The Early to Middle Pleistocene boundary in the Baza Basin (Spain)

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Received 31 May 2006; received in revised form 2 May 2007; accepted 17 June 2007

Abstract

The continental vertebrate fauna of Cúllar Baza-1 (Granada, Spain) occur immediately above the Matuyama/Brunhes polarity boundary, and therefore represent an initial record for the Middle Pleistocene. All polarity zones for the Late Pliocene through Middle Pleistocene are found in an 80 m section, which includes this fossil quarry. The existing collection of abundant remains of micro-mammals, macro-mammals and lithic artifacts (indicating human activity) can now be assigned an earliest Middle Pleistocene age of 0.75 Ma. Another section, 25 km across the Neogene Baza Basin, also has the Matuyama/Brunhes polarity boundary. However, in this case the Huéscar-1 fossil quarry and the Puerto Lobo sites are both below the polarity boundary, thus representing a record of the late Early Pleistocene at ~0.9 Ma. Differences in micro-mammal species across these Matuyama/Brunhes boundaries are significant and justify an approximately coincident biostratigraphic boundary between the Biharian and Toringian stages.

1. Introduction

The intra-montane Guadix-Baza Basin is the largest of the late Neogene inland basins of the Betic Cordillera. As a consequence of the Alpine Orogeny, this Basin was isolated from the sea during the late Miocene (Sanz de Galdeano and Vera, 1992). The Basin had an internal drainage of approximately 4000 km² and could be divided into two sub-basins. Generally, the Guadix Basin to the southwest was filled with alluvial deposits, while lacustrine deposits, along with fluvial/alluvial marginal deposits (Fig. 1), dominated the Baza Basin to the northeast.

Six hundred meters of late Neogene continental sediment infilling is exposed in the marginal northeastern part of the Baza Basin (Gibert L, 2006). Gravity and seismic studies indicate >2500 m of lacustrine sediments buried near the town of Baza (Alfaro et al., in press). The paleo-environments within the Baza Basin included a shallow saline lake complex, surrounded by saline mudflats, freshwater ponds, small rivers with floodplains and deltas (Gibert L. et al., 2005, 2007). The grass-covered upland slopes merged into alluvial fans from the surrounding mountains. The Baza Basin continued accumulating sediment until tectonic movements and stream piracy initiated rapid and prolonged erosion (Calvache and Víseras, 1997), stripping the softer, upper strata and leaving behind the more resistant layers that make up the present-day topography.

The Baza Basin has produced >40 fossil vertebrate sites of Late Miocene, Pliocene and Pleistocene age, along with some lithic artifact sites of Pleistocene age showing the activity of early man (Ruiz-Bustos, 1976, 1984; Gibert J. et al., 1998, 2006). Magnetostratigraphic studies from the northeastern part of the Basin (Gibert L. et al., 2006; Scott et al., 2007) have generated a polarity sequence for the Orce-Venta Micena sections (three magnetozones, reverse-normal-reverse) revealing the Pliocene/Pleistocene boundary and calibration of the MN17 (mammal Neogene zone) upper boundary. The youngest deposits in these sections are of Early Pleistocene age (pre-Jaramillo chron or >1.1 Ma), bounded by an upper erosion surface at 965 m asl. Other areas in the Basin have supplied fossils that indicate younger fauna than in the Orce-Venta Micena area; these are Puerto Lobo-Huéscar and Cúllar, the focus of this report. Both of these younger areas have
well-exposed sedimentary sections, interbedded with fossiliferous sites and thus are well suited for detailed magnetostratigraphic research. This study furthers our general goal of developing a wider and more complete chronologic and biostratigraphic framework for the Baza Basin. All geologic observations in this report are the product of the authors, unless specifically referred.

2. The Cúllar section

In 1975, Cúllar Baza-1 (CB-1) was the initial paleontological excavation in the Baza Basin, which now includes numerous archeological/paleontological quarries, mostly concentrated in the Orce area, 20 km to the NE (e.g. Venta Micena, Fuente Nueva-3). An early Middle Pleistocene age was assigned to CB-1 using faunal criteria (Ruiz-Bustos and Michaux, 1976; Ruiz-Bustos, 1984).

A preliminary magnetostratigraphic and paleontologic study was made ~2 km NW from the CB-1 quarry (UTM 30537120E, 4159537N, Z = 890–905; Fig. 2) (Agustí et al., 1999). Situated ~50 m stratigraphically below the CB-1 level, that study consisted of a 14 m section with 10 paleomagnetic and three paleontologic levels. The Cúllar section in this current report is meant to supersede and expand these preliminary observations. We will emphasize the following advantages: (A) an additional 70 m of overlying strata were sampled; (B) the paleontological quarry CB-1 was included within the new section; (C) most of the samples from the new collection have high-quality remanent polarities (mostly reddish-brown silts and paleosols); and (D) field tests were conducted to indicate the stability and antiquity of remanence. By incorporating the results from the preliminary section (Agustí et al., 1999) into this expanded section, the following features were revealed: (1) the paleontological site CU-A will not be considered further, since it has only a sparse collection of post-cranial bones, as none were originally reported (Agustí et al., 1999); (2) the upper 4 m of that preliminary section are not part of the Baza Formation, but are unconsolidated or poorly consolidated claystones, sandstones and conglomerates composed of intra-basin clasts and discontinuous calcrete beds that belong to the much younger post-erosional, valley in-fill deposits; and (3) the paleontological site CU-C, within these post-Baza deposits, is Late Pleistocene or latest Middle Pleistocene, as are the uppermost three normal polarity samples in the preliminary report. Our observations indicate that these young post-Baza Formation deposits are extensively preserved along the flanks of the present Cúllar River Valley and are significantly younger than the erosive opening of the Basin (Fig. 3).

