercus* values decrease sharply. *Hedera* is continuously present. Single maximal peaks of *Myriophyllum* (8.7%), *Potamogeton* (2.4%) and *Zygnema* (7.6%) are observed. There is a maximum of *Concentricystes circulus* (1.4%), along with high “indeterminable grains” values and dinocysts.

pz6: 2299.5-2059 cm (13 samples)

Only three samples provided palynomorphs. Pinaceae have reached 58%. *Picea* is still well represented (5-11%). *Carpinus* and *Pterocarya* have nearly disappeared. Psilate monolete spores, indeterminable grains, *Concentricystes* and dinocysts are relatively high. The concentration is low.

pz7: 2059-1947 cm (7 samples)

All samples (six variably preserved samples and one sterile) belong to the same disturbed core section. They display a slight drop of Pinaceae, and a re-increase of *Carpinus*, *Quercus* and *Ulmus-Zelkova*.

pz8: 1947-1375 cm (25 samples)

The pollen assemblages are very different from all those below. The AP are dominated by Pinaceae (up to 80.6%) and *Quercus*. *Cathaya-t.* pollen reaches unprecedented high values of 8.1%. Of secondary importance come: *Tsuga* that

presents for the first time a continuous curve with slightly increasing values, as well as low *Carpinus*, *Carya* and *Ulmus-Zelkova*. *Pterocarya*, and *Parrotia* only have frequent occurrences. Ericaceae have a progressively increasing continuous curve. *Picea* has nearly dropped off the assemblages. Most of the NAP values are very low, besides Poaceae that fluctuate around 3%.

pz9: 1375-1333 cm (3 samples)

This zone is characterised by low values of Pinaceae, and maxima of *Tsuga* and Ericaceae. *Carpinus* has re-increased, as well as *Quercus*, *Carya* and *Ulmus-Zelkova*. *Fagus* values are over 1.6%. *Parrotia* values increase progressively through this zone but remain moderate.

pz10: 1333-1290 cm (3 samples)

This zone is similar to the preceding one and the top of zone 8. Pinaceae values have re-increased. *Cathaya-t.* pollen occurs with 7%.

pz11: 1290-1214 cm (7 samples)

The second most important split in the diagram (fig. 3 and 6) starts with this zone, with first three good samples and then four sterile ones. The cold and/or dry AP group is low. *Tsuga* has dropped off the diagram. The warm and/or humid group on the other hand reaches maximal values of 70% owing mostly to *Quercus* (54%). *Artemisia* and Poaceae display a small increase. However the indeterminable and the reworked grains are high especially in the second and third samples. The concentration dramatically decreases to zero.

pz12: 1214-1136 cm (6 samples)

Four sterile samples start this zone in a continuation of the preceding zone. Then two good samples are available with progressively increasing concentration values. They offer good similarities with the preceding zone: very low group of AP cold/and/or dry, very high *Quercus*, and good presence of *Artemisia* and *Poaceae*. Eleven percents of indeterminable grains have been counted.

pz13: 1136-1049 cm (9 samples)

This zone is made of 5 good samples and 4 sterile ones with low but progressively increasing values of *Pinaceae*. High percentages of *Carpinus* (up to 24%), *Carya* (up to 31%) and *Ulmus-Zelkova* (up to 16.7%) occur. The top sample has relatively high *Artemisia* and *Poaceae* percentages (9.8 and 13.7%) as well as maximal diagram values for some NAP: *Amarantaceae-Chenopodiaceae* (1.5%), *Cichorioideae* (1.8%) and *Asteroideae* (2.9%), and also for *Mougeotia* (3%).

pz14: 1049-984 cm (7 samples)

This zone has a very varied preservation state (6 good samples and one sterile). *Pinaceae* are abundant (up to 75%). A second peak of maximal values for *Picea* is reached at the top of a short bell-shape curve (12-13%). The AP are otherwise present in very low amounts. A diagram maximum of *Cyperaceae* at 8.4% has been observed in this zone. For the other NAP, only *Poaceae* have a reasonable presence with 4-6%. Maxima of *Typha-Sparganium* (3.3%) and *Spirogyra* (4.5%) have been reached. The first sample contains very high quantities of indeterminable grains (45%).

pz15: 983-638 cm (33 samples)

This zone contains 31 samples and two sterile ones (at the top). In this overall rather homogenous AP-rich zone, some poorly defined vegetation successions can be detected. The first half is characterised by more Ericaceae and *Osmunda* and the last one by *Abies* (regular occurrences in the lower 2/3 of this zone, then again reaches values of > 1%), *Cathaya*-t. and *Typha-Sparganium*. The NAP are discreetly dominated by Poaceae. *Artemisia*, Asteroideae, Cichorioideae and Amarantaceae-Chenopodiaceae are regularly present. Reworked pollen grains and *Zygnema* spores are occasional. High concentration values are often reached in this zone (> 150,000 grains per g of dry sediment or per ml of wet sediment) (fig. 2).

