



# Human migration into Europe during the late Early Pleistocene climate transition

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## ABSTRACT

A critical assessment of the available magnetostratigraphic and/or radiometric age constraints on key sites bearing hominin remains and/or lithic industries from southern Europe (Italy, France, Spain) leads us to propose that the main window of early hominin presence in southern Europe is broadly comprised between the Jaramillo subchron and the Brunhes–Matuyama boundary (i.e., subchron C1r.1r, 0.99–0.78 Ma). Within the dating uncertainties, this ~200 ky time window broadly coincides with the late Early Pleistocene global climate transition that contains marine isotope stage (MIS) 22 (~0.87 Ma), the first prominent cold stage of the Pleistocene. We suggest that aridification in North Africa and Eastern Europe, particularly harsh during MIS 22 times, triggered migration pulses of large herbivores, particularly elephants, from these regions into southern European refugia, and that hominins migrated with them. Finally, we speculate on common pathways of late Early Pleistocene dispersal of elephants and hominins from their home in savannah Africa to southern Europe, elephant and hominin *buen retiro*. In particular, we stress the importance of the Po Valley of northern Italy that became largely and permanently exposed only since MIS 22, thus allowing possibly for the first time in the Pleistocene viable new migration routes for large mammals and hominins across northern Italy to southern France and Spain in the west.

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## 1. Introduction

The pioneering magnetostratigraphic study of Parés and Pérez-Gonzalez (1995) provided the first robust evidence for the presence of hominins in northern Spain at Gran Dolina (Carbonell et al., 1995) (Fig. 1) as early as the Early Pleistocene, specifically, sometime in the late Matuyama reverse polarity chron between the Brunhes–Matuyama boundary (0.78 Ma) and probably after the Jaramillo normal subchron (0.99 Ma). A very similar magnetostratigraphic profile placing evidence of hominins in reverse polarity sediments just below a transition correlated to the Brunhes–Matuyama boundary was reported at the nearby site of Sima del Elefante by Parés et al. (2006). However, more recently reported cosmogenic burial dates from Sima del Elefante seem to indicate that hominin occupation was earlier at around 1.1–1.2 Ma (Carbonell et al., 2008), which would be in the Matuyama prior to the Jaramillo. In the Guadix–Baza Basin of southern Spain, hominin sites first dated to a generic pre-Brunhes–Matuyama boundary interval (Oms et al., 2000) have been recently reassigned to a pre-Jaramillo age interval of 1.2–1.25 Ma using magnetostratigraphic data from a composite profile (Scott et al., 2007). In this regard, a candidate for the oldest site in Europe may as

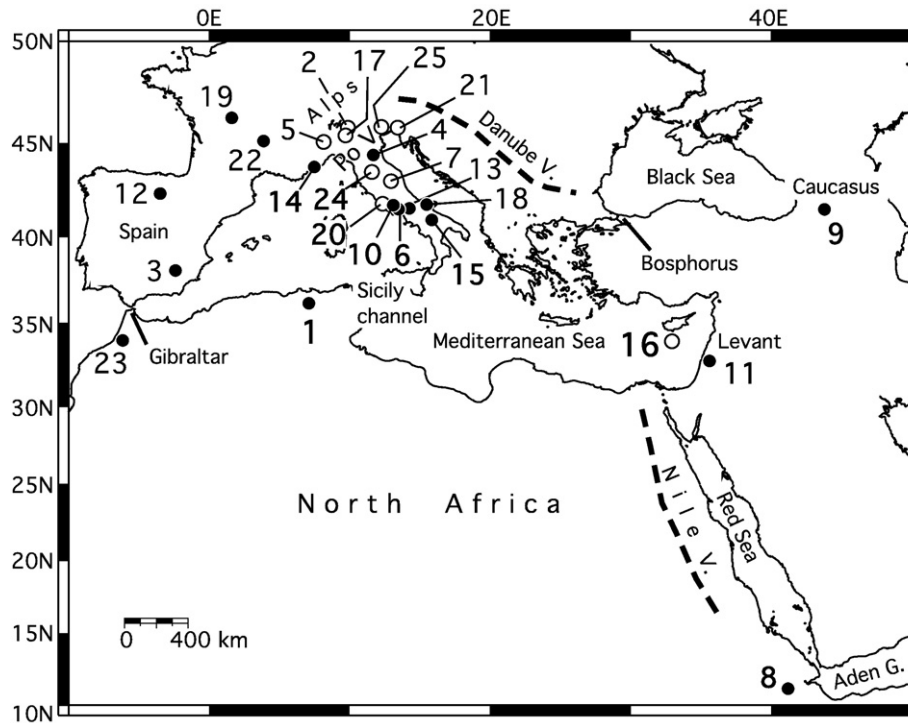
well be represented by the apparently even older site of Pirro Nord in southern Italy (Fig. 1), where biostratigraphic-based arguments were used to indicate hominin occupation sometime in the 1.3–1.7 Ma time range (Arzarello et al., 2007).

Although the evidence that Spain was occupied sometime before the Brunhes–Matuyama boundary is well documented, the precise timing of first colonization of southern Europe remains a complicated issue because age estimates of key sites, including those in Spain mentioned above, are controversial (e.g., Dennell and Roebroeks, 1996; Villa, 2001; Roebroeks, 2001; Antón and Swisher, 2004). This is also well exemplified by the case of the Ceprano man, thought to have lived in central Italy around the Brunhes–Matuyama boundary (Manzi, 2004) until a recent study showed that rather than being a candidate for one of the oldest occupation sites in southern Europe, the hominin-bearing level was in fact only ~0.45 Myr-old (Muttoni et al., 2009).

Accordingly, we attempt in this paper a critical assessment of the age data of key sites from southern Europe (Italy, France, Spain) bearing early hominin remains (bones, teeth) and/or Mode I or Mode II lithic tools. Mode I tools, also known as Oldowan, were produced in Africa as early as ~2.6–2.5 Ma (Semaw et al., 1997; Quade et al., 2004) by simple lithic reduction strategies involving the use of hammerstones to detach flakes from pebble cores. Mode II tools, also known as Acheulean, were produced in Africa as early as ~1.6–1.5 Ma (Asfaw et al., 1992; Quade et al., 2004) by more elaborate technologies involving shaping and retouching of stones to produce biface tools, and are therefore much less

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**Fig. 1.** Location map of key sites discussed in the text (black circles indicate sites with proof of hominin presence; white circles indicate other sites of interest discussed in the text): Ain Hanech (1); Bagaggera (2); Barranco León (3); Cà Belvedere (4); Castagnone (5); Ceprano (6); Colle Curti (7); Cúllar (3); Danakil (8); Dmanisi (9); Estrecho del Quipar (3); Fontana Ranuccio (10); Fuente Nueva-3 (3); Gesher Benot Ya'aqov (11); Gran Dolina (12); Evron (11); Huéscar-1 (3); La Pineta (13); Leffe (2); Le Vallonnet (14); Notarchirico (15); ODP Site 967 (16); Pianengo [and several other Po Valley cores] (17); Pirro Nord (18); Pont-de-Lavaud (19); Ponte Galeria (20); Sima del Elefante (12); Slivia (21); Solana del Zamborino (3); Soleilhac (22); Thomas Quarry (23); 'Ubeidiya (11); Upper Valdarno (24); Venice (25).

likely to be confused with artifact-like phenomena of geological origin (geofacts; Haynes, 1973). For our analysis, the distinction between Mode I and Mode II technologies has virtually no chronologic significance insofar as Mode II artifacts were well known by Africans when Mode I tools were still being used by the earliest Europeans (e.g., at Sima del Elefante; Carbonell et al., 2008). Plausibly, the existence in Europe of Mode I technology at the time of Mode II technology in Africa reflects cultural drift under low demographic density conditions that limited the maintenance and transmission of highly sophisticated Mode II techniques in sparsely populated environments (Lycett and von Cramon-Taubadel, 2008). Our survey is focused primarily on sites with magnetostratigraphy and correlations with a reference astronomical time scale that incorporates geomagnetic polarity reversals and/or radiometric dates based on established methods (K–Ar or the more accurate Ar–Ar dating) when provided with basic details on the laboratory procedures followed (Ludwig and Renne, 2000). We also discuss sites dated with relatively new types of exposure dating (see a critical review by Ludwig and Renne, 2000), and using mammalian biozonations.

A further motivation for this assessment of early hominin sites is the continued development of new information on the evolution of the Po Valley of northern Italy, which was studied using drill cores distributed from Venice in the east (Kent et al., 2002) to Pianengo near Milan in the west (Muttoni et al., 2003; Scardia et al., 2006) as well as from the adjacent Southern Alps margin at Leffe (Muttoni et al., 2007) and Bagaggera (Scardia et al., 2010) (Fig. 1). These extensive studies of climate, faunal, floral, and sea level changes constrained to the late Early Pleistocene by magnetostratigraphy suggest that the Po Valley may have acted as an important migration gateway to southern Europe at the inception of major northern hemisphere glaciations. We therefore turn our attention in the second part of the paper to the geologic and climatic record of critical areas of northern Africa and the Mediterranean region where hominins (and mammals in general) may have transited from Africa and/or western Asia to southern

Europe. Based on this knowledge, we formulate a testable hypothesis on the timing, pathways, and potential environmental causes of mammal and hominin immigration to southern Europe that is consistent with (or at least not contradicted by) what we would regard as the best-dated archeological record from the literature.

## 2. Chronology of early hominin presence in southern Europe

Magnetostratigraphy is frequently applied to date sedimentary sequences containing hominin remains or artifacts. The method consists in retrieving, with appropriate laboratory techniques, the sequence of polarity reversals registered in rocks by suitable ferromagnetic minerals for correlation with the reference geomagnetic polarity time scale. As for any analytical technique, a magnetostratigraphic study should meet some fundamental quality criteria in order to yield reliable age data, as summarized recently by Langereis et al. (2010). For example, samples should be collected in continuous stratigraphic context and all of them should be fully treated in the laboratory by applying demagnetization techniques that demonstrably include vector subtraction. The minerals responsible for the magnetic remanence should be determined, and no systematic correlation between magnetic mineralogy and polarity should be observed. Ancillary sections to test the lateral reproducibility of polarity intervals should accompany a reference magnetostratigraphic section, if possible. Polarity stratigraphy should be erected using the latitude of the virtual geomagnetic pole calculated for each sample's characteristic magnetic component plotted as function of stratigraphic horizon. All the above should be clearly described and illustrated in accessible publications.