In the present study, a magnetostratigraphic section was developed 2 km SE of the town of Cúllar. This section starts near the Cúllar River (UTM coordinates:}

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**Fig. 1.** Location maps. The Baza Basin (SE Iberian peninsula) showing the stratigraphic sections and paleontological sites. 1—Cúllar section and quarry CB-1; 2—Puerto Lobo sections and sites; 3—Loma Quemada sites; 4—Huéscar-3 site; 5—Sabinar section; 6—Orce sections and quarries FN-1, VM, BL-5, and FN-3; 7—Oria road section.
Fig. 2. Aerial photos. The Cúllar (top) and Puerto Lobo (bottom) areas, showing the primary and ancillary magnetostratigraphic sections as dashed lines.
The Puerto Lobo section was located in the northern margin of the Baza Basin, 3 km SE of the town of Huéscar and 25 km north from the Cúllar section (Fig. 1). This area is adjacent to a far-ranging normal fault (Soria et al., 1987) with a minimum estimated displacement of 30 m (direction 049/70N). In a previous study of a subaqueous landslide of Early Pleistocene age, a few reverse polarity samples were collected from the upthrown side of this fault (Gibert L. et al., 2005). On the downthrown side of the fault are the stratigraphically higher fossil sites of Puerto Lobo and Huéscar-1, along with the new magnetostratigraphic sections (Fig. 2).

The Puerto Lobo section (UTM coordinates 30543408E, 41582540N, Z = 935–965; Fig. 2) starts in strata from the distal fluvial facies (mudflats, overbank deposits) rich in...
metamorphic grains of southern provenance. North-directed paleocurrents dominate in this northeastern margin of the Basin, where small local ponds had developed. These deposits belong to the same lithostratigraphic unit as those in the highest topographic position across the fault, in the upthrown block. The Puerto Lobo (PL) paleontological site (Agustí, 1984) is located in the topographically lower (older) part of the down-faulted block. Higher in the section there are palustrine deposits, capped by a continuous alluvial unit composed of cross-bedded gravels and siltstones with paleocurrents towards the SW. This uppermost unit shows a distinct change in clast composition and provenance (Mesozoic carbonate from the north and east) compared to the lower part of the section (metamorphic grains from the southern mountains).

The site of Huéscar-1 (HU-1) (UTM 30543727E, 4183228N, Z = 948) is located in the next valley (Barranco de Las Cañadas), <1 km NE of PL (Fig. 2). There are two other paleontological sites in these younger deposits of the down-faulted block: Loma Quemadada-1 and -2 (LQ-1, LQ-2), 2 km W (30541848E, 4181276N, Z = 900) (Soria et al., 1987). LQ-1 and LQ-2 have a micromammal fauna similar to that from PL (Agustí, 1984). The site of Huéscar-3 (HU-3) (30543408E, 4182540N, Z = 1000) is located close to the PL section, but is on the other side of the fault in the upthrown block. The HU-3 fauna are Pliocene in age (Sesé, 1989), thus much older than those from sites on the down-dropped side.

The Puerto Lobo and Barranco de Las Cañadas areas expose a variety of lithologies and show lateral changes in local facies. Wherever possible, we collected the reddish-brown siltstones for these preliminary magnetostratigraphic sections. Good exposures allow for the integration of biostratigraphic and paleomagnetic data into a lithostratigraphic frame. These results offer an opportunity to examine of biostratigraphic diversity (Alberdi et al., 2001), as well as a more complete biostratigraphy.

4. Methods

Recent work in the Baza Basin provided a detailed lithostratigraphic frame for the NE sector, around Ocre-Venta Micena, along with the magnetostratigraphic location of the Pliocene–Pleistocene boundary (Scott et al., 2007). This present study is an expansion both northwards to Huéscar and southwards to Cúllar. Numerous stratigraphic sections have been measured in and between these three areas, permitting some insight into the complexity of deposition facies and the paleo-topographic relationships across this part of the Baza Basin. These different paleo-geographical situations show lateral lithologic changes, ranging from the coarse-grained facies typical of paleo-margins to the fine-grained sulfate-dominated facies around the central paleo-lake. Although a detailed lithostratigraphic correlation between these three marginal sites remains elusive, the addition of magnetozones greatly improves the temporal correspondence.

4.1. Sampling methodology

We chose the most propitious sections in the two areas to study. These sections have three characteristics: (1) abundant reddish-brown, fine-grained lithologies for paleomagnetic sampling; (2) ease of correlation to other nearby sections; and (3) close to or including paleontological sites to calibrate the polarity sequence. In 2003, we collected preliminary samples (n = 11) from both sections (Cúllar and Puerto Lobo). This provided an outline of the polarity zonation and an indication of the magnetic behavior of the different lithologic types. Additional samples were collected in 2004 (n = 16), expanding the sections. In 2005, we made more detailed collections (n = 41) extending the sections and refining the position of each magnetozone boundary.

In the Cúllar section, we tested the continuity of the uppermost magnetozone boundary (R to N) by collecting samples in stratigraphically equivalent beds along the Oria road (n = 5) (UTM 30559593E, 4158301N, Z = 970) (Fig. 2). We also collected samples (n = 4) from a boulder-sized tilted block, broken from the wall of a paleo-channel (Fig. 5). The orientation of the remanent magnetic vector in strata within this rotated block would be a specific test for the antiquity of remanence. This field test would indicate which magnetic components were produced at an early diagenetic stage and which components were produced after the bank collapsed into the paleo-channel. At Puerto Lobo the upper part of the section showed weakly held remanence and ambiguous polarities, so we resampled (n = 6) equivalent strata in reddish-brown lithologies (taking advantage of a local facies change) at Barranco de Las Cañadas (just above the site HU-1) (Fig. 2).

4.2. Paleomagnetism

We collected block samples (Cúllar n = 55, Puerto Lobo n = 13) directly through the sections, in shallow excavations made by hand, and in road cuts. From each oriented block, at least three specimen cubes (10–15 cm³) were cut and sanded (without water), then cleaned with compressed air. Measurements were made at the Berkeley Geochronology Center with a three-axis cryogenic magnetometer (noise level 1 × 10⁻¹² Am²) enclosed within a room-sized magnetostatic shield (average field 350 nT). Alternating field (AF) demagnetization (static three-axis, to at least 12 mT) was followed by thermal demagnetization (in at least eight steps) starting at 90 °C (non-inductive furnace, residual field <2 nT). Polarity results exclude two unstable samples at Cúllar and three at Puerto Lobo. In general, the quality of the remanence recorded was excellent for the
common light reddish-brown siltstones/claystones (93% of samples) or was poor for the light gray mudstones, sandstones and carbonates (7% of samples). All specimens have a two-component magnetization (Fig. 4) made up of a low-coercivity/low-temperature component (toward the modern field direction) and a higher temperature component (in the normal or reverse direction). Variable ratios between the modern and ancient remanence components are the cause for the variations in demagnetization response (Fig. 4). The modern field component was effectively reduced by AF treatment followed by heating to 200°C (000°/53°, α95 = 2.8°, n = 45; goethite only: 000°/53°, α95 = 2.3°, n = 44).