Palaeovegetational interpretation

The 15 pollen zones have been divided into three main groups (fig. 2) for a palaeovegetational interpretation.

pz1

The existence of a mixed forest with some open terrestrial spaces is suggested. Spruces were growing on the nearby hills. The deciduous tree assemblage has a clear riparian component. A marsh had developed around the lake. Towards the top, there is a slight development of the deciduous species and the closing of the landscape both on land and in the wet zones around the lake.

pz2-10

In pz2, a diversification of the deciduous forest, the development of light-demanding trees and of open terrestrial spaces takes place. This zone also sees a clear decline of the marshy vegetation, besides some surviving bulrushes. Pz3 is

characterised by a sharp drop in the values of most tree taxa except *Betula* and *Eucommia* (*E. ulmoides*, the hardy rubber tree, is a tree that can withstand periods of drought and lives in relatively open habitats) which both reach their maximal development and the clear rise of *Artemisia*, *Sanguisorba minor*, Poaceae and other herbs. A totally different landscape has developed, similar to a wooded steppe with an extensive grass layer. The persistence of some warm temperate tree pollen is explained both by the location of BOIV near glacial refugia (Leroy and Arpe 2007) and by the over-representation of trees in relatively open landscapes (Davies and Fall 2001). In pz4, the first step towards tree recovery takes place with elms as pioneers. Pz4 has a very dynamic deciduous forest with clear successions of trees linked to a climatic improvement. The forest becomes closer and then opens slightly again in zone 5. The aquatic vegetation also changes rapidly from possibly deeper to shallower waters. No reliable palaeovegetational reconstructions, besides erosion and the influence of the underlying Eocene, can be derived from pz6-7. After the transition pz7/8, the vegetation changes completely (see dendrogram in fig. 2). It is now a mixed forest dominated by coniferous trees, Pines and *Tsuga*, with an understorey of Ericaceae. Some oaks live in more sheltered locations. In zone 9, a slight decrease in Pine dominance allows the further development of oaks, heathers (not necessarily the same species as in pz5) and *Tsuga*. Other altitude-loving species develop towards the top, such as *Abies* and *Fagus*, which must have been growing not far from the lake. In zone 10, Pines spread again. The lake vegetation remains very sparse.

pz11-15

If the assemblages of pz11-13 can be relied upon, a deciduous forest largely dominated by oak develops. Later it becomes more diverse with the addition of other

deciduous species. The herbs such as various composites and grasses are clearly present too. In pz14, the deciduous forest disappears (usually 5%) a second time and is replaced by conifers; an open pine forest dominates the landscape with spruce in more sheltered locations. The development of a wooded steppe, with some similarities to that of pz3, is likely. The lake might have been shallow with edges covered by marshy vegetation (sedges and grasses), different in composition from pz1. A relatively open deciduous woodland is reconstructed for pz15, close to climatic interglacial conditions but without well-defined vegetation successions. The lake remains shallow. *Alnus* along with *Osmunda* illustrate a transformation of the marsh into a forested swamp along the shores of the lake.

Discussion

The homogenous sections and the sterile levels

Some taphonomical discussion is provided for four disturbed depth zones before a climatic signal can be derived from the sequence.