With these basic criteria in mind, we review the published literature on early hominin sites from southern Europe; key dates for this discussion are the ages of the Pleistocene astronomical time scale of Lourens et al. (2004). These ages are essentially the same, within the resolution of polarity transition durations of typically 5 kyr

(Clement, 2004), as in the geomagnetic polarity time scale since Cande and Kent (1995) adopted in the geologic time scale of Berggren et al. (1995). The key ages are (Fig. 2):

- Brunhes–Matuyama boundary (beginning of C1n) = 0.781 Ma
- Matuyama–Jaramillo boundary (beginning of C1r.1r) = 0.988 Ma
- Jaramillo–Matuyama boundary (beginning of C1r.1n) = 1.072 Ma
- Matuyama–Cobb Mountain boundary (beginning of C1r.2r) = 1.173 Ma
- Cobb Mountain–Matuyama boundary (beginning of C1r.2n) = 1.185 Ma
- Matuyama–Olduvai boundary (beginning of C1r.3r) = 1.778 Ma
- Olduvai–Matuyama boundary (beginning of C2n) = 1.945 Ma

Until very recently, the beginning of the Pleistocene was placed near the top of the Olduvai (~1.78 Ma) but more germane to this discussion is that the Early Pleistocene is usually considered to extend up to the base of the Brunhes (0.78 Ma), the youngest chron of predominantly normal polarity that includes the Middle and Late Pleistocene (Lourens et al., 2004). Thus, geologic formations regarded as Pleistocene that have a stable reverse polarity magnetization can be considered most probably older than 0.78 Ma, i.e., Early Pleistocene. Magnetostratigraphy in such a context is an extremely valuable dating tool although further evidence is needed to restrict the reverse magnetizations to a particular interval of the Matuyama. On the other hand, there is ambiguity with stable normal polarity magnetization, even when there is a stratigraphic upward succession of reverse to normal polarity, because the normal polarity can represent either the Brunhes or the Jaramillo normal polarity (sub)chron [the very short (~10 kyr) Cobb Mountain normal polarity subchron is rarely expected to be encountered especially in discontinuous continental sections]; independent evidence for Early Pleistocene attribution is needed. A stratigraphic upward succession of normal to reverse polarity

magnetozone would imply Early Pleistocene but other evidence or arguments are needed to distinguish between the Jaramillo–Matuyama from the much older Olduvai–Matuyama transition. Reversal excursions are generally too short or ephemeral to be useful for reliable correlations (e.g., Langereis et al., 1997).

2.1. Italy

2.1.1. Ceprano and Fontana Ranuccio

A hominin cranium from Ceprano, Italy (Ascenzi et al., 1996, 2000; Bruner and Manzi, 2007) (Fig. 1) has been commonly regarded as representative of one of the oldest hominins in Europe (e.g., Dennell, 2008) and considered by Manzi (2004) to be associated with the Brunhes–Matuyama polarity chron boundary (0.78 Ma), although no direct paleomagnetic evidence was available to support the interpretation. However, new paleomagnetic data from two long cores drilled at Ceprano show no evidence for reverse polarity magnetizations down to 45 m below the hominin level (Muttoni et al., 2009). Taking into account available K–Ar age constraints from the region, this study indicated an age of around 0.45 Ma (+0.05, –0.1 Ma), or Middle Pleistocene and well up in the Brunhes normal polarity chron, for the hominin level at Ceprano (Fig. 2). Evidence for the Brunhes–Matuyama boundary was found at Fontana Ranuccio but well below (~40 m) the level that yielded hominin teeth and a Mode II tool industry (Muttoni et al., 2009), in agreement with a K–Ar leucites age of  $0.46 \pm 0.01$  Ma reported for this level (Biddittu et al., 1979) (Fig. 2).

2.1.2. Cà Belvedere

At Cà Belvedere (Monte Poggiolo) in northern Italy (Fig. 1), Mode I knapped pebbles (Bisi et al., 1992; Villa, 2001; Peretto, 2006) were recovered from a ~4 m-thick sequence of sandy gravels overlain by a soil horizon and resting unconformably on the Pliocene–Pleistocene

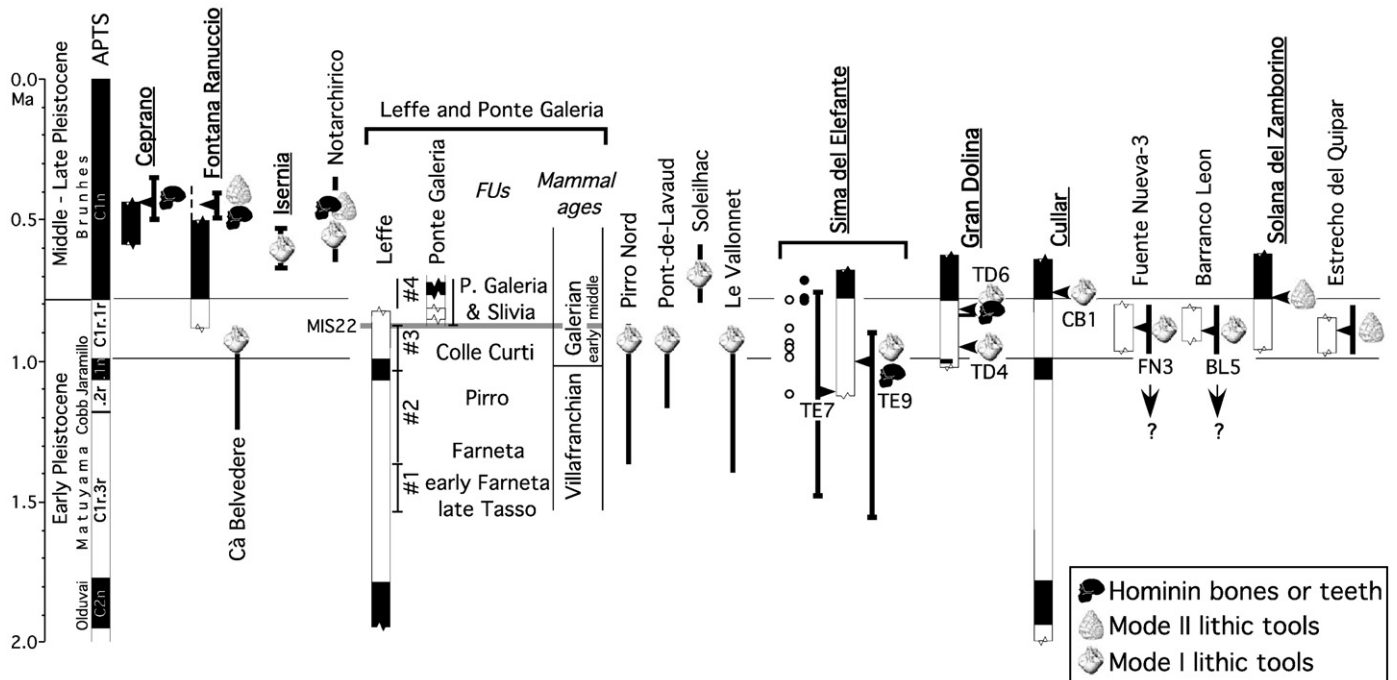


Fig. 2. Chronologies based essentially on magnetostratigraphy and/or radiometric age data of key late Early–Middle Pleistocene sites from Italy, France and Spain bearing proof of hominin presence (Mode I or Mode II lithic tools and/or hominin remains) plotted against the astrochronological polarity time scale of the Pleistocene (Lourens et al., 2004) (black is normal geomagnetic polarity, white is reverse polarity). Relevant to the discussion of the Villafranchian–Galerian faunal transition are the magnetostratigraphies from Leffe in northern Italy, with indication of mammal associations from #1 to #4 comprehensively attributed to Faunal Units (FU) from late Tasso–early Farneta (#1) to Slivia (#4) (Muttoni et al., 2007), and of Ponte Galeria in central Italy, the type section of the Ponte Galeria FU, which is probably coeval to the Slivia FU from northern Italy (Palombo and Ferretti, 2005). The derived Mammal ages are also indicated. For the critical Sima del Elefante section, we show the sample data used to erect the polarity stratigraphy (Carbonell et al., 2008), where closed (open) circles represent normal (reverse) polarity. What we regard as the best-dated earliest sites with proof of hominin presence are underlined in bold. See text for discussion.

marine to infralittoral Argille Azzurre Formation (Antoniazzi et al., 1992; Gagnepain et al., 1992). Paleomagnetic analyses on 40 samples stratigraphically distributed through the soil horizon and the underlying tool-bearing sandy gravels (Gagnepain et al., 1992) found evidence of north-directed and downward-pointing magnetizations in 32 consecutive samples from the soil horizon to the lower part of the sandy gravels, followed below by three samples with south-directed and upward-pointing magnetizations with inclinations of  $-10^\circ$  to  $-20^\circ$ . Five additional samples with highly dispersed downward-pointing magnetizations were reported from the base of the tool-bearing sandy gravels.

Despite the occurrence of magnetizations almost exclusively oriented north-and-down (normal polarity), Gagnepain et al. (1992) speculated that the original magnetizations were in fact acquired during a reverse polarity interval (attributed to the Matuyama Chron,  $>0.78$  Ma) but in all but three samples, these original magnetizations were entirely overprinted by normal polarity magnetizations during successive and pervasive pedogenic alteration processes. Three electron spin resonance (ESR) dates on quartz grains indicated an average age of  $1.065 \pm 0.165$  Ma for the sandy gravels (Peretto et al., 1998; see also Villa, 2001 and Bahain et al., 2007), which would place the tool-bearing sandy gravels of Cà Belvedere in a time window comprised between 0.9 and 1.23 Ma, which is largely dominated by reverse polarity (late Matuyama Chron) even though virtually only normal polarity magnetizations were found throughout the sampled unit. We therefore provisionally place Cà Belvedere in the late Matuyama around 1 Ma (Fig. 2), based largely on the ESR dates, which are known to have significant uncertainties (Ludwig and Renne, 2000), and stress the need of more definitive paleomagnetic data.