A few samples displayed a more complex magnetization, with higher temperature components showing both normal and reverse polarity. These samples were adjacent to magnetozone boundaries, apparently reflecting an integration of ambient magnetic fields and events. This was most
noticeable in a sample (+28 m) within the middle normal zone. As a test this block was cut into 17 specimens (as small as 2 cm³), producing five normal (012/54, ±95° = 8.9°), five reverse (206/−56, ±95° = 21.3°) and seven intermediate results. These detailed specimens spanned only 7 cm vertically; however, the polarities were irregularly distributed in three dimensions. Since this sample was of typical lithology (siltstone with immature paleosol textures), we assume that the ambient field changed polarity during the pedogenic alteration process affecting this bed.

Sample directions were calculated both from furthest position along great circle trends (shown) and from least-squared line-fit of vector endpoints. The line-fit results were similar to the great circle trends (75% have <10° difference), although slightly less consistent and usually (68%) closer to the modern field. The stratigraphic sequences of paleomagnetic directions are displayed as the angular difference (Δ) between a specimen direction (S) and the expected normal direction (N) (Hoffman, 1984). This plot directly reflects the multiple component nature of these vector data. Calculations of VGP latitudes would yield the same polarity zonation, but are not shown as an explicit caution against interpreting minor directional variations as geomagnetic phenomenon.

4.3. Paleontology

4.3.1. Introduction

In the absence of radiometric dates, rodent biochronology is helpful for temporal calibration of a polarity sequence. Below, we briefly review the history of rodent biostratigraphy in the Cúllar and Puerto Lobo regions and comment on taxonomic issues. In later sections we discuss the specimens in detail and then interpret their biostratigraphic significance.

For a variety of reasons, some biological and some probably related to collecting bias, most of the Guadix-Baza micromammal samples are dominated by arvicolid rodents. Fortunately, the diversity of arvicolid species in the Basin, combined with their rapid speciation throughout the holarctic region during the late Neogene, makes their remains useful for correlation purposes. Nevertheless, there is considerable disagreement on fossil arvicolid taxonomy among European investigators. It is beyond this treatment to summarize all the pertinent literature. A more comprehensive review will be published elsewhere. At this point, we choose to treat most European ‘‘Microtus-like’’ species as members of the genus Microtus, with a common Mimomys ancestor. Thus Allophaiomys, Stenocranius, Iberomys, Terricola, etc. are considered subgenera of Microtus. Also, following van der Meulen (1978), we do not recognize the subgenus Pitymys in Europe. This name is reserved for the North American M. (Pitymys) pinetorum and its relatives, although its ancestor, M. cumberlandensis, apparently immigrated back into North America from Asia during the Middle Pleistocene (van der Meulen, 1978). Fossil relatives may eventually crop up in the Old World. For many years Arvicola has been considered to represent a genus separate from Microtus, evolved from the extinct Mimomys savini. However, a new paradigm of Arvicola evolution has been proposed (Ruiz-Bustos, 1999) suggesting that Arvicola and Microtus share a common Mimomys ancestor, with M. savini as a separate sterile Mimomys lineage. In either case, the progression of evolution in the first lower molar (ml) of European Arvicola has been extensively documented (e.g., Heinrich, 1990; Ruiz-Bustos,
1999; Maul et al., 2000), and the morphology of Arvicola molars can be valuable for correlation purposes. For instance, Spanish populations of fossil Arvicola with relatively small molars and negative enamel differentiation can be assumed to be older than ones of larger size and negative differentiation or with positive differentiation (Ruiz-Bustos, 1999). Likewise, rootless Microtus m1s demonstrate many features that have both taxonomic and evolutionary meaning, including complexity of pattern (number and form of triangles) and enamel differentiation. However, there are a number of named species in western Europe with overlapping m1 morphologies, and with sparse fossil material it is often difficult or impossible to make a satisfactory species identification. For example, there are at least five “Allophaiomys-type” species with m1 morphology that are somewhat advanced over “typical” Microtus (Allophaiomys) pliaenaicus from the type locality of Bettia, Romania (Kormos, 1930; Hir, 1998) including M. ruffoi (Pasa, 1947), M. burgondiae (Chaline, 1972), M. nutiensis (Chaline, 1972), M. chalinei (Alcalde et al., 1981), M. vandermeuleni (Agustí, 1991), and M. lavocati (Laplana and Cuenca-Bescos, 2000). We agree with Ruiz-Bustos (1999) that M. chalinei, originally described from Cueva Victoria in south-eastern Spain (and also identified from Atapuerca in north-western Spain; Cuenca-Bescos et al., 2001), is an Arvicola, though its dental complexity excludes it from ancestry of modern A. terrestris or A. sapidus. Microtus vandermeuleni was recently allocated to the genus Tibericola (Úñay et al., 2001; Agustí and Madurell, 2005).