The homogeneity of the pollen spectra of pz1 (22.5 m) on such thicknesses of sediment is unusual. Mollusc and ostracod assemblages suggest permanent freshwaters (fig. 2). A great homogeneity of the first 29 m of lake 3 (cores BO II and BO III) has also been observed (fig. 7). An explanation may be proposed bearing in mind that the lake was permanent and probably at least a few meters deep. The homogenous sections could be suspensates that have settled down in their conical basins and feeding conduits. Canals et al. (1990) mention a suspensate that is more

than 100 m thick, although most of them would be 3 to 20 m thick. A palynological analysis of modern samples taken in the depression of the southern lobe (B1) of lake Banyoles indicates the continuous presence of marine dinoflagellate cysts (from the underlying marine Eocene sediment) and spores of *Concentricystes circulus* (signs of erosion and reworking) but otherwise the spectra are typical of the modern pollen rain (Leroy 1990; Serra et al. 2005). This would indicate that the suspensates are dominantly formed by sediment coming from the lake and not from the Eocene. Another possibility is that the spectra come from an area of the lake where the suspensate spills over during floods or during periods of water mixing (Serra et al. 2005). Therefore in brief, a new depression would start with an active spring (formation of the homogenised sediment with homogenous palynological spectra); later when the spring disappears, the depression becomes “old” with a quiet sedimentation. The “normal” sediment (with changes in the spectra reflecting climatic change) would be formed in depressions that have self-sealed. The role of bioturbation by large mammal feet, especially *Hippopotamus*, or pedoturbation, has been considered but rejected. In the lakes themselves *H. amphibious* schools tend always to follow the same network of paths presumably to avoid impediment by aquatic vegetation and turbidity by mud lifting (McCarthy et al. 1998). However when levels become too low, lakes turn into muddy wallows where schools of *Hippopotamus* concentrate and this is not the case as the lake has been shown to be deep.

In pz6-7, the spectra are nearly sterile in palynomorphs or show traces of runoff (*Concentricystes*). The increase in Pinaceae is a sign of differential preservation. The only noticeable influence of Eocene marine sediment is the dinocysts (already in pz5). Terrestrial gastropods are well represented and indicate sedimentation on a

shallow lake bank. Ostracods reflect the influence from the Eocene or are absent. Moreover, the pedogenesis and a strong Eocene impact of pz6-7 suggest a sudden apparent emersion in an otherwise deep-water lake. In pz11-14, the sediment is often barren of pollen or very poor due to oxidation. The sediment shows traces of emersion. Some terrestrial gastropods become present again. *Gyraulus cristata* occurrences indicate aquatic vegetation and possible, but rare, periods of emersion. An ostracod assemblage representative of brackish environments is noted but the environment remains under water mostly. On the whole, pz11-14 indicate a pronounced shallowing in water depths. The sharp change at 984 cm (pz14/15 boundary) is marked in the sediment by a very clear contact, suggesting that, as for the Tres Pins sequence, the record is incomplete due to a series of small unconformities (Leroy 1997). The role of *Hippopotamus*, a gregarious animal, could better explain the environment of pz6-7 and pz11-14 by damage to the banks of rivers and lakes as it gets out of the water-holes for feeding on land and back in to spend the day in the water. Faulting linked to active karst cannot however be ruled out.

The disappearance of pollen in the final samples of the record is most likely caused by emersion. The distinct shallowing of the lake is illustrated in the pollen diagram with the wooded swamp of the beginning of pz15, the development of sedges and bulrushes in the second part of pz15 and the poor preservation of samples at 895 and 880 cm (peaks of hornbeam and oaks, closing up of the forest over the water body).

Multidisciplinary interpretation of the BO IV sequence

The lower part (pz1-2)

The relative high AP values suggest conditions close to interglacial. Pz2 is similar to pz1, but has more *Artemisia*. It may represent a transition with the two adjacent zones.

The first climatic cycle (pz3-10)

A quasi-complete climatic cycle is represented from a wooded steppe (pz3) to a coniferous forest (pz9-10), with a thermophilous forest in between, first deciduous, then mixed. The climate changed from very dry to warmer and dry, then warm and humid and finally cool and humid. The mollusc assemblages remain fairly constant throughout this zone, indicating permanent waters, whereas the ostracods indicate a slight salinisation. The climatic cycle starts by a diversification of the ostracod fauna. The steppic period sees an important temporary increase in the concentration of shells and, at 2790 cm (pz3), *Metacypris* temporarily regresses suggesting a slight decrease of permanent waters during the steppic vegetation zone. This ostracod species increases again and peaks at 2740 cm (pz4). *M. cordata* is no longer present in the second part of the climatic cycle. At the optimum (pz4), the climate must have been more humid than at present and certainly without a dry summer. The mean annual temperature must have however been close to the present one.

From the top of pz8 to 14, the presence of *Cyprideis torosa* indicates that waters become slightly brackish. The climatic cycle ends with a cooler and overall wetter climate than pz1-5.