#### 2.1.3. Isernia

At La Pineta near Isernia (Fig. 1), Mode I lithic tools (Villa, 2001; Peretto, 2006) were found in levels immediately below a tuff level dated by K–Ar to  $0.73 \pm 0.04$  Ma (Coltorti et al., 1982; mineral used for analysis not specified). This age was supported by a biotite K–Ar date of  $0.73 \pm 0.07$  Ma from a second tuff level from the nearby section of Belfiore, traced ~5 m above the tool-bearing layers at La Pineta by means of lithostratigraphy (Coltorti et al., 1982). Paleomagnetic analyses were conducted at La Pineta showing the presence of ‘clearly reverse’ to ‘possibly reverse’ to ‘indeterminate’ magnetic polarities such that the section was attributed to the Matuyama Chron, in broad agreement with the K–Ar dates, but no details on the paleomagnetic procedures were provided (Coltorti et al., 1982). Recent sanidine Ar–Ar dates of  $0.610 \pm 0.01$  Ma and  $0.606 \pm 0.072$  Ma have been obtained at La Pineta from a tuff level located immediately above the tool-bearing layers and virtually coincident with the level previously dated by K–Ar to  $0.73 \pm 0.04$  Ma (Coltorti et al., 2005). This new date would place La Pineta well into the Brunhes normal polarity chron and is at odds with the ‘clearly reverse’ paleomagnetic interpretation by Coltorti et al. (1982). In this respect, Coltorti et al. (2005) reported that ‘the palaeomagnetic investigations revealed that the magnetic polarity underwent a major change from negative in the part of the section below the first occupation layers, to positive in the layers overlying the occupation layer’. Again, however, no details on the paleomagnetic procedures were provided in support of this inference. Therefore, we place La Pineta at ~0.6 Ma (Fig. 2) on the strength of the recent Ar–Ar date but regard the magnetic characterization as incomplete and ambiguous.

#### 2.1.4. Notarchirico

The ~6 m-thick sedimentary succession of Notarchirico in southern Italy (Fig. 1) contains at least nine archeological levels, which yielded Mode I lithic tools alternating with Mode II lithic tools, as well as a hominin femur (Villa, 2001). Thermoluminescence (TL) analyses on quartz grains from the sedimentary succession yielded a contradictory range of dates whereby the oldest date falls stratigraphically above a younger one (Villa, 2001). Nonetheless, Villa (2001) presents an argument that some of these TL dates are reliable, noticing that the one at  $0.640 \pm 0.07$  Ma is virtually coincident with an Ar–Ar age of  $0.654 \pm 0.011$  Ma reported (as a personal communication by J.P. Raynal) for a tephra level from the nearby Vulture volcanic complex, which according to geochemical data is present also in primary depositional context within the tool-bearing sequence at Notarchirico. The picture is complicated somewhat by an age of  $0.359 (+0.154, -0.097)$  Ma obtained on the hominin femur by the uranium-series disequilibrium method (Villa, 2001). Although the precise age of the Notarchirico tool-bearing sequence is unclear, the available evidence would place it no older than within the Brunhes normal polarity chron, to a time span broadly comprised between 0.36 and 0.65 Ma (Fig. 2), although there are no paleomagnetic data to confirm (or refute) this.

2.1.5. Pirro Nord

The Pirro Nord karst fissure fills from Apulia in southern Italy (Fig. 1) yielded three cores and six flakes made of flint and characterized by scar geometries considered incompatible with those produced naturally in geofacts (Arzarello et al., 2007). These tools were attributed to a Mode I industry and were found in association with large and small mammal remains pertaining to the Pirro Faunal Unit (FU) (Arzarello et al., 2007). The Pirro FU is placed between 1.3 and 1.7 Ma in virtually all Italian mammal biochronologies (e.g., Gliozzi et al., 1997; Breda and Marchetti, 2005; Palombo and Mussi, 2006; Sardella et al., 2006; Palombo and Sardella, 2007; Masini and Sala, 2007). However, none of the localities that collectively define the Pirro FU is provided with direct radiometric age estimates or paleomagnetic analyses (Napoleone et al., 2003; contra Arzarello et al., 2007). The age of the Pirro FU is primarily based on the inference that it should be younger than the Olivola and Tasso FUs, which were magnetostratigraphically calibrated as occurring close to the Olduvai–Matuyama boundary (1.78 Ma) at localities in the Upper Valdarno of central Italy (Torre et al., 1993; Napoleone et al., 2001; Fig. 1), and older than the Colle Curti FU, magnetostratigraphically calibrated to the base of the Jaramillo subchron (1.07 Ma) at the type locality of Colle Curti in central Italy (Coltorti et al., 1998; Fig. 1). The quality of the magnetostratigraphic study on the sedimentary succession at Colle Curti is, however, difficult to evaluate because no demagnetization data were illustrated and discussed despite the indication of pervasive normal polarity remagnetizations associated with iron sulphides (Coltorti et al., 1998). We notice, moreover, that exclusively normal polarity was found by Giraudi et al. (2003) throughout the whole stratigraphic succession at Castagnone in northwestern Italy (Fig. 1) that straddles a Messinian to mid-Pleistocene time interval known to encompass ~25 polarity reversals (Berggren et al., 1995; Lourens et al., 2004), casting serious doubt on the primary nature of the magnetic remanence. Nonetheless, the Castagnone locality yielded a small mammal association attributed to the Colle Curti FU, retrieved from levels with normal paleomagnetic polarity ascribed to the Jaramillo subchron (Giraudi et al., 2003).

#### 2.1.5. Pirro Nord

In a magnetostratigraphic study on the Lefte lacustrine sequence from northern Italy (Muttoni et al., 2007) (Fig. 1), a large mammal association (#2, with *Pachycrocuta brevirostris*, *Stephanorhinus* ex gr. *etruscus*, *Pseudodama eurygonos*, and *Cervalces* cf. *carnutorum*) compatible with the Pirro FU was described from levels coeval to and older than the Jaramillo subchron. This assemblage was succeeded by a large mammal association (#3, with *Mammuthus meridionalis vestinus*, *Megaloceros verticornis*, and *Megaloceros* sp.) compatible with the Colle Curti FU from levels coeval to and younger than the Jaramillo subchron, with the top of this association placed at an unconformity correlated to MIS 22 at 0.87 Ma (Fig. 2; the significance of this unconformity and of the overlying mammal association #4 are described in Section 3). According to data from Lefte, therefore, the Pirro FU–Colle Curti FU transition could be placed within the Jaramillo at ~1 Ma rather than

phically above a younger one (Villa, 2001). Nonetheless, Villa (2001) presents an argument that some of these TL dates are reliable, noticing that the one at  $0.640 \pm 0.07$  Ma is virtually coincident with an Ar–Ar age of  $0.654 \pm 0.011$  Ma reported (as a personal communication by J.P. Raynal) for a tephra level from the nearby Vulture volcanic complex, which according to geochemical data is present also in primary depositional context within the tool-bearing sequence at Notarchirico. The picture is complicated somewhat by an age of  $0.359 (+0.154, -0.097)$  Ma obtained on the hominin femur by the uranium-series disequilibrium method (Villa, 2001). Although the precise age of the Notarchirico tool-bearing sequence is unclear, the available evidence would place it no older than within the Brunhes normal polarity chron, to a time span broadly comprised between 0.36 and 0.65 Ma (Fig. 2), although there are no paleomagnetic data to confirm (or refute) this.

below the Jaramillo at 1.3 Ma as proposed by Arzarello et al. (2007) based on uncalibrated mammal chronologies from the literature (e.g., Gliozzi et al., 1997; Masini and Sala, 2007). Hence, the lithic artifacts from Pirro Nord may be as young as the upper age limit of the Pirro FU at Lefte at ~1 Ma (Fig. 2), provided that the faunal unit is in fact isochronous over this geographic range.

## 2.2. France

Following the compilation of Carbonell et al. (2008), we discuss the chronostratigraphy of the following sites with lithic tools from France.

### 2.2.1. Pont-de-Lavaud

This site is located on the northern side of the Massif Central (Fig. 1) and yielded Mode I lithic tools from alluvial deposits of Formation D, located 90 m above the modern valley floor of the Creuse River (Despriée and Gageonnet, 2003; Carbonell et al., 2008 and references therein). Ten ESR analyses on bleached sedimentary quartz samples from Formation D yielded an average ESR age of  $1.07 \pm 0.09$  Ma (Despriée et al., 2006; Bahain et al., 2007 and references therein). These data are reminiscent of very similar ESR dates from Cà Belvedere (Italy) and would place the lithic artifacts from Pont-de-Lavaud before the Brunhes–Matuyama boundary in a time window (0.98–1.16 Ma) straddling the Jaramillo subchron (Fig. 2). However, neither magnetostratigraphic nor more conventional radiometric age data are thus far available to confirm this age attribution.

### 2.2.2. Soleilhac

At Soleilhac in Haute-Loire, France (Fig. 1), Mode I lithic tools were found in a 1–2 m-thick level of gray silts and sands termed bed C pertaining to a lacustrine succession contained in a maar depression (Thouveny and Bonifay, 1984; Carbonell et al., 2008 and references therein). Two long cores drilled near the archeological site were studied for magnetostratigraphy (Thouveny and Bonifay, 1984). The lower part of bed E (base of the lacustrine succession, comprised of blue clays and pyroclastics) showed scattered paleomagnetic directions after alternating field demagnetization whereas thermal demagnetization revealed the presence of reverse or intermediate directions. The top of bed E and the overlying bed D (lacustrine silts and sands) showed stable normal polarity magnetizations. Toward the top of the cores, above bed B, two samples at 5.2 m depth showed reverse directions, two samples at 5 m depth showed intermediate magnetizations, and, finally, two samples at 3 m depth showed normal magnetizations. Thouveny and Bonifay (1984) inferred that the Soleilhac lacustrine succession recorded a virtually continuous reverse-normal-reverse-normal polarity sequence, with the lithic tool-bearing level contained in the lower normal polarity interval. This normal polarity interval was interpreted as the Jaramillo subchron based on a comparison between the Soleilhac fauna and the fauna from the Italian locality of Isernia (discussed above). The Isernia fauna was considered somewhat more evolved (i.e., younger) than the fauna from Soleilhac, and because the Isernia fauna was placed close to the Brunhes–Matuyama boundary based on the old K–Ar age of  $0.73 \pm 0.04$  Ma of Coltorti et al. (1982), the supposedly normal polarity interval of the seemingly older Soleilhac fauna was attributed to the Jaramillo subchron (Thouveny and Bonifay, 1984). However, as discussed above, the Isernia site has been recently re-dated by means of Ar–Ar to ~0.6 Ma which would be well into the Brunhes (Coltorti et al., 2005). Moreover, according to Raynal et al. (2001), a pumice ash-fall layer in the lacustrine succession below the archeological bed C at Soleilhac is correlative to a pumice layer from the nearby locality of Neschers dated by means of Ar–Ar to  $0.58 \pm 0.02$  Ma (Lo Bello et al., 1987). Given these uncertainties (coupled with insufficient information on the experimental procedure used to erect the polarity stratigraphy at Soleilhac), the new date of ~0.6 Ma

for the Isernia fauna as well the date of ~0.58 Ma for the Neschers pumice suggest that the lithic artifacts from Soleilhac may be younger than the Brunhes–Matuyama boundary (Fig. 2).