Ruiz-Bustos and Michaux (1976) first reported arvicolid rodents from the Cúllar Baza-1 (CB-1) locality. Agustí (1986) proposed a rodent biochronology for the early and middle Pleistocene, including new material from the localities near Cúllar (CU-A, B, C) assigned to the Upper Biharian. Localities near Huéscar (HU-2, LQ-1 and PL) were assigned to the Middle Biharian European land mammal age (ELMA), older than the Cúllar Baza and Cúllar localities. Sesé (1989) reviewed much of the rodent material from the Guadix-Baza Basin, and reported specimens from HU-1. The age suggested for HU-1 was “middle Pleistocene”, while PL and LQ were “lower Pleistocene”, and CB-1 was Biharian. An attempt to correlate paleontological localities in the Cúllar area with the geomagnetic polarity time scale (Agustí et al., 1999) placed CB-1 in the Toringian ELMA with CU-A, B and C beneath, in the Biharian. A normal polarity zone at the level of CU-C was assumed to be from the earliest Brunhes (based on geologic observations described in this current report, site CU-C is out of stratigraphic context and is now assigned to the late Brunhes). CU-A and -B, in sediments of reversed polarity, were placed just below the Brunhes in chron C1r.1r (this current report changes the assignment to an older chron: C1r.2r). These latter localities were allocated to the Biharian. An arvicolid rodent biochronology for the Guadix-Baza area was proposed (Agustí et al., 1999), with Arvicola caninaus representing the Toringian (following Fejfar et al., 1998) and three superposed Biharian zones, from youngest to oldest Terricola arvalidens, Allophaiomys burgondiae and Allophaiomys plioenaicus. They confirmed the earlier placement of CB-1 in the Toringian, but did not refer to localities in the Huéscar area. A new biostratigraphic scheme was proposed for the Orce region in a recent comment paper by Agustí et al. (2007), but the utilization of paleontological sites located in landslide zones (O-2, O-3; Gibert L. et al., 2006, 2007) and post-erosional deposits (Cu-C) to build this biostratigraphy makes it of questionable value.

4.3.2. Methods

We reviewed the existing collection of rodents from the Cúllar and Huéscar areas housed at the Paleontological Institute of Sabadell, along with some specimens provided by Ruiz-Bustos. Two sets of sites bear on calibration of the polarity sequence in the Cúllar area: Cúllar Baza-1, CU-A, -B, -C. CB-1 produced numerous macro- and microfauna remains (Ruiz-Bustos, 1976) while Agustí (1984) and Agustí et al. (1999) described a few rodents from these Cúllar sites. Four paleontological sites are known from the Huéscar area: HU-1, HU-3, Puerto Lobo and Loma Quemada (Agustí, 1984; Sesé, 1989). HU-1 has produced a large collection of macrofauna with some species of microvertebrates (Sesé, 1989). Puerto Lobo and Loma Quemada have produced only microvertebrates (Sesé, 1989; Agustí and Madurell, 2005). HU-3 is located 300 m SE from HU-1 and is topographically 50 m higher but has produced a Late Pliocene (Ruscinian) macro- and microfauna (Sesé, 1989). This is explained by the presence of a normal fault between these sites (Soria et al., 1987). The specimens from HU-1 and -3 are not located in the Institute of Paleontology in Sabadell. For these sites we will rely entirely on the published faunal account (Sesé, 1989). Other records in the database include both references from the literature and our independent assessment of material examined in the Institute of Paleontology in Sabadell.

5. Results

5.1. New paleomagnetic data

Two new polarity sequences are now available in the Baza Basin: Cúllar (81 m) in the southwest and Puerto Lobo (31 m) in the northeast. The extensively sampled Cúllar section has six major magnetozones: a 1.5 m reverse zone in the lowest strata, followed by a 7.5 m normal zone, then a 24 m reverse zone, a short normal zone of 2.5 m, another long reverse zone (25.5 m), and at the top, a 19 m normal magnetozone (Figs. 6 and 7). Near the base of the uppermost normal zone is the paleontological/archaeological site CB-1 with abundant mammalian remains and lithic tools indicating human activity (Fig. 8). Near the base of the lower long reverse polarity zone would be
the projected stratigraphic level of site CU-B (using the correlation of Agustí et al., 1999). A very short normal zone (<10 cm) was found 3 m above the lowest normal zone. This cryptozone was inadvertently discovered in the tilted block used for the conglomerate/tilt stability test. A short (< 50 cm) magnetozone, this time with reverse polarity, was found within the 2.5 m middle normal magnetozone.
Fig. 7. Cúllar section correlated with GPTS. Geomagnetic polarity time scale (after Gradstein et al., 2004) is shown with correspondence to Cúllar polarity zones, Δ (calculated from Dec. and Inc.) and lithostratigraphy. Cos (Δ) = sin (Inc N)*sin (Inc S) + cos (Inc N)*cos (Inc S)*cos (Dec N-Dec S) (N = 000°, 57°; S = specimen direction).
The more sparsely sampled Puerto Lobo sections have two magnetozones: a 18 m reverse zone, followed by a 13 m normal polarity magnetozone (Fig. 9). This lower reverse zone includes the sites of PL, LQ-1, LQ-2 and HU-1, with their large collection of micro- and macro-fauna. No fossiliferous sites have been described from the upper normal zone; however, we identified lithic artefacts in the conglomeratic gravel bed that caps this section.

5.2. Magnetochronology

Both studied sections present an almost continuous sedimentary sequence typical of the marginal facies of an underfilled basin. No evidence of extensive sedimentary hiatuses have been identified, with missing time restricted to levels with immature paleosols and local erosional surfaces. Some features common to these Baza sections argue for relatively complete sequences (after McMillan et al., 2002): high sedimentation rates (~10 cm/kyr) and the large number of strata. This kind of sedimentary record facilitates the correlation of the identified polarity zones with the GPTS (Geomagnetic Polarity Time Scale, after Gradstein et al., 2004). Using the paleontological data as a general age guide, as well as other tested polarity sequences in the Basin (summarized by Scott et al., 2007), these new polarity zones can be correlated to the Pliocene-Pleistocene part of the GPTS.

For the Cúllar section we correlate the lowest normal zone to the Olduvai magnetochron (C2n), and the underlying reverse zone to the end of the early Matuyama (C2r.1r). The normal polarity zone in the middle of the section would then correlate to the Jaramillo subchron (C1r.1n). The upper (19 m) normal zone, starting just below site CB-1, would correlate to the Brunhes magnetochron (C1n). A very thin normal zone (<10 cm, tilt tested) identified 3 m above the lowest normal zone could be the Gilsa subchron (C1r.2r.5n, after Channell et al., 2002). The other short zone, a reverse within the middle normal zone is interpreted as C1r.1n.1r (see Guo et al., 2002). Other possible correlations have significant flaws. If the long upper normal zone corresponds to the Jaramillo subchron, then the fauna of CB-1 would be 1.0–1.1 Ma, which is probably too old. If the lowest normal zone corresponds to the Jaramillo subchron (therefore, the middle normal to the Santa Rosa (C1r.1n.1r) (Singer and Brown, 2002) or the Kamikatsuura subchron (Coe et al., 2004), then sediment accumulation would have begun late in this area, and then proceed very rapidly (>25 cm/kyr). This would require the paleo-Cúllar Valley/Fan to change from a paleo-topographic high to a paleo-topographic low.