Parts of another climatic cycle (pz11-15)

In ps14, the development of a wooded steppe, with more Pines than in pz3, is also caused by a clear lowering of precipitation. The vegetation of pz15 in comparison to the optimum of pz4 shows a more important role for *Parrotia persica* and *Corylus*, and the less important role for *Pterocarya*. The mollusc assemblages indicate more temporary waters and a stronger terrestrial influence. The ostracods confirm this trend: the waters are clearly brackish and the environment more littoral. This trend tends to increase through the climatic cycle indicating that local factors have become more significant than the climate for the local palaeolimnology (as in the top of the infill of Tres Pins, Leroy 1997).

Climacic vegetation and refugia

In the sequence of BO IV, the typical climacic forest is reflected by assemblages with *Quercus*, *Carya* and *Carpinus betulus*-t.. In the Early Pleistocene, based on a fossil leaf study at Crespià, these palynotaxa are most likely related to *Quercus cerris*, *Q. faginea*, *Carya minor* and *Carpinus suborientalis* (Roiron 1992). In the Holocene, the climacic vegetation is deciduous oak (Perez-Obiol and Julià 1994), possibly with *Q. robur*, *Q. humilis* and *Q. petraea* (Perez-Obiol R., personal communication, 2006).

DNA studies of deciduous oaks in the Iberian peninsula which suggest maintenance of the oaks along the coasts (Atlantic and Mediterranean) “with several isolated populations surviving in several northern valleys of favourable microclimates” and inwards re-colonisation to the centre of the peninsula (Olalde et al., 2002). Eastern Catalonia would therefore have fallen into this category already since the Early Pleistocene. The modelling of summer-green tree distribution during the last glacial maximum also confirms north-eastern Catalonia as a key refugial

zone (Leroy and Arpe 2007). Although in the grid point where Banyoles is (60 x 60 km) only cool summer-green trees may have survived, survival of warm summer-green trees is expected in the grid points to the north and east of Banyoles (Leroy and Arpe 2007). Forcing the atmospheric model with a warmer North Atlantic SST increases the precipitation considerably leading to a wider area with cool and warm summer-green trees (Arpe pers. comm.). The loss of species between a Lower Pleistocene oak-hickory-hornbeam forest and a Holocene oak forest can have several causes, the disappearance within glacial refugia themselves possibly being one combined with the more extreme glacial periods (Leroy 2007). Alternatively Bennet et al. (1991) have suggested the disappearance from refugia during interglacial times.

The age and environment of the rodents and the environment during the Cobb-Mountain subchron

Three rodent teeth have been recovered from 890-881 cm depth (fig. 2). They are assigned to two arvicolid species: *Allophaiomys chalinei* and a large size *Mimomys* sp. size of *savini* (Leroy et al. 2001). Each species is indicative of two successive biozones of the second half of the Early Pleistocene (Chaline 1977; Agustí et al. 1987). The fossils from lake 1 suggest an Early Biharian age; and comparisons to Atapuerca and Le Vallonnet sites indicate an age older than the Jaramillo Chron.

At these depths, the palaeolake has temporary and slightly brackish waters. A mollusc sample taken 10 cm above (880-875 cm) contains *Vertigo antivertigo*, a marshy species, and *Anisus leucostomus* from temporary aquatic environments rich in organic matter. The teeth have been found near two pollen samples (895 and 880

cm in pz15) whose poor preservation suggests also a period of temporary emersion. These rodent teeth appear in the deciduous forest phase of an interglacial period. It can also be concluded that the taphonomic and environmental conditions are those of lake edges with a wooded swamp (*Alnus* with *Osmunda*).

The whole normal polarity zone attributed to the Cobb-Mountain subchron is part of pz8, which is the second part of an interglacial when the climate becomes cooler but remains humid. In contrast to marine sediment with low sedimentation rates (an average of 4 cm per 1000 yr is suggested in Lisiecki and Raymo 2005), no relocation of the palaeomagnetic signal is expected here (Løvlie and Leroy 1995).

Obliquity-forcing and sedimentation rates

In the BO IV record, the sequence displays two main interruptions. The disturbance of pz6-7 has most likely not obliterated more than a few thousand years because the transition from pz5 to 8 appears as normal vegetation succession (Leroy 2007). However higher up in the sequence, the duration of the emersion of pz11-14 is less easy to constrain. The similarity of the pollen samples, for example within pz11-12, tends to lend support to a sedimentary event (such as lake bank collapse). Also a more thorough development of conifers such as *Tsuga* would have been expected at the end of pz15 based on a comparison to the first climatic cycle and climatic cycles at other sites (Leroy 2007). Hence the sequence above 28 m allows the reconstruction of one glacial-interglacial cycle with vegetation succession and parts of another cycle.