### 2.2.3. Le Vallonnet

The Le Vallonnet cave in the Alpes-Maritimes of southern France (Fig. 1) yielded abundant Mode I lithic tools (Bernal and Moncel, 2004; Carbonell et al., 2008 and references therein) and mammal remains (but no hominins) as extensively described by De Lumley (1988) (see also Bernal and Moncel, 2004; Echassoux, 2004; Moullé et al., 2006). De Lumley (1988) dated the cave deposits to 0.98–0.91 Ma based on their Epivillafranchian mammal association. The cave deposits are enclosed between an upper and a lower stalagmitic floor; the base of the upper stalagmitic floor yielded an ESR age of  $0.91 \pm 0.06$  Ma, whereas the top of the lower stalagmitic floor yielded an ESR age of  $1.37 \pm 0.12$  Ma (Yokoyama et al., 1988). Yokoyama et al. (1988) also reported normal polarity directions from level III of the cave stratigraphy, which they interpreted as pertaining to either the Brunhes or the Jaramillo or the Olduvai, but without illustrating any data or providing any information on the experimental procedure used to obtain the polarity stratigraphy. Gagnepain (1996, unpublished doctoral thesis) provided inconclusive paleomagnetic data from Le Vallonnet, which, as he stated, ‘did not allow to establish a clear magnetic polarity for the succession’. Nevertheless, the Le Vallonnet cave deposits are still often attributed to the Jaramillo subchron (e.g., Bernal and Moncel, 2004; Echassoux, 2004; Moullé et al., 2006). Leaving aside the elusive Jaramillo possibility, we retain a generic ESR age window of ~0.9–1.4 Ma for the tool-bearing deposits at Le Vallonnet (Yokoyama et al., 1988; but see Ludwig and Renne, 2000) (Fig. 2) and stress that neither convincing magnetostratigraphic nor more conventional radiometric age data are thus far available to confirm this age attribution.

## 2.3. Spain

The clearest evidence of hominin presence in Europe in the Early Pleistocene (i.e., before the Brunhes–Matuyama boundary) surely comes from magnetostratigraphic studies on classic localities from Spain at Atapuerca (Sima del Elefante and Gran Dolina) and in the Guadix–Baza Basin.

### 2.3.1. Gran Dolina (Atapuerca)

The Gran Dolina karst fissure fills (Fig. 1) was the discovery site for convincing evidence of Early Pleistocene hominins in Europe that yielded several hominin remains and Mode I lithic tools from stratigraphic unit TD6, as well as additional Mode I lithic tools from the underlying unit TD4 (Carbonell et al., 1995). Both stratigraphic units yielded reverse polarity directions and are located just below a well-defined upper normal–lower reverse paleomagnetic polarity transition interpreted as the Brunhes–Matuyama boundary (Parés and Pérez-Gonzalez, 1995, 1999). One sample from the section base yielded a normal polarity direction that was tentatively attributed to the Jaramillo subchron (Parés and Pérez-Gonzalez, 1995, 1999). Recent TL dates are consistent with biostratigraphic and paleomagnetic data and would indicate a probable numeric age of ~0.9–0.95 Ma for the oldest hominin remains at Gran Dolina (Berger et al., 2008). Hence, the available age constraints place the hominin remains at Gran Dolina before the Brunhes–Matuyama boundary but most likely after the Jaramillo subchron (Fig. 2).

### 2.3.2. Sima del Elefante (Atapuerca)

In the Sima del Elefante karst fissure fills (Fig. 1), Parés et al. (2006) found a paleomagnetic polarity reversal interpreted as the Brunhes–Matuyama boundary, with the lowermost Mode I tool bearing levels within reversely magnetized strata attributed to the Matuyama Chron. In a subsequent study, Carbonell et al. (2008) confirmed and

expanded the results of Parés et al. (2006) and reported Mode I lithic tools and a hominin mandible from level TE9 within reverse polarity strata lying below normal polarity strata interpreted as the Brunhes Chron. In addition, two samples were studied for cosmogenic Al/Be burial dates; level TE9 provided a burial age of  $1.22 \pm 0.16$  Ma, whereas level TE7 (with no hominin evidence) located ~1.5 m below provided a burial age of  $1.13 \pm 0.18$  Ma (Carbonell et al., 2008). The Sima del Elefante level TE9 thus emerges as one of the oldest records of hominin occupation in Europe, attributed an age of ~1.1–1.2 Ma on the basis of the cosmogenic burial dates (Carbonell et al., 2008), which would place TE7 and TE9 below the Jaramillo subchron. However, we notice that the Jaramillo was not found, only reverse magnetizations below what was identified as the Brunhes–Matuyama boundary, and that the formal statistical errors for the burial age estimates were quoted at only the 68% confidence interval whereas at 95% confidence these data would indicate associated analytical uncertainties of  $1.22 \pm 0.32$  Ma for TE9 and of  $1.13 \pm 0.36$  Ma for TE7. This would suggest that the uncertainty in the age range of hominin level TE9 is more like 0.9 to 1.54 Ma (and 0.77 to 1.49 Ma in TE7 level below), which would not preclude that hominin occupation at Sima del Elefante occurred sometime between the Jaramillo and the Brunhes–Matuyama boundary (Fig. 2).

### 2.3.3. Cúllar

In the Guadix–Baza Basin near the town of Cúllar (Fig. 1), 5 sections have been correlated into a ~60 m-thick composite section (Agustí et al., 1999). Paleomagnetic analyses have been conducted on the ~15 m-thick lowermost section, revealing the presence of an upper normal–lower reverse polarity transition interpreted as the Brunhes–Matuyama boundary (Agustí et al., 1999). A site named Cúllar Baza-1 with lithic tools (six flakes and two choppers; Roebroeks and van Kolfschoten, 1994) is present in the middle of the ~15 m-thick uppermost section, some ~40 m above the inferred Brunhes–Matuyama boundary and therefore presumably within strata pertaining to the Brunhes Chron, although no paleomagnetic analyses have been carried out to confirm this polarity attribution, which is inferred from lithological correlations with the lower section (Agustí et al., 1999). In a subsequent study, Gibert et al. (2007) reported the magnetostratigraphy of an ~80 m-thick and continuous Cúllar section located ~2 km southeast of the 5 sections used by Agustí et al. (1999) to build their composite section. This new section extends from the Olduvai Subchron upward across the Jaramillo Subchron and directly to the tool-bearing Cúllar Baza-1 site (not sampled by Agustí et al., 1999), which was found only 2 m above the Brunhes–Matuyama boundary within an additional ~17 m of strata pertaining to the Brunhes Chron. To explain the incongruent position of the Cúllar Baza-1 site with respect to polarity stratigraphy, Gibert et al. (2007) infer that the Brunhes–Matuyama boundary found by Agustí et al. (1999) in their lowermost section occurs at a disconformity whereby the overlying normal polarity strata are Late Pleistocene in age. Following Gibert et al. (2007), we place the tool-bearing Cúllar Baza-1 site in the earliest part of the Brunhes Chron, close to the Brunhes–Matuyama boundary (Fig. 2).

### 2.3.4. Fuente Nueva-3 and Barranco León

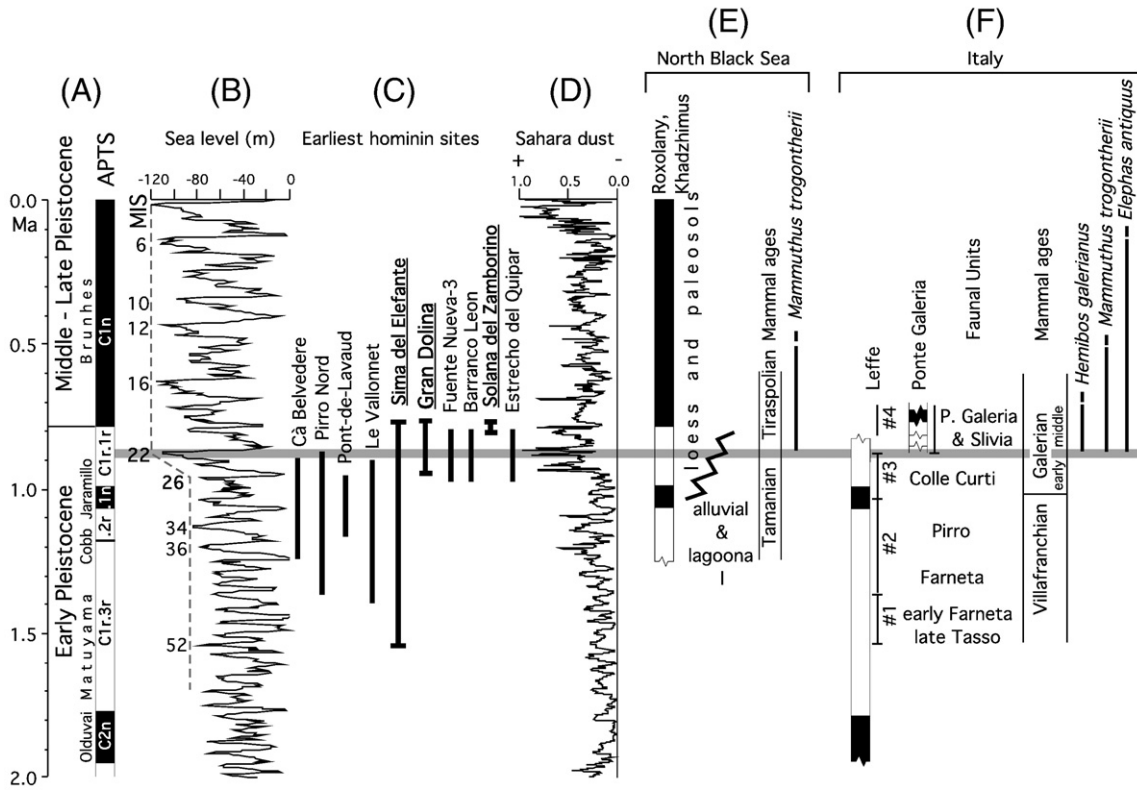
At these sections from the Velez Valley of the Guadix–Baza Basin near Orce (Fig. 1), levels with Mode I lithic tools are embedded within several meters of section with exclusive reverse polarity attributed to a generic Matuyama Chron (Oms et al., 2000). Oms et al. (2000) had cautiously suggested that these sections might be older than the Jaramillo (i.e., >1.07 Ma) based on micromammal biostratigraphy, namely the presence of *Allophaiomys burgondiae* at Fuentenueva-3. However, *A. burgondiae* is present in central Italy in the Colle Curti FU (Masini and Sala, 2007) that at Lefte in northern Italy was found to straddle the Jaramillo subchron and extend up to MIS 22 at 0.87 Ma (Muttoni et al., 2007).