Fig. 8. Lithic artifacts. Flint lithic tools from CB-1 quarry (1987 collection, after Vega Toscano, 1989).
Fig. 9. Magnetostratigraphic data, GPTS correlation- Puerto Lobo sections. Magnetic information, lithostratigraphy and correlation to GPTS for the Puerto Lobo sections have the same conventions as in Figs. 6 and 7.
This younger model is unsupported by the observed stable mid-fan deposition environment draining westward into the nearby paleo-Lake Baza with its distinct, but stable subenvironments (Gibert et al., 2007).

For the less densely sampled Puerto Lobo sections, we correlate the upper (13 m) normal magnetozone to the Brunhes chron (C1n). This is guided by the youthfulness of the faunal assemblage from sites HU-1 and PL. We discount the other possibility of correlating the normal magnetozone to the Jaramillo subchron, as this would make these faunas 1.2–1.3 Ma. This is probably too old, as the HU-1 and PL micromammals appear distinctly younger than those from the Orce-Venta Micena area (Fuente- nueva-3, Barranco León-5) which are of this older age (Scott et al., 2007).

These new results disagree with some previously published chronologies for the sites CB-1 or Hu-1, dated using biochronological methods (Hernández Fernández et al., 2007) and for those dated using the amino-acid racemization techniques (Torres et al., 1997; Ortiz et al., 2000, 2004).

5.3. Tests for antiquity of remanence

5.3.1. “Tilt block” test

Different components of magnetization can be acquired during different events in a sample’s history. A continuing challenge in magnetostratigraphic research is to determine which, if any, of the remanent components were acquired at the time of deposition, or at least early in the process of lithification-diagenesis. To examine the antiquity of remanence, the fold and conglomerate tests were developed by Graham (1949). These tests take advantage of unusual geologic situations where changes have occurred in the orientation and/or position of newly deposited strata. Some examples are: rip-up clasts, intra-formational conglomerates, bioturbation and slumps. These events physically rotate the young rock, along with any remanent direction that was already stably magnetized. If the rock had not acquired a stable remanence before rotation, it would now have that opportunity, but in a new orientation. These types of tests allow a comparison of the remanent directions (both measured and expected) at the time of deposition and after the time of change. The shorter the duration between deposition and rotation, the more stringent the temporal constraints will be for the acquisition of remanent components.

In the Cúllar section, we found a situation where a migrating paleo-channel cut into a newly deposited overbank deposit, causing blocks to cave off the paleo-channel wall. These fallen blocks were then rotated and incorporated into the conglomeratic channel deposit. A boulder-sized tilted block (60 × 40 cm) was found within the paleo-channel, and used for a conglomerate or “tilted block” test. The block (Fig. 5) has a rectangular shape and is composed of reddish-brown sandstone and siltstone (bedding: strike 285°, dip 60°N). The block’s original stratigraphic position can be recognized in the parent sediment located in the adjacent walls of the paleo-channel. Four samples (six specimens) were collected from this block, spanning 30 cm of tilted strata.

Tilted samples show stable magnetic components at about 90° from the expected paleo-field directions (000°/+57° or 180°/−57°). These components are also distinct from those in samples collected from in-situ strata back from the channel walls. However, after correcting for the bedding within the block, the sample directions have reverse inclinations (−70°, in block coordinates) for three levels and an approximately antipodal normal inclination (+60°) for the other level (Fig. 11). Using these limited data, we can identify some additional features, since non-antipodal paleomagnetic directions can be sensitive indicators to the presence of secondary magnetization (Scott and Hotes, 1996). Fig. 11 shows that the great circle through these tilted bi-polar data includes the modern field direction (within 7°). This was unexpected, since reverse polarity was the ambient field direction both before and for a long time after the channel-forming event. This means that among the secondary components, the reverse post-depositional magnetizations (either pre- or post-tilting) were not as important as the younger (modern) normal component. Apparently, the processes of near-surface alteration (weathering in the modern normal field) dominate the secondary magnetization in these tilted samples. A similarly directed, modern secondary component is common in the data from most in-situ samples through out the Cúllar section. The magnitude of this secondary component can be calculated at ~20% (relative to the pre-tilting remanence intensity at 200°) using the methodology in Scott and Hotes (1996). These techniques also calculate an original average inclination of 65° for these tilted samples (Fig. 11). Considering the limited number of samples in this test, this successfully approximates the expected mean inclination of 57°.

The observations from this ‘tilted block’ field-test produce four conclusions: (1) Much of the natural remanent magnetization (NRM) was acquired at an early stage of diageneric and lithification. (2) No significant ambient (reverse field) component of remanence was acquired after the block broke loose and was incorporated in the paleo-channel deposit. (3) A pre-tilting normal zone (<10 cm thick) of short duration was found. The presence of this very thin subzone within the tilted block is another indication of rapid and early NRM acquisition. (4) Laboratory demagnetization techniques (AF followed by thermal) can greatly reduce the secondary magnetizations in samples, but can still leave a 20% residual component directed toward the modern (normal) field.