As the sediment is of Calabrian age, a glacial-interglacial cycle in lake 1 is believed to be forced by obliquity and therefore to have a duration of c. 41 ka (Leroy and Dupont 1994; Leroy et al. 1999; Ruddiman 2006; Leroy 2007). More specifically, the oxygen isotope record DSDP Site 607, which is at the same latitude as

Banyoles, is clearly dominated by the periodicity of the obliquity (Raymo et al., 1989). In core BOIV, excluding the 352 cm-long pz6-7, the resolution obtained for the first climatic cycle (2807-1290 cm) is of a sample every 800 yr and a sedimentation rate of 29 cm/ka (a first order approximation because the sedimentation rate must have varied with compaction, water depth and climate). This rate is lower than that from the last climatic cycle in the same lacustrine basin: 100 cm/ka at La Draga where the time resolution is 260 yr between samples (Perez-Obiol and Julià 1994). In both sites, there is a similar type of carbonate sediment rich in fossils and no overburden by younger sediment (therefore not leading to additional compaction).

Complements to the dating of the sequence

A first source of dating has been obtained by micromammals (Early Biharian). This has been complemented by (1) the presence of several plants now extinct in Europe, (2) cyclopalynostratigraphy and (3) the detection of a 9 ka-long magnetic reversal. The last three points although previously briefly published are further developed here.

Plant extinction

The three lakes of Bòbila-Ordis contain a range of plants that have now disappeared from Europe (*Tsuga*, *Carya*, *Eucommia ulmoides*, *Parrotia persica*, *Parthenocissus*, *Pterocarya fraxinifolia* and other species) or which survive in only very limited areas of southern Europe (*Zelkova abelicea* and *Z. sicula*). The precise moments of their disappearances are still unknown; however for many of them it is around the transition from the obliquity-forced climatic cycles to the eccentricity-forced one (Bertini 2000; Leroy 2007). To explain their disappearance the following hypotheses are proposed: their non-survival in their refugia during glacial or

interglacial times, rather than glaciations pushing and keeping plants in warmer latitudes, south of insurmountable west-east mountain barriers (see also Bennett et al., 1991; Leroy, 2007).

Cyclopalynostratigraphy

Vegetation successions can be used as a tool in stratigraphy for the often undated Plio-Pleistocene pollen diagrams. Counting the number of these cycles (one aspect of cyclopalynostratigraphy) provides a more accurate estimation of duration and increases the probability of fitting sequences correctly either in the magnetostratigraphy or in the marine oxygen isotopic stratigraphy (Leroy 2007).

The BO IV sequence at Bòbila-Ordis (lake 1) is the oldest of three nested lakes bounded by normal faults (fig. 1 and 7). Chronologically the next younger lake (lake 2) belongs to a glacial stage with an interstadial stage (known in outcrop in the Ordis quarry) and the most recent one (lake 3) to an interglacial period and part of a glacial period (known by drilling and outcrops in the Ordis quarry). Figure 7 presents selected palynological curves for the three lakes. Three periods of vegetation succession have been highlighted in grey on figure 7: two from the BO IV sequence and one from lake 3. The Bòbila-Ordis stratigraphic series covers altogether four different glacial and four different interglacial periods (but not necessarily contiguous ones), all belonging all to the Early Pleistocene (Leroy et al., 2001).

Cobb-Mountain subchron

A detailed palaeomagnetic investigation shows a reverse palaeomagnetism at the exception of a short zone of normal polarity at 1670-1405 cm (in pz8) (Løvlie and Leroy 1995) (fig. 2). Chronostratigraphic constraints based on the presence of rodent teeth belonging to the Late Calabrian, coinciding climatic events, and estimated sedimentation rates suggest that the event estimated to have a duration of 9 ka can be correlated to the Cobb-Mountain subchron (ca 10-12 ka-long). This

subchron is dated at 1.211-1.201 Ma or at 1.185-1.173 Ma according to, respectively, Cande and Kent (1995) or Horng et al. (2002). Owing to a significant lag in the acquisition of the magnetic signal in marine sediments, the interglacial of the first climatic cycle is correlated with the marine oxygen isotopic stage (MIS) 35 (Løvlie and Leroy 1995). The two climatic cycles, based on this age model, have hence been correlated to MIS 36-33. Comparing the amplitude of the interglacial stages of core ODP Site 677 (Shackleton et al. 1990), MIS 33 is indeed a poorly developed interglacial stage as is the second climatic cycle, reinforcing the age model.