In a subsequent study, Scott et al. (2007) assembled the magnetostratigraphies from Fuente Nueva-3 and Barranco León of Oms et al. (2000) with the published magnetostratigraphies from Fuente Nueva-1 and Barranco de Orce that have exclusively reverse polarity (but none with proof of hominin presence), and studied for magnetostratigraphy an additional ~6 m-thick section (Mojona Mine) from the lowest levels in the Velez Valley, where they found exclusively normal polarity (Scott et al., 2007 and references therein). These 5 magnetostratigraphic sections were pieced together by correlation of continental facies (palustrine, alluvial, fluvio-palustrine) producing a normal–reverse composite polarity sequence that is, however, still affected by extensive sampling gaps in the lower part, notably between the Mojona Mine normal polarity interval and the reverse polarity interval of the 4 upper sections. To augment the stratigraphic coverage, Scott et al. (2007) sampled 4 sections in the nearby Salar Valley (none with proof of hominin presence), finding exclusively reverse polarity in 3 sections (Venta Micena, Cañada del Salar, and Camino del Llano) and a reverse-normal–reverse polarity sequence at Rincon de la Losa from the lowest levels in the Salar Valley. These 4 magnetostratigraphic sections were pieced together by correlations of continental facies (palustrine, alluvial, fluvio-palustrine) producing a presumably more continuous reverse–normal–reverse composite polarity sequence for the Salar Valley, which was correlated again by means of continental facies to the discontinuous Velez Valley polarity sequence, producing a composite reverse–normal–reverse polarity sequence thought to be valid for the Guadix–Baza Basin of the Orce area (Scott et al., 2007). The normal polarity interval was attributed to the Olduvai subchron (1.95–1.77 Ma) essentially because the mammal faunas from the overlying reverse polarity interval at Fuentenueva-1 are similar to faunas found at the hominin site of Dmanisi in Georgia, which is dated to around 1.7 Ma or younger (Gabunia et al., 2000). The Guadix–Baza overall composite reverse–normal–reverse polarity sequence was therefore attributed to the Matuyama–Olduvai–Matuyama interval, prior to the Jaramillo Subchron, which was not found, and would imply that the tool bearing levels at Barranco León and Fuente Nueva-3 would now fall between the Olduvai and the (undetected) Jaramillo subchrons at ~1.2–1.25 Ma (Scott et al., 2007).

We suggest that physical correlations of strata between the tool-bearing Fuente Nueva-3 and Barranco León sections of exclusively reverse polarity and the remainder of the (supposedly coeval) sections of reverse polarity are ambiguous because the embedding palustrine sediments appear to be monotonous and/or laterally discontinuous (see Figs. 2 and 3 in Scott et al., 2007). Hence, it cannot be precluded that the tool-bearing levels lay entirely above and thus could be younger than the Fuente Nueva-1 and Barranco de Orce sections. All that can be said with any confidence concerning the age of the tool bearing levels at Fuente Nueva-3 and Barranco León sections is that they predate the Brunhes–Matuyama boundary (0.78 Ma) and postdate the Olduvai–Matuyama boundary (1.77 Ma), falling either before or after but not during the Jaramillo subchron (Fig. 2).

### 2.3.5. Solana del Zamborino and Estrecho del Quipar

In the ~27 m-thick Solana del Zamborino fluvio-lacustrine section from the Guadix–Baza Basin (Fig. 1), Scott and Gibert (2009) found convincing evidence for the Brunhes–Matuyama boundary, with Mode II lithic tools located immediately above the polarity reversal boundary at a nominal age of 0.77–0.75 Ma (Fig. 2). Estrecho del Quipar in the Guadix–Baza Basin near Caravaca (Fig. 1) yielded Mode II lithic tools and hominin teeth from a 10 m-thick sequence of fine-grained paleosols infilling a relict weathering cavity (rock shelter). Magnetostratigraphic analyses from two sections, encompassing a total of ~6.2 m, indicate the presence of exclusive reverse polarity pertaining to the Matuyama Chron (Scott and Gibert, 2009). Based on the presence of micro-mammals, notably *Microtus*



**Fig. 3.** Climatic and ecologic boundary conditions to earliest main hominin migrations to southern Europe. (A) The Pleistocene astrochronological polarity time scale (Lourens et al., 2004) (black is normal geomagnetic polarity, white is reverse polarity). (B) Benthic  $\delta^{18}\text{O}$  SPECMAP record (Shackleton, 1995) scaled to the 120 m glacio-eustatic drop at the last glacial maximum time (Fairbanks, 1989). (C) Summary of earliest hominin sites of southern Europe; the best-dated sites are underlined in bold (from Fig. 2). (D) Rock-magnetic record of ODP Site 967 (IRM<sub>0.9T</sub> at AF<sub>120 mT</sub>), which shows increases of hematite-rich aeolian dust supply from the Sahara into the eastern Mediterranean Sea since ~0.95 Ma with a burst at 0.87 Ma (MIS 22). (E) Composite magnetostratigraphy of northern Black Sea sections, indicating the onset of major arid-glacial loess deposition within Chron C1r.1r, broadly coeval with the base of the Tiraspolian mammal age and the associated first occurrence (FO) of the Asian *M. trogontherii* (Dodonov et al., 2006). (F) Magnetostratigraphy from Leffe in northern Italy with indication of mammal associations from #1 to #4 compressively attributed to Faunal Units (FU) from late Tasso–early Farneta (#1) to Slivia (#4) (Muttoni et al., 2007), placed aside the magnetostratigraphy from Ponte Galeria in central Italy, the type section of the Ponte Galeria FU, which is probably coeval to the Slivia FU from northern Italy (Palombo and Ferretti, 2005). The derived Mammal Ages are also indicated together with the FOs in Italy of *M. trogontherii*, *E. antiquus*, and *H. galerianus* during MIS 22 time (Slivia & Ponte Galeria FUs).

*huescarensis*, found at the Huéscar-1 site of the Guadix–Baza Basin within a composite magnetostratigraphic sequence about 10 m below a polarity reversal interpreted as the Brunhes–Matuyama boundary (Gibert et al., 2007), Scott and Gibert (2009) propose a nominal age of ~0.9 Ma for the Estrecho del Quipar lithic tools and hominin remains (Fig. 2).

2.4. Summary

In summary, we regard the best-dated sites with proof of early hominin presence in southern Europe as (i) Ceprano, Fontana Ranuccio, and Isernia in Italy, compressively dated to ~0.35–0.6 Ma within the Middle Pleistocene, (ii) Cúllar Baza-1 and Solana del Zamborino in Spain, virtually coincident with the Brunhes–Matuyama (Early–Middle Pleistocene) boundary (~0.78 Ma), and (iii) the pre-Brunhes–Matuyama boundary (Early Pleistocene) sites of Sima del Elefante, broadly dated to ~0.8–1.5 Ma, and of Gran Dolina, dated to ~0.99–0.78 Ma (assuming the lower normal polarity interval represents the Jaramillo subchron). Next are Fuente Nueva-3, Barranco León, and Estrecho del Quipar from Spain, which predate the Brunhes–Matuyama boundary (0.78 Ma) and postdate the Olduvai–Matuyama boundary (1.77 Ma), falling either before or after but not during the Jaramillo subchron. The other sites we evaluated are affected by large age uncertainties. The magnetostratigraphic data from Cà Belvedere, Soleilhac, and Le Vallonnet do not meet basic quality criteria, whereas the radiometric ages of several late Early Pleistocene faunal units of the Italian mammal biochronology (e.g.,

Gliozzi et al., 1997) used by Arzarello et al. (2007) at Pirro Nord are poorly known. ESR or similar dating techniques used at Cà Belvedere, Notarchirico, Le Vallonnet, and Pont-de-Lavaud are associated with potential analytical errors of up to ±15–30% (Ludwig and Renne, 2000; Zhao et al., 2001) or ±10–25% (Rink et al., 2007), and may not (yet) be suitable as stand-alone dating tools. This is due to several uncertainties including difficulties to determine the correct rate of trapping of electrons stimulated by cosmic and terrestrial radiation, incomplete resetting of the sample’s timer by exposure to sunlight (bleaching), and a basic lack of procedure standardization (see the review of Ludwig and Renne, 2000).

Several sites bearing as evidence of early hominins exclusively Mode I lithic tools that have been regarded as suspiciously similar to geofacts have been excluded from our compilation. These include sites from the Massif Central and Haute-Loire of France (Blassac, Chilhac III, Perrier-Etouaires, Saint-Eble, le Coupet, La Roche-Lambert), some associated with ages much older than 1 Ma, that yielded ‘tools’ that most probably have been produced by volcanic processes (Raynal et al., 1995), whereas the only *in situ* tool from Monte Peglia and some of the artifacts from Colle Marino in central Italy ‘look like geofacts’ according to Villa (2001). For the remainder of the sites in our compilation bearing only Mode I tools (Isernia, Pirro Nord, Pont-de-Lavaud, Le Vallonnet, Cúllar Baza-1, Fuente Nueva-3, and Barranco León), we rely on the lack of reported suspicion that they could represent geofacts.

From the above we conclude that the available magnetostratigraphic data from Italy, France, and Spain indicate that the main earliest

hominin presence in southern Europe occurred sometime during the Matuyama Chron (before the Brunhes–Matuyama boundary at 0.78 Ma but after the Olduvai–Matuyama boundary at 1.77 Ma). Within this broad age window, dates of the two best-dated oldest sites (Sima del Elefante and Gran Dolina) overlap within error resolution in the temporal range between the Jaramillo and the Brunhes–Matuyama boundary (~0.99–0.78 Ma), whereas data from the remaining sites of generic pre-Brunhes–Matuyama boundary age (Fuente Nueva-3, Barranco León, and Estrecho del Quipar) do not contradict the hypothesis of earliest peopling during this age window (Fig. 2). This allowable age window coincides with a most profound climate and faunal turnover known as the late Early Pleistocene revolution, as described below.