5.3.2. Stratigraphic continuity tests

Changes in paleomagnetic polarity should be independent of lithologic changes, and should be reproducible and continuous between outcrops. To check the continuity of
Fig. 10. Detailed maps and cross-section profiles. Digital relief maps show the location of fossil sites and cross-sections. Topographic profiles have geologic cross-sections, with polarity, paleo-current directions, and paleo-environments indicated. The Cu´llar profile (A-B-C) shows the 6 polarity zones through 81 m of section. The superseded results of Agustı´ et al. (1999) are 2 km W and 50 m below the CB-1 quarry. Their normal samples are in post-Baza Formation deposits from the current episode of erosion. The Puerto Lobo-Barranco de las Cañadas section (A-B) shows an upper zone of ambiguous polarity in PL (diagonal lines), which upon re-sampling 600 m to the north in B. Cañadas, was found to be a normal magnetozone.
the upper magnetozone boundary in the Cúllar section, we collected five additional samples along the Oria road, 1 km east of the primary Cúllar section. Samples were from stratigraphically equivalent beds; however, fewer palustrine strata were present owing to a facies change (moving up the paleo-slope from the ancient Lake Baza). The change from reverse to normal magnetozone was found in light brown and reddish-brown siltstones on both sides of the boundary (Figs. 6 and 12). A less specific test for continuity of magnetozones across facies involves the correspondence between part of the Cúllar section’s middle (24 m) reverse zone (reddish-brown siltstones) and the (10 m) reverse zone fragment (Agustí et al., 1999) 2 km north-west, in more distal, gray mudstones and yellow sandstones. In our initial Puerto Lobo section, samples (gray sandstones) above the continuous reverse magnetozone had scattered directions (ambiguous polarity). Thus, we collected six samples from equivalent upper stratigraphic levels, 1 km north-east in Barranco de Las Cañadas (above the site HU-1). These additional samples were from reddish-brown siltstones, and indicate a long (13 m) normal polarity magnetozone (Figs. 9, 10), including the uppermost exposures intercalated with cross-bedded conglomerate.

5.4. Biostratigraphy

Strata from the Cúllar area were used in an initial attempt to calibrate the Early to Middle Pleistocene boundary by Agustí et al. (1999). Our stratigraphic observations and paleomagnetic results differ significantly from theirs, and therefore influence the biostratigraphic evaluations. Paleontologic and biostratigraphic modifications are noted below. We found one m1 referred to Terricola arvalidens from CU-C and another m1 of Castillomys crusafonti from CU-B in the collections of the Paleontology Institute in Sabadell. Both were figured by Agustí et al. (1999). However, we did not find any specimens of Stenocranius gregaloides from the CU-C site as reported by Agustí et al. (2007). As indicated by the crenulated anteroconid in the drawing (Agustí et al., 1999; Fig. 3.1), the “Terricola” m1 from Cu-C is from a juvenile individual. The area of the crenulations was broken off when we recently viewed it, but the specimen is otherwise intact. No identifiable molars were found in the collections from CU-A and none were reported (Agustí et al., 1999). Castillomys crusafonti was reported from four stratigraphic horizons, spanning 70 m (Agustí, 1986; Agustí et al., 1987; Garcés et al., 1997) in the Galera Highway section (15 km

Fig. 11. Antiquity of remanence field test. Paleomagnetic results from the tilt-block shown in Fig. 5 (4 sampled levels, 6 specimens total). Directions in the present or in-situ coordinate frame are shown on the left, showing the bedding plane within the block (strike 285°, dip 60°N). The nearly antipodal directions are grouped at 038°, −32° (5 specimens, 3 stratigraphic levels), and at 226°, +54° (1 specimen, 1 stratigraphic level). Directions in the ancient bed coordinate frame are on the right, showing the bedding plane within the block as horizontal (although N is not paleo-north). The concentric circle at 57° inclination (+ or −), represents expected values. Note that the reverse polarity group (118°, −70°, α95 = 8.6°, k = 100.3) and the normal sample (341°, 57°) are not exactly antipodal. Also, the great-circle connecting these bi-polar data passes close to the modern field direction (diamond), which is the common secondary direction in other Cúllar results). Non-antipodal paleomagnetic directions provide the following parameters: $x = 63°$, $β = 11°$, $γ = 23°$, $s = 0.22$ (using methods in Scott and Hotes, 1996). These calculations indicate 22% of the demagnetized remanence is still held by a secondary component in the direction of the modern field.
Fig. 12. Correlation panel for Cúllar, Orce and Huéscar sectors. Lithostratigraphic and magnetostratigraphic correlations between 3 areas with paleontological sites: CB-1 (Cúllar Baza-1), FN-1 (Fuentenueva-1), VM (Venta Micena), BL-5 (Barranco León-5), FN-3 (Fuentenueva-3), PL (Puerto Lobo) and HU-1 (Huéscar-1). The correlation Cúllar to Orce is based on the C2n (Olduvai) polarity zone. The correlation Orce to Huéscar is based on linking a sequence of 9 lithostratigraphic sections (Gilbert L, 2006). The offset on the Puerto Lobo fault (minimum shown) is based on matching clast provenance. The correlation Puerto Lobo to Barranco de las Cañadas is based on physically following key beds.
northeast of Cúllar). This long-lived species is of little value for zonal calibration purposes at this stratigraphic level.

As noted above, we found a stratigraphic disconnect between localities CU-B and CU-C with a 70 m hiatus between. The site CU-C and the deposits that produced the purported *Terricola arvalidens* molar occur in post-erosional basin sediments (not in the Baza Formation); therefore, the CU-C fossils must be considerably younger than those from CB-1. This produces a correlational problem, as *M. arvalidens* fossils from elsewhere in Europe occur earlier than *Arvicola cantianus* and *Microtus brecciensis*, the species from CB-1 (Table 1). The anatomy of the broken arvicolid m1 from CU-C is similar to some m1 morphotypes from *Microtus (Terricola) arvalidens*, but it can also be duplicated in modern pine vole species, including the extant *M. duodecemcostatus* from Spain (Brunet-Lecomte, 1988). Closure of buccal reentrant angle (BRA) 3 and lingual reentrant angle (LRA) 4, modest penetration of BRA 4 and LRA 5 forming incipient but distinct T6-7 in the anteroconid, plus the distinct positive enamel differentiation, identify the molar piece as from an advanced species of *Microtus*. The overall pattern, with T4-5 confluent certainly suggests the subgenus *Terricola*.

Brunet-Lecomte (1988; Fig. 16) also showed that a relatively simple morphology of m1, as demonstrated by the CU-C specimen, can change with age (wear) into a more complex molar in modern pine voles. We interpret the arvicolid specimen from CU-C as a Late Pleistocene or sub-Recent specimen of *M. duodecemcostatus* or another related, morphologically advanced species. Therefore, the “Terricola arvalidens” zone of Agusti et al. (1999) is not confirmed in the Cúllar sections. We do not know what arvicolids existed directly below the Brunhes-Matuyama boundary at Cúllar, although we can speculate based on the rodents from Puerto Lobo and Huéscar-1.