Conclusions

Extensive palynological analyses have been performed on a sequence cored in the Early Pleistocene lacustrine series of Bòbila-Ordis (N-E Catalonia, Spain): the BO IV core. This sequence is likely to be the only high-resolution pollen record dating of the Cobb-Mountain subchron published so far. This reversal falls entirely in a pollen zone characteristic of the second half of an interglacial with vegetation typical of a cooler and humid climate.

The 22.7 bottom metres of the sequence are very homogenous and have most likely been affected by suspensates over underwater springs. This is then followed by a quasi-complete climatic cycle with vegetation succession. A second, but incomplete, climatic cycle has been observed. The two cycles are affected by bank collapse possibly linked to the activities of *H. amphibius*. Karst cannot however be ruled out. The two climatic cycles of the upper metres have been correlated to

MIS 36-33 owing to joint lines of dating, quite uncommon for an Early Pleistocene continental section. All together the Bòbila-Ordis lacustrine series (at least 3 lakes connected by normal faults) have provided us with long and sub-continuous sequences of lacustrine phases spanning at least four glacial periods and four interglacial periods.

These continental records deserve more attention as they provide us with the environments where Early Pleistocene fauna (s. l.) lived and evolved, such as hominids in Spain (Orce and Atapuerca Gran Dolina), France (Vallonnet and Pont-de-Lavaud) and Italy (Campo Grande di Ceprano) (Falguères 2003; Moullé et al., 2006).

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Figure captions

Fig. 1a: Location map of Banyoles in N-E Spain. Plotted with OMC:

www.aquarius.geomar.de/omc/omc_intro.html.

Fig. 1b: Simplified stratigraphic section of the Bòbila Ordis lacustrine series. The three nested lakes are indicated by Arabic numerals. J-S: section investigated in Julià and Suc (1980). The direction of faulting is indicated by arrows. Horizontally not to scale. Arabic numbers are lake numbers. Modified from Løvlie & Leroy (1995).

Fig. 2: Lithology, molluscs, ostracods, two cumulative pollen diagrams (with Pinaceae and without Pinaceae), concentration graph (in number of grains per g of dry sediment as dots or per ml of wet sediment as crosses, the value for the arrow is 320,000), zonation, dendrogram and interpretation of the BO IV sequence. Star = rodent teeth depths. Black rectangle = Cobb-Mountain magnetic reversal. Temp. water assembl. = temporary water assemblages including *Cypricercus*, *Cypris pubera*, *Eucypris* and *Potamocypris*.

Fig. 3: Ostracod assemblages of sediment core BO IV and the overlying limestone (data provided by M. Coen). Zonation from the pollen diagram. The data are presented in concentration values: number of valves per 30 g of dry sediment. The top sample has been taken in the limestone of the plateau. Temp. water assembl.= temperate water assemblage.

Fig. 4: Detailed pollen diagram of the BO IV sequence, Bòbila Ordis. Lower part (5210-2937 cm). Ten times exaggeration curve. Analyses: S. Leroy. A. = Asteraceae; Amar.-Chenop. = Amarantaceae-Chenopodiaceae; *aquil.* = *aquilinum*; ind.= indeterminated; *persic.* = *persicaria*; psil. = psilate; *rham.* = *rhamnoides*; *sel.* = *selaginella*; *vulg.* = *vulgare*;

Fig. 5a and b: Detailed pollen diagram of the BO IV sequence, Bòbila Ordis. Middle part (2937-1290 cm). More details in fig. 4. Analyses: S. Leroy.

Fig. 6: Detailed pollen diagram of the BO IV sequence, Bòbila Ordis. Top part (1290-638 cm). More details in fig. 4. Analyses: S. Leroy.

Fig. 7: Selected palynological curves for the three lakes of Bòbila Ordis. The sequence of taxa has been chosen to emphasise vegetation successions (grey strips). G: glacial period; IG: interglacial period; IS: interstadial period. Numbers next to them are Marine Isotopic Stages (MIS) numbers.