### 3. Late Early Pleistocene climate and faunal revolution

Kent et al. (1971) studied ice-rafted detritus in North Pacific deep-sea sediment cores with magnetostratigraphy and found evidence of cooling beginning at about 1.2 Ma and becoming very intense between the Jaramillo subchron and the Brunhes–Matuyama boundary (Chron C1r.1r, 0.99–0.78 Ma), and suggested that this interval probably corresponds to the initiation of mid-latitude glaciations of Europe and North America. Shackleton and Opdyke (1976) analyzed planktonic foraminifera  $\delta^{18}\text{O}$  data from equatorial Pacific core V28-239 with magnetostratigraphy and first identified MIS 22 within C1r.1r as most likely to represent the first major northern hemisphere continental glaciation of Middle Pleistocene character, whereas prior to MIS 22 global climate was characterized by higher frequency (~40 kyr) and lower amplitude glacial fluctuations extending back through the Olduvai subchron. Berger et al. (1993) used planktonic foraminifera  $\delta^{18}\text{O}$  data from ODP Site 806 from the equatorial Pacific and confirmed an abrupt change in global climate variability from ~40 kyr lower-amplitude glacio-eustatic oscillations to ~100 kyr higher-amplitude oscillations between MIS 23 and MIS 22, and introduced the term ‘climate revolution’ to describe this change. Shackleton (1995) used benthic foraminifera  $\delta^{18}\text{O}$  data from ODP Site 677 (SPECMAP) and found a marked change of climate variability similar to that of Berger et al. (1993) with MIS 22 standing out as the first most prominent cold stage of the Pleistocene. Head and Gibbard (2005) adopted for the critical interval under discussion the same ODP Site 677 (SPECMAP) data of Shackleton (1995) and pointed out the existence of a series of discrete cold events from MIS 36 (~1.2 Ma) to MIS 13 (~0.54–0.46 Ma) with MIS 22 judged as the first most profound.

From the above, we see that the marked change to higher amplitude in global climate variability occurred broadly between MIS 36 (~1.2 Ma) and MIS 13 (~0.54–0.46 Ma) (e.g., Head and Gibbard, 2005; Lisiecki and Raymo, 2005), and that within this transition, MIS 22 at ~0.87 Ma stands out, representing the first major northern hemisphere continental glaciation of the Pleistocene (Shackleton and Opdyke, 1976; Berger et al., 1993; Shackleton, 1995; Lourens et al., 2004) (Fig. 3A, B). This climate transition occurs within Chron C1r.1r, the same magnetostratigraphic window that we believe includes the best-dated sites with evidence of the earliest peopling of southern Europe (Figs. 2 and 3C).

It is possible that MIS 22 within the late Early Pleistocene global climate transition caused a critical climate change in Africa, the hominin homeland, as well as in Europe that triggered hominin migrations to southern Europe. For example, rock-magnetic data from Ocean Drilling Program Site 967 south of Cyprus (Fig. 1) revealed sudden increases of hematite-rich aeolian dust from the Sahara since ~0.95 Ma with a noticeable burst in dust production and therefore aridity at 0.87 Ma (MIS 22) (Larrasoana et al., 2003) (Fig. 3D). More recently, Trauth et al. (2009) analyzed published dust flux records from the Arabian Sea, the eastern Mediterranean Sea, and the Atlantic Ocean, and concluded that an increase in aridity started in Africa at ~1.5 Ma and culminated at ~1 Ma. Enhanced aridity during this time

matched a progressive vegetation shift in sub-Saharan Africa from C3 trees and shrubs to arid-adapted C4 grasses between ca 1.5 and 0.7 Ma as evidenced from stable carbon isotope records (Ségalen et al., 2007). At about the same time, the onset of deposition of arid-glacial loess occurred across the lowlands of the northern Black Sea coastal area and the East European plains. Here, magnetostratigraphic studies (e.g., at Roxolany and Khadzhimus near Odessa; Dodonov et al., 2006) place this major facies change mainly in Chron C1r.1r, the reverse polarity interval between the Jaramillo and Brunhes (e.g., Tsatskin et al., 2001; Dodonov et al., 2006; Faustov et al., 2009) (Fig. 3E).

Enhanced aridification in Africa and Eastern Europe during the late Early Pleistocene and notably MIS 22 may have set in motion herds of mammals, possibly including hominins, to more sustainable refugia of southern Europe. Areas of southern Europe like northern Italy or the Apennines of central Italy were also characterized by forest withdrawal and onset of steppe or open vegetation at MIS 22 time (Bertini, 2000; Muttoni et al., 2007). However, climatically favourable refugia located in the southern peninsulas of Iberia, Italy and the Balkans, as well as along the North Africa shores, sheltered a large number of temperate species during Pleistocene glacial periods (e.g., Bennett et al., 1991), and several of these refugia geographically overlap with sites of hominin presence outlined in this study (Carrion et al., 2003; Médail and Diadema, 2009). We should therefore expect to find the first appearance of African and Asian emigrants in southern Europe at about MIS 22 time. An important locality where this prediction can be tested is Leffe in northern Italy (Muttoni et al., 2007). Here, the loess and paleosol levels above a major unconformity correlated to MIS 22 record the first occurrence of *Elephas antiquus* (mammal association #4, Fig. 3F), which is regarded as a taxon that immigrated to southern and western Europe from Africa (Lister et al., 2005; Palombo and Ferretti, 2005; see also below). However, the best locality where the entrance in southern Europe of *E. antiquus* as well as of several other migrant taxa from Africa and Asia has been studied is the Roman Basin of central Italy, typified by the site of Ponte Galeria (Fig. 1). Here, Ambrosetti et al. (1972) described the presence of an unconformity at the base of the Ponte Galeria Formation corresponding to the so-called Cassian erosional phase dated at around 1 Ma from published radiometric dates. More recent paleomagnetic data indicate reverse polarity (late Matuyama) in the *Helicella* clays located immediately above the base of the Ponte Galeria Fm. and containing cold-adapted small mammals and molluscs (Kotsakis et al., 1992), and normal polarity (Brunhes) in the overlying *Venerupis senescens* clays (Kotsakis et al., 1992; Florindo and Marra, 1995). Accordingly, the Cassian unconformity can be correlated to the sea level fall of MIS 22 at ~0.87 Ma (Kotsakis et al., 1992; Florindo and Marra, 1995; Marra et al., 1998; Milli et al., 2004) (Fig. 3F).

The Cassian unconformity marks a turnover from late Villafranchian to middle Galerian faunas, characterized by the appearance of new types of adaptation accompanied by wide-ranging changes in climate and vegetation (Azzaroli, 1983). In particular, the Ponte Galeria FU [as well as the probably equivalent but undated Slivia FU from northeastern Italy (Milli et al., 2004; Palombo and Ferretti, 2005; Raia et al., 2006)] differs from Villafranchian faunas by a general increase in large herbivore richness and a parallel reduction of large predators (Fig. 3F; Palombo and Mussi, 2006), and records the first occurrence in Italy of the African emigrant *E. antiquus*, previously described at Leffe, as well as of *Mammuthus trogontherii* and *Hemibos galerianus* (e.g., Martínez-Navarro and Palombo, 2004; Palombo and Ferretti, 2005; Sardella et al., 2006; Masini and Sala, 2007). Notably, *M. trogontherii* is regarded as a taxon that immigrated to southern and western Europe from Asia and, together with the African emigrant *E. antiquus*, co-existed with before replacing resident populations of *M. meridionalis* (Lister et al., 2005; Palombo and Ferretti, 2005), whereas *H. galerianus* is considered an immigrant from India (Martínez-Navarro and Palombo, 2004).



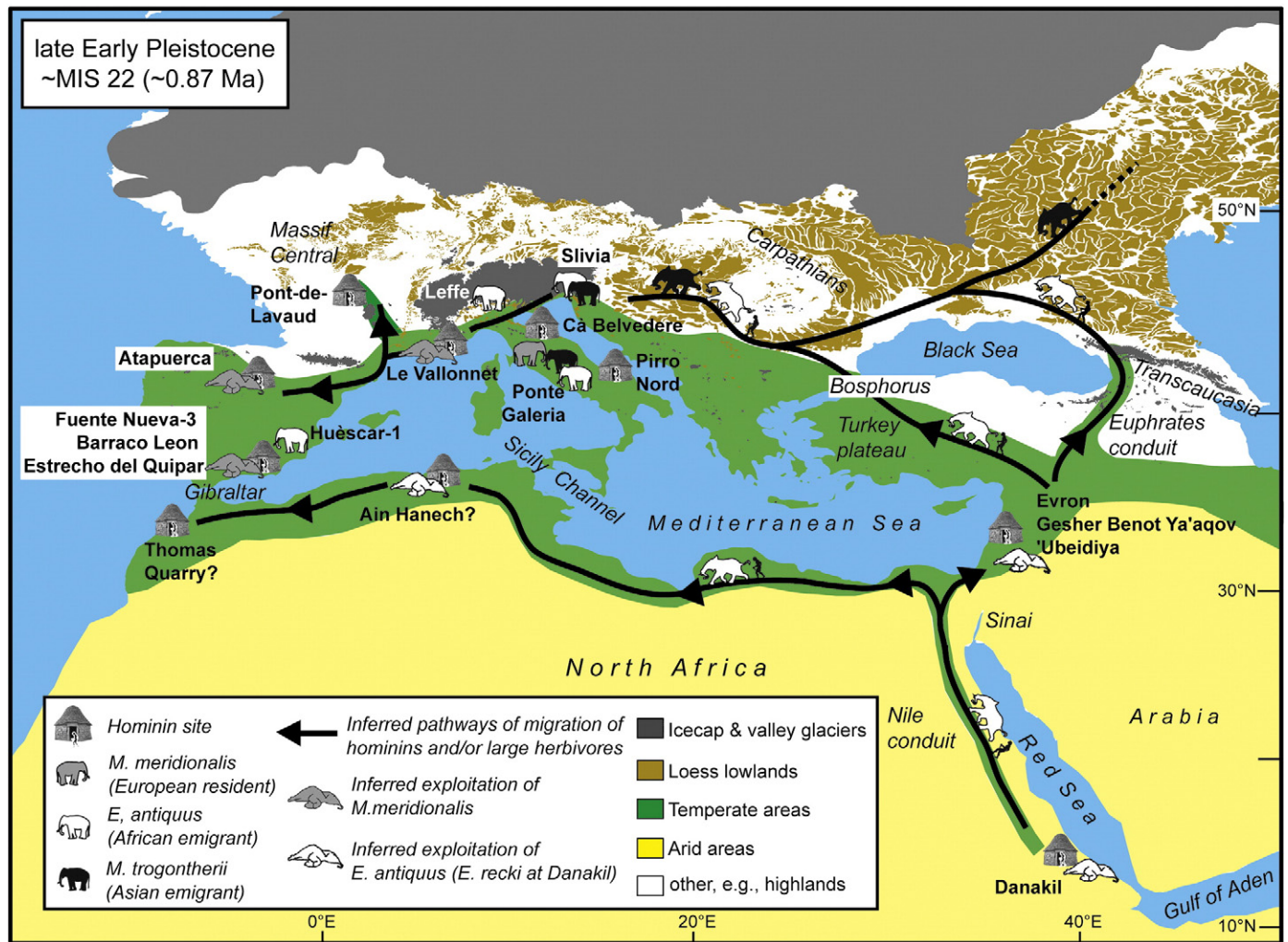
This faunal renewal is recognized elsewhere in southern Europe, e.g., in Greece (Kostopoulos et al., 2007) and Spain at Huéscar-1 (Fig. 1) where *E. antiquus* (van der Made and Mazo, 2001) first occurs in levels dating to before the Brunhes–Matuyama boundary (Gibert et al., 2007). Outside southern Europe, MIS 22-related faunal turnovers are also recognized in northwestern Europe (base of Cromerian Complex Stage), Eastern Europe (base of Tiraspolian mammal Stage of Russia) as well as elsewhere in Russia, as summarized by Head and Gibbard (2005 and references therein). In Eastern Europe, the onset of major loess deposition during the Jaramillo subchron and mainly the subsequent Chron C1r.1r essentially coincides with the Tamasian–Tiraspolian faunal turnover and the associated first occurrence in these regions of the Asian emigrant *M. trogontherii* (Dodonov et al., 2006) (Fig. 3E), which we would place at essentially the same time (together with *E. antiquus*) in southern Europe at Slivia and Ponte Galeria (Fig. 3F).