The arvicolid species from Puerto Lobo and Huéscar-1 (Sesé, 1989), including *Mimomys savini* (both localities) and *Microtus huéstrensis* (HU-1), are consistent with a late Biharian date, in agreement with Fejfar et al. (1998) and Agustí et al. (1999). Both species were reported by Cuenca-Bescos et al. (1999) from Trinchera Dolina at Atapuerca, in sediments of reversed polarity directly beneath the Brunhes-Matuyama boundary. To date, *Arvicola cantianus* (= *A. mosbachensis* of Maul et al., 2000) has not been recorded from the Matuyama chron. In fact, this species does not seem to appear anywhere in Europe until about

Table 1
Faunal list

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Compilation made for selected micro-mammals (rodents) and large mammals from Pleistocene palaeontological sites in the Baza Basin and in northern Spain (Atapuerca). Data compiled from Mazo et al. (1985), Alberdi et al. (1989), García and Arsuaga (1999), van der Made (1999), Gibert J et al. (2001, 2002), van der Made and Mazo (2001), and Scott et al. (2007).
Although an archaeological and mammal assemblage with *Arvicola cantianus* was initially reported from sediments older than 0.73 Ma at Iserna la Pineta (Coltorti et al., 1982), new dates place this association at about 0.61 Ma (Coltorti et al., 2005).

The paleontological sites located in the area of study can be sequenced from older to younger (Figs. 12 and 13; Tables 1 and 2) as follows: [Early Pleistocene] Cúllar Baza-A and B (CU-A, CU-B); [late Early Pleistocene] Puerto Lobo (PL), Loma Quemada (LQ) and Huéscar-1 (HU-1); [earliest Middle Pleistocene] Cúllar Baza-1 (CB-1); and the much younger [Late Pleistocene?] Cúllar Baza-C (CB-C). These sites (except for CU-A, -B) are located in a higher stratigraphic level than the Lower Pleistocene paleontological/archeological quarries of the Orce-Venta Micena sector (VM = Venta Micena, BL-5 = Barranco Leon-5 and FN-3) (Table 1). The sites PL, LQ, and HU-1 are placed between the Jaramillo and Brunhes polarity zones, indicating a range in age of less than 200 kyr.

Agusti and Madurell (2005) identified "*Allophaiomys* ruffoi from VM and "*Allophaiomys* lavocati from FN-3, PL and LQ. Specimens from VM we have viewed and the m1s illustrated from FN-3 by Agusti and Madurell (2005) can be duplicated in the type material of "*Allophaiomys* plocaenicus from Betfia II, Romania, illustrated by Hir (1998; Fig. 11). The PL and LQ specimens we have examined are advanced over the simpler m1 morphotypes reproduced by Hir (1998), and they do not display the combination of distinctive narrowing of T4-5, tendency towards closure of the dentine isthmus between T4-5 and the anteroconid, and the reduced but elongated anteroconid shape that characterizes *M. lavocati*. For now, until more specimens have been collected and a quantitative analysis has been completed, we prefer to view the specimens from PL and LQ as *Microtus* sp.

The new paleomagnetic and stratigraphic information presented in this paper, which place the Cúllar Baza-1 site at 0.75 Ma (basically at the Matuyama-Brunhes boundary) also sets a new date, at least in Spain, for the Toringian-Biharian ELMA. As noted above, the extinct water vole *Arvicola cantianus* has been generally used to define this boundary (see Fejfar et al., 1998; Maul et al., 2000), and has not previously been recorded from sediments securely dated older than 0.61 Ma. But such changes are to be expected as the stratigraphic and paleomagnetic history of more basins becomes established. Since LMAs are defined on the basis of fauna and not, strictly speaking, dates, it is conceivable that the Toringian-Biharian boundary could be of different times in different areas of Europe. Theoretically, within a context of mosaic morphological evolution, the *A. cantianus* dental morphology could evolve at different rates in different areas. However, we think that once established, a successful arvicolid species would explosively disperse through Europe within a few hundred years. The modern introduction and dispersal of the extant North American muskrat, *Ondatra zibethicus*, in Europe is a good example (Danell, 1996). Also, the paucity of...
appropriate sediments for radiometric dating and the minimal number of long stratigraphic sequences for magnetostratigraphic determinations in other European settings can leave considerable flexibility in estimates of the Toringian-Biharian boundary.

6. Chronostratigraphy and geological implications

Paleomagnetic polarity changes are worldwide events with the advantage of chronostratigraphic horizons, that of providing a glimpse into the events and processes happening at that specific time. Contemporaneous features and influences such as paleo-geography, paleo-environments, fauna and neo-tectonics can be compared accurately at magnetozone boundaries or interpolated between boundaries. The Early Pleistocene has boundaries that are approximated by the limits of two normal polarity chrons, the Olduvai (C2n) and the Brunhes (C1n). For now, there are three sections in the Baza Formation with one or more of these ‘boundary’ reversals: Cúllar, Huéscar-Puerto Lobo (both from this report) and the composite Orce sections (Scott et al., 2007). These sections represent the processes of accumulation at three distinct points around the edges of the Baza Basin, the south-central, the north-eastern and the south-eastern, respectively, and provide an opportunity for direct comparison and contrast (Figs. 12 and 13).

As a general observation, the Pliocene–Lower Pleistocene boundary (top of Olduvai zone) in the Orce area is at 900 asl (Salar Valley; Scott et al., 2007), compared to the same zone in Cúllar, also at 900 m asl. The Lower–Middle Pleistocene boundary (base of Brunhes zone) in Cúllar is at 965 m (asl.) and in Huéscar-Puerto Lobo at 955 m (asl.), but as of yet is not identified around Orce owing to erosion and/or non-deposition.

Specific comparisons of paleo-environments can begin at the start of the Pleistocene, when the Orce area, which had been experiencing a period of protracted lacustrine deposition, was the site of an advancing fluvial system coming from an eastern highlands. Meanwhile in Cúllar, the alluvial fan deposition, coming from the southern highlands continued. As the Middle Pleistocene begins, the Huéscar-Puerto Lobo area had been changing from ponds and marshes fringing the northern Basin margins to small, local fans and alluvial drainages coming from an emergent neo-tectonic structure (Botardo Hill) (Fig. 13). Simultaneously at Cúllar, palustrine facies was prograding onto the Cúllar fan, with an expansion of palustrine and distal alluvial environments replacing the mid-fan and alluvial facies.