In conclusion, there are sound arguments and data to consider the spread in Europe of African and Asian emigrants as characterizing the

most important faunal turnover of the late Early Pleistocene, and to place its base (=base of middle Galerian in Italy = base Cromerian in northwestern Europe = base Tiraspolian in Eastern Europe, etc.) at MIS 22 at ~0.87 Ma (Head and Gibbard, 2005 and references therein).

#### 4. Migration pathways

We speculate that profound global environmental changes associated with the late Early Pleistocene climate transition may have driven the migration of large herbivores such as *E. antiquus* from Africa and *M. trogontherii* from Asia into more habitable southern European refugia (Fig. 3E,F) and this closely coincided with the earliest immigration of hominins (Fig. 3C). A large herbivore–hominin migration wave around MIS 22 time may have left traces in the African and European archeological and geological records. The Danakil depression at the northern end of the East African rift system was a likely staging area for this migration (Fig. 4). Indeed, hominin remains have been found there associated with water-rich environments



**Fig. 4.** Paleogeographic scenario of Europe showing possible pathways of migration of large herbivores (notably elephants) and hominins during the late Early Pleistocene at ~0.87 Ma (~MIS 22). Sites exclusively bearing proof of hominin and/or elephant presence straddling this time interval are illustrated. Remains of elephants have been found in the following key localities: *M. meridionalis* (European resident) in level TD6 at Gran Dolina (van der Made and Mazo, 2001), at Fuente Nueva 3 and Barranco León (Oms et al., 2000), and Le Vallonnet (Moullé et al., 2006). *M. trogontherii* (Asian emigrant) at Cúllar Baza 1 (van der Made and Mazo, 2001) and Soleilhac (Moullé et al., 2006). *E. antiquus* (African emigrant) in the Roman Basin, including Ceprano and Fontana Ranuccio (Biddittu et al., 1979; Celletti et al., 2001; Biddittu and Celletti, 2001), at Notarchirico (Piperno and Tagliacozzo, 2001), Soleilhac (Aouadi, 2001), Geshert Benot Ya'aqov and possibly also Evron (with *E. sp.*; O'Regan et al., 2005). The inferred extension of the northern European icecap and of the coeval Alpine-type valley glaciers at MIS 6 (in dark gray; redrawn from Ehlers and Gibbard, 2004) is used as proxy for the MIS 22 ice covers. The distribution of Pleistocene loess deposits (in orange) is from Haase et al. (2007). The oldest loess deposits have been magnetostratigraphically dated in the Eastern European Plain to the late Early Pleistocene (Dodonov et al., 2006). Due to MIS 22 glacial expansion, coastlines are at the -120 meter isobath (Fairbanks, 1989), except for the eastern Po Valley–Adriatic Sea (Kent et al., 2002; Scardia et al., 2006; see Fig. 5) and the Caspian Sea (Ehlers and Gibbard, 2004). In green and yellow are the inferred distributions of, respectively, temperate and arid (Koeppen-like) areas (redrawn from Peel et al., 2007).

(Martinez-Navarro et al., 2004; Abbate et al., 2004) magnetostratigraphically constrained to the Jaramillo–Matuyama boundary (0.99 Ma) (Albianelli and Napoleone, 2004). However, by the time of deposition of the fluvio-deltaic Aro Sand just before the Brunhes–Matuyama boundary (Albianelli and Napoleone, 2004) there is no more evidence of hominins or mammals in general (Abbate et al., 2004). From the Danakil, the most likely route across the Saharan desert barrier was through the Nile Valley (Fig. 4) (Derricourt, 2005; Vermeersch, 2006) whose modern drainage system was apparently structured in the late Early Pleistocene possibly around 0.8 Ma (Said, 1993).

From the southern Mediterranean shores [e.g., Ain Hanech in northern Algeria (Sahnouni et al., 2002, 2004; Geraads et al., 2004) and Thomas Quarry in Atlantic Morocco (e.g., Raynal et al., 2002)], potential migration paths to southern Europe are crossings of the Gibraltar Strait and/or the Sicily Channel but these are considered unlikely routes (Derricourt, 2005; Villa, 2001). The Gibraltar Strait has been open to the Atlantic since the end of the Miocene and even highly fluctuating Pleistocene sea levels would not have substantially affected the ~5 km wide central channel, now 300 m deep (Derricourt, 2005) and experiencing tectonic uplift since at least the late Pleistocene (Gracia et al., 2008). According to Straus (2001), the chronological and archeological data indicate that it is only in the terminal Paleolithic (~11 ka) that a credible case can be made for trans-Gibraltar human contacts. The routes in and out of Iberia are largely over the Pyrenees and occasional claims for hominin and other mammalian dispersal across the Gibraltar Strait have no convincing evidence to support them (O'Regan, 2008). An even less likely migration route was the Sicily Channel, now ~145 km wide, which was submerged (albeit possibly reduced to ~1/2 of its present width) even during maximum Pleistocene low-stands based on evidence of mammal endemism indicating that Sicily acted as an archipelago during the Pleistocene (Villa, 2001; Marra, 2005). Moreover, Villa (2001) has shown that Middle Pleistocene settlement of Italy came from the north and not via Sicily–northern Africa.

More plausibly, hominins and large herbivores migrated from Africa by land via the Sinai corridor (Derricourt, 2005) into the Levant, marked by a convincing hominin presence in the Early Pleistocene at Geshen Benot Ya'aqov (Goren-Inbar et al., 2000), Evron (Ron et al., 2003), and 'Ubeidiya (Opdyke et al., 1983; Martinez-Navarro et al., 2009) (Fig. 4). They may have eventually accessed southern Europe through the Bosphorus, which was at least intermittently exposed during the Pleistocene based on a wealth of geophysical and geological data suggesting that throughout the past two million years, the Black Sea was predominantly a freshwater lake (Ryan et al., 2003). Alternatively, large mammals and hominins may have exploited a route through a paleo-Euphrates conduit into Transcaucasia and, from there, into the lowlands of the northern Black Sea coastal area. Both routes (Bosphorus and Euphrates) seem viable considering that lower Paleolithic tools have been found throughout Turkey including the Marmara region, as well as in the Euphrates river basin (Kuhn, 2002). Notably, most of the fluvial terraces in the Euphrates river basin are interpreted as dating from the late Early Pleistocene onwards, and these terraces often contain lithic artifacts (Demir et al., 2007).

From the lowlands of Eastern Europe or the northern Black Sea coastal area, migration routes were possibly westward along a Danube corridor into the northern Adriatic area and the Po Valley of northern Italy and from there along coastal routes to southern Italy and across the Maritime Alps and the Pyrenees into Spain (Fig. 4). Alternative migration routes to southern Europe passing across Central Europe to the north of the Alpine glaciated area are less favored considering the harsher expected climate closer to the Fennoscandian ice sheet during the prominent cold stage of MIS 22 (~0.87 Ma). It is possibly not until post-MIS 22 interglacials that there is evidence of hominins venturing as far north as Pakefield in the UK

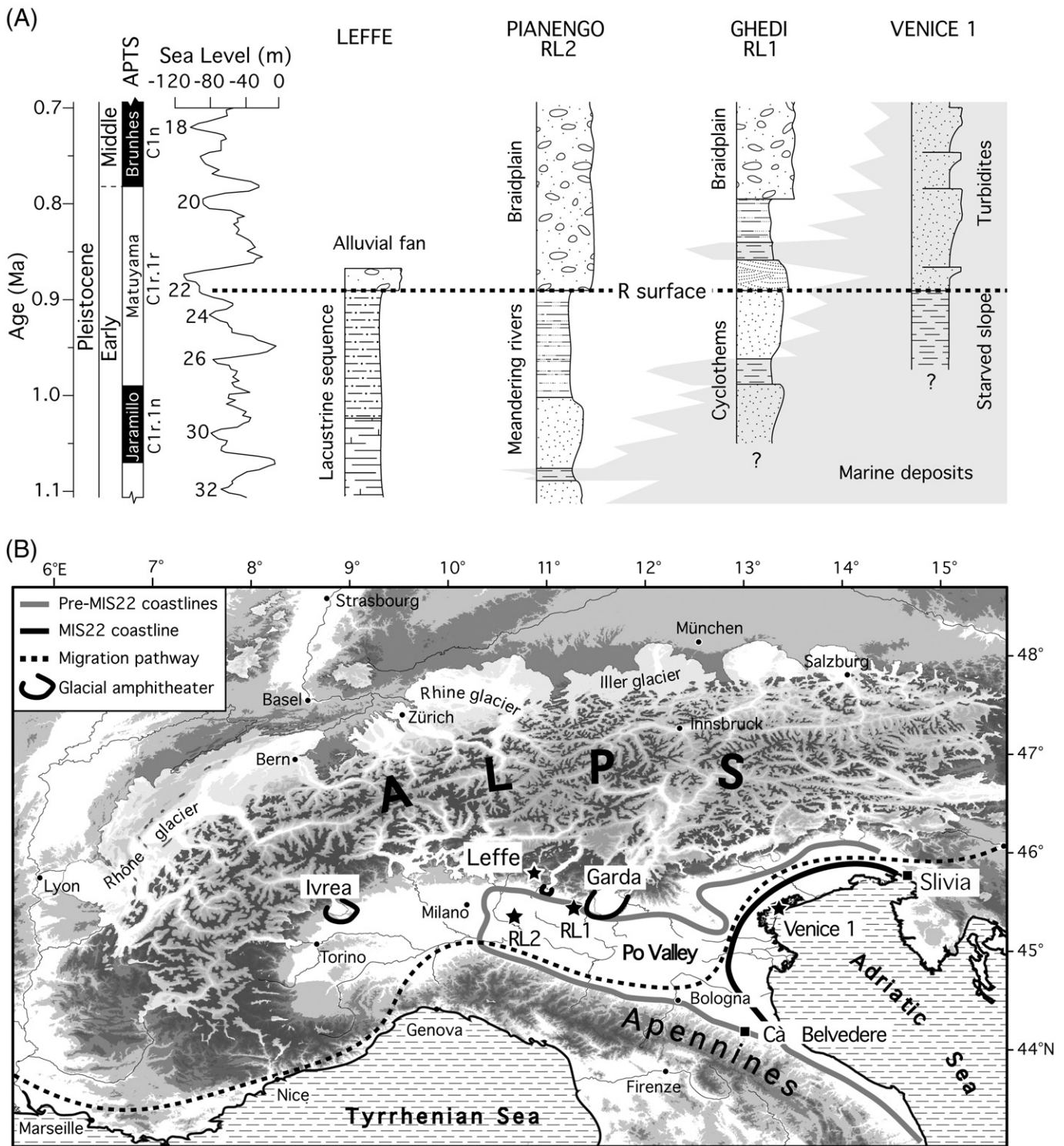
(Parfitt et al., 2005, 2010; Lee et al., 2006). (See 'Note Added in Proof at the end of paper').