Sedimentation rate in fine grain deposits of the Orce area was ~10 cm/kyr (Scott et al., 2007) through the Early Pleistocene, while in the Cúllar area the sedimentation rate was slower until after the Jaramillo subchron. The Cúllar area experienced an accelerated sedimentation after the Jaramillo and into the Brunhes, reaching equivalent rates to those from the Early Pleistocene deposits of Orce. This acceleration of sedimentation rate in the Cúllar area was a long-term process interpreted as a product of the prograding paleo-lake Baza and its marginal valley floor (Figs. 14 and 15). Other processes, such as neo-tectonic uplift and changing paleo-climates, were secondary variables to the Cúllar section’s specific paleo-geographic location. However neo-tectonic activity, on both the regional and local scale, was the dominant process at the Huéscar marginal sites. Meanwhile, in the central facies of the paleo-Lake Baza there was continuous sedimentation in which paleoclimate was the primary triggering factor (Gibert L. et al., 2001, 2007; Gibert L., 2006).

The chronology and biostratigraphy of the Baza Basin’s Pleistocene fossil vertebrate sites starts in the Orce area, with MN17 fauna (Fuentenueva-1 quarry) at ~1.5 Ma, ~25 m above the Olduvai normal zone. The paleontological/archeological quarries of Venta Micena (1.3 Ma), Barranco León (1.25 Ma) and Fuentenueva-3 (1.2 Ma) provide an Early Pleistocene fauna ~50 m above the Olduvai normal zone (Scott et al., 2007). Then the fossil sites below the Matuyama/Brunhes boundary in the Huéscar area (Puerto Lobo, Loma Quemada and Huéscar-1) provide a late Early Pleistocene fauna at 0.9 Ma.
Fig. 14. Age versus sediment accumulation. Sediment accumulation rates are compared between the Cúllar and Orce sections, based on magnetozone boundaries. At the position of the Cúllar section, the aggrading valley floor environments (palustrine/lacustrine) arrived soon after the Jaramillo subchron, which significantly increased the sediment accumulation rate. Projecting this rate to the upper strata, gives an approximate age of 600 Kya. Note that the top of the Orce sections is an erosion surface, and that the uppermost strata are pre-Jaramillo in age (Scott et al., 2007). Therefore, this figure shows a minimum accumulation rate for Orce, so that the associated fossil quarries might be slightly older than shown. In Cúllar section, the reference magnetozone boundaries are used as ‘hinge’ points for accumulation trends in a second refined curve (following McMillan and Stoner, 2005).

Fig. 15. Depositional model for Cúllar area. Schematic model which explain changes in sedimentation rate across the Cúllar margin during the Late Pliocene to Middle Pleistocene. Neogene sedimentation starts slowly, with the onlapping alluvial fan at ~2.1 Ma. A change to higher sedimentation rates, owing to the aggrading valley floor, finally reaches the Cúllar section about 0.9 Ma as the paleo-Baza Basin continues to fill. This process of net accumulation stops sometime after 0.6 Ma, and reverses into an erosional mode, that continues today.
Then immediately above the Matuyama/Brunhes boundary is the paleontological/archeological quarry at Cúllar Baza-1 that provides an initial fauna from the Middle Pleistocene at 0.75 Ma. And finally, the Cúllar Baza-C site (Agustí et al., 1999), which is from post-Baza Formation deposits, provides a new opportunity to examine fauna from approximately the Middle/Late Pleistocene boundary (~0.1 Ma).

7. Conclusions

- A study of the lithostratigraphy, magnetostratigraphy and micro-mammal paleontology was made at two sections in Quaternary deposits of the Baza Basin.
- Magnetostratigraphy of the Cúllar section (81 m) has located both the Pliocene–Pleistocene boundary and the Lower Pleistocene–Middle Pleistocene boundary. The paleontological/archeological quarry Cúllar Baza-1 is only 2 m above the Matuyama-Brunhes (Lower–Middle Pleistocene) boundary. Six major polarity zones have been identified in this section. The normal zones are correlated to the Olduvai (C2n), Jaramillo C1r.1n), and the early part of the Brunhes (C1n) chrons. The base of Cúllar section is dated at ~2.0 Ma.
- The top of both studied sections are some of the last deposits before stream piracy captured the drainage of the previously endorheic Baza Basin. Extrapolation of sedimentation rates suggests an age for the top of the Cúllar section at around 600 Kya. This indicates that the opening of the Basin occurred during the Middle Pleistocene, around 600 Kya.
- An age of ~0.75 Ma can be given to the extensive Cúllar Baza-1 fauna and lithic artifacts.
- Magnetostratigraphy of the Puerto Lobo sections (31 m), 25 km to the north near Huéscar has also located the Lower Pleistocene–Middle Pleistocene boundary. Two polarity zones have been identified in this section and are correlated to the latest Matuyama (C1r.1r) and the initial part of the Brunhes (C1n) chrons.
- An age of 0.9 Ma can be given to the paleontological sites of Huéscar-1 and Puerto Lobo.
- The change from the Biharian to the Toringian stages can be approximated by the Matuyama/Brunhes polarity change.
- Throughout the Pleistocene, local and regional neotectonic activities have played important roles, along with the changing climate, in influencing the distribution of depositional facies and paleo-environments found within the Baza Basin. However, paleo-geographic location will determine when, and where these influences are manifested as sedimentary deposits.
- The presence of early humans in the Baza Basin can be found at 1.3–1.2 Ma in the Orce area (previous work), at 0.75 Ma in the Cúllar area, and again at ~0.7 Ma in the Huéscar area.

Acknowledgments

We are grateful to the Paleontological Inst. Crusafont and Dr. A. Ruiz-Bustos for facilitating the review of the fossil material. We thank Dr. F. Tortosa for facilitating detailed digital elevation maps of the area, L. Smeenk for laboratory assistance and Dr. C. Fernández-Canyadell for his useful comments which improved the manuscript. This project was funded in part by the generous support of Earthwatch Institute a National Science Foundation grant (EAR-0207582) and project CGL2005-05337 BTE from the Spanish Government.

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