It is thus possible that the Po Valley was a viable migration gateway to southern Europe during the late Early Pleistocene. The Po Valley consequently deserves special attention, especially considering the large amount of new data becoming available that bear on its climatic and geologic evolution during the Pleistocene.

## 5. The Po Valley gateway

The Po Valley represents one of the best-studied areas for climate-driven changes in style of deposition occurring at MIS 22 within Chron C1r.1r, when a drastic reorganization of vegetation and fluvial drainage patterns occurred at the onset of major Pleistocene glaciations in the Alps. Enhanced cooling at this time is reflected by a generalized event of forest withdrawal and strong progradation and aggradation of alluvial fan bodies from the Southalpine margin towards the Po Valley. In intermountain basins like Leffe (Fig. 5A,B), this massive pulse of alluvial fan progradation terminated a long history of Early Pleistocene lacustrine sedimentation with a major unconformity at around MIS 22 time (Muttoni et al., 2007). At the foothills of the Southern Alps, these pulses of alluvial fan progradation resulted in valley damming and lake formation (Scardia et al., 2010). More southward in the Po Valley, a major shift from mainly meandering to exclusively braided fluvial systems occurred at this time. This shift in style of deposition is recorded by a regional unconformity termed the 'R surface' that was seismically traced in the subsurface across much of the Po plain and its age constrained magnetostratigraphically in several cores (e.g. Pianengo, Ghedi; Fig. 5A, B) to MIS 22 (Muttoni et al., 2003, 2007; Scardia et al., 2006, 2010) (Fig. 3F). More eastward in the Adriatic Sea, the 'R surface' seems to correlate to the onset of progradation of basinal turbidites onto a previously starved slope setting, occurring (shortly) before the Brunhes–Matuyama boundary in the Venice core (Kent et al., 2002; Massari et al., 2004; Fig. 5A, B). At MIS 22 during Chron C1r.1r, Alpine valley glaciers reached the Po Valley apparently for the first time, as testified by the reverse polarity magnetization of (glacio)lacustrine deposits associated with the early stages of building of the Ivrea (Carraro et al., 1991), Iseo (Scardia et al., 2006), and Garda (Cremaschi, 1987) morainic amphitheatres (Fig. 5B). Increasing rates of erosion during the waxing and waning of major Alpine valley glaciers starting at MIS 22 time (and including the subsequent particularly dry and cold MISs 16, 12, 6, and 2; Kukla and Cilek, 1996) determined also the onset of a long-term phase of isostatic uplift in the southern Alps (Scardia et al., 2006), western and central Alps (Champagnac et al., 2007, 2009), as well as possibly in other glaciated mountain chains of Europe and Asia (Kukla and Cilek, 1996).

In summary, Pleistocene glacial stages starting with MIS 22 at ~0.87 Ma were characterized by enhanced glacier development and glacio-eustatic lowstands, as well as substantial forest withdrawal in the Alpine region. Long phases of persistent low forest cover (steppe-forest at low altitudes), coupled with marked base level glacio-eustatic falls, promoted physical erosion and the progradation of alluvial fans from the Alps and probably also the Apennines (which consequently experienced long-term isostatic uplift) toward the peripheral plains. Here, sediments were redistributed by braided river systems and ended up in the northern Adriatic Sea as basinal turbidites, as observed in the Venice subsurface. One of the main outcomes of these studies is that the Po Valley was largely submerged as far west as Milan during Early Pleistocene lowstands, whereas it was only since MIS 22 at ~0.87 Ma that large stretches of the Po Valley became more persistently exposed. This may have opened possibly for the first time in the Pleistocene viable new migration routes for large mammals and hominins across northern Italy to southern France and Spain in the west (Figs. 4 and 5B).



**Fig. 5.** Correlation of stratigraphic data (A) from the Southern Alps-Po Plain area (B) around MIS 22 (~0.87 Ma) within subchron C1r.1r (0.99–0.78 Ma). (A) At MIS 22 time, the intensification of glacial activity in the Alps triggered the onset of high-energy sedimentation in different orographic and geodynamic settings of the Southern Alps-Po Valley system, e.g., Leffe (Muttoni et al., 2007), Pianengo (Muttoni et al., 2003), Ghedi (Scardia et al., 2006), and Venice (Kent et al., 2002) [time scale of Lourens et al. (2004)]. (B) As a consequence of high-energy fluvial progradation and eustatic lowstand at MIS 22 time, large stretches of the Po Valley became exposed for the first time, thus potentially opening new migration pathways (black line = MIS 22 coastline; dark gray line = nominal pre-MIS 22 coastline; black dashed line = potential migration pathway). The extension of the Alpine valley glaciers during the Last Glacial Maximum is from Ehlers and Gibbard (2004).

**6. Summary and conclusions**

A critical assessment of magnetostratigraphic and/or radiometric age constraints from key early hominin sites from Italy, France and Spain suggests that the main earliest peopling of southern Europe occurred sometime during the Matuyama Chron, before the Brunhes–

Matuyama boundary at 0.78 Ma but after the Olduvai–Matuyama boundary at 1.77 Ma. More specifically, the best-dated oldest sites show temporal ranges overlapping within Chron C1r.1r, between the Jaramillo subchron and the Brunhes–Matuyama boundary (0.99–0.78 Ma), whereas the remainder of the oldest sites do not contradict this time window.

Our preferred timing of the earliest peopling of Europe (0.99–0.78 Ma) may be related to the response of African and southern European climate to the inception of major northern hemisphere glacial oscillations corresponding to MIS 22 during the late Early Pleistocene. The onset of enhanced aridity in the Sahara at ~0.95 Ma with a burst at 0.87 Ma (MIS 22) and the broadly coeval late Early Pleistocene development of extended loess steppes across the Eastern European Plain during the first major advances of the northern European and Alpine icecaps may have set in motion herds of large herbivores, notably *E. antiquus* from Africa and *M. trogontherii* from Asia, towards southern European refugia, and may have consequently motivated the immigration of hominins along with or after them. This follow-the-herd hypothesis, similar to hypotheses put forward by other authors (e.g., Turner, 1999; Arribas and Palmqvist, 1999), but more time-focused within the Pleistocene global climate record, is consistent with the suggestion by Palombo and Mussi (2006) that hominins first inhabited Italy in close temporal contiguity with the renovated middle Galerian faunas characterized by increasing numbers of middle-sized herbivores (and fewer predators).

We attempted to trace potential migration routes from a presumed East African homeland to southern Europe. The most likely route with large herbivores in mind is through the Nile Valley to the southern Mediterranean shores and across the Sinai corridor into the Levant. From the Levant the hominin-large herbivore migration would have proceeded into the Eastern European loess lowlands either across central Turkey–Bosphorous or across the Euphrates conduit, then from Eastern Europe into the Po Valley of northern Italy, which became largely exposed above sea-level for the first time in the Pleistocene at the MIS 22 low-stand; large herbivores and hominins may thence have migrated westward into southern France and Spain.

Three critical hominin sites apparently violate our age model (and possible related causes) of first main hominin immigration to southern Europe during C1r.1r. These are Fuentenueva-3 and Barranco León in southern Spain (Scott et al., 2007) and Pirro Nord in southern Italy (Arzarello et al., 2007), all of which yielded only Mode I lithic tools and have been attributed to the Matuyama before the Jaramillo. Further studies are required at Fuentenueva-3 and Barranco León in order to find the Jaramillo subchron and determine its position with respect to the archeologic levels in a continuous stratigraphic section or core, whereas at Pirro Nord, the current biostratigraphic age attribution of the sparse lithic tools needs to be tested with direct radiometric or magnetostratigraphic age constraints.

The climate-driven herd migration hypothesis predicts that sites containing proof of hominin presence in southern Europe should be associated with middle Galerian immigrant taxa from Africa and Asia. This does not necessarily mean, however, that sites containing proof of hominin presence associated with late Villafranchian taxa should be considered *ipso facto* older than Galerian sites. In fact, the middle Galerian faunal renovation could have taken place diachronously throughout physiographically complex southern Europe (e.g., Italy; Palombo et al., 2003), such that latest Villafranchian faunal relicts (Pirro Nord?) overlapped in time, and hence coexisted in space, with middle Galerian populations. Mammal associations could become quite interesting if independently dated rather than relied upon as accurate dating tools for regional or continental correlations across this critical time interval.

#### Note added in proof

Just published paleomagnetic and paleobotany data from the tool-bearing site of Happisburgh-3 (UK) indicate hominin presence before the Brunhes–Matuyama boundary during either MIS 21 (~0.84 Ma) or MIS 25 (~0.95 Ma) (Parfitt et al., 2010). The younger age attribution is compatible with our model whereby first colonization of Europe occurs at MIS 22 (~0.87 Ma) and subsequent spread including to higher latitudes during the prominent warm stage of MIS 21 or later.

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