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Magnetostratigraphic data on the first colonization of Europe by early hominins during the late Early Pleistocene.

PhD Thesis

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CONTENTS

ABSTRACT

It is generally accepted in the paleoanthropological literature that the colonization of Europe by early hominins, intended as *Homo erectus* derived forms such as *Homo heidelbergensis*, occurred before the last magnetic polarity reversal that is dated back to 0.78 Ma and marks the transition form the Matuyama reversal polarity chron to the actual normal polarity chron known as Brunhes. The still ongoing debate concerns the possibility for early hominins to have firmly settled in Europe before 1 Million years ago. All the European sites presenting proper chronologies put the first convincing evidence of human occupation during the latter part of the Matuyama reverse polarity chron spanning from the top of Jaramillo normal polarity subchron (0.99 Ma) to the base of the Brunhes normal polarity chron (0.78 Ma). It seems therefore plausible that the first stable human residents came to Europe during the latter part of the Matuyama reverse polarity chron. This relatively brief period of time coincided with a major reorganization of the changing environmental conditions in Europe and elsewhere known as the Early late Pleistocene climate Revolution (EPR). The EPR coincided with the onset of the major Pleistocene glaciation in the Northern hemisphere that triggered the modification of the drainage patterns and consequently brought the formation of the modern fluvial systems especially the Danube in Eastern Europe and the Po in Italy. These environmental changes brought to the formation of new habitats characterized by lowlands colonized by grasslands during glacial/interglacial transitions, while steppic loess environments characterized full glacial periods and closed temperate forests full interglacial periods. The EPR caused also a faunal turnover as a consequence to the environmental changes, species adapted to a closed forest environment belonging to the so-called Villafranchian faunal association were substituted with species more adapted to the newly formed environments belonging to the so-called Galerian faunal association. It seems probable that the opening of the Danube-Po getaway constituted a fundamental element for the migrations of these animals and of early hominins to take place from Africa/Levant across the Balkans into southern Europe since MIS 22.

After providing an initial review of the chronology presented for the sites manifesting human occupation of the Mediterranean area we investigated five new sites in order to provide new evidences that will substantiate the hypothesis of the colonization of Europe by early hominins not antecedent the EPR following the Danube-Po migration pathway. The first site is the Arda river section in northern Italy that provides a continuous record of the transition from marine sedimentation typical of the Pliocene-Early Pleistocene to late Early Pleistocene-Holocene continental sedimentation. Even though no human evidences have yet be found in this locality the discovery mammal layer with a mixed Villafranchian-Galerian faunal assemblage just preceding the EPR proves the first contact that occurred between these two faunal associations. The second investigated site is Kostolac, in Serbia, that even thus not revealing any evidence of human occupation, strongly supports the “follow the herd” hypothesis since it yields the first occurrence of the *Mammuthus trogontherii* in the Pannonian region just before the Brunhes-Matuyama boundary at the bottom of a loessic sequence. This suggests that the first income of this species in the

investigated region occurred just after the EPR taking advantage of the Danube-Po gateway. The third presented site is the stratigraphic sequence from the cave of Kozarnika in Northern Bulgaria. Evidences of human occupation of the cave are known throughout the entire stratigraphic sequence as far down as the bottom of the loess deposit that is located between the Jaramillo normal magnetic polarity subchron and the Brunhes normal polarity. The acquired data strongly support the idea that the income of hominins in the investigated region started with MIS 22 along the Danube drainage system from the Black sea into Europe. The fourth investigated site it the Greek site of Megalopolis where an archeological site bearing a specimen of *Elephas antiquus* with slaughtering evidences lies in an alternation between lignite and sediment levels. The Brunhes-Matuyama boundary lies at the bottom of the sequence but there is no evidence yet of human occupation of the area during the critic time lapse for this study. Strong evidence of the connection between the variation in the deposited facies and the glacial-interglacial cycles was observed therefore we dated the archeological site back to ~450 ky. The last investigated site is the deposit of the Prince’s cave near Ventimiglia (Northern Italy), where a preneanderthalian human ilium was found in a complex stratigraphic context. Only normal magnetic polarity, interpreted as the Brunhes chron, was observed throughout the entire sequence that was therefore attributed to the middle Pleistocene. Evidences on the oldest units deposited in the cave jointly with the uplift rates for that region suggest that the cave was probably submerged during the EPR and therefore no human frequentation was possible in this site before MIS 7.

Except for the Prince’s cave deposit, whose age resulted being to young, all the other sites give evidences of the colonization of Europe by early hominins not antecedent MIS 22 following the Danube-Po migration pathway, therefore supporting the central role of the EPR in the first stable peopling of the European continent.

RIASSUNTO

É generalmente accettato nella letteratura paleoantropologica che la colonizzazione dell'Europa da parte dei primi ominidi, intesi come forme derivate dal *Homo erectus*, quali *Homo heidelbergensis*, sia avvenuta prima dell'ultima inversione di polarità magnetica datata a 0.78 Ma che segna la transizione fra il crono a polarità inversa Matuyama e l'attuale crono a polarità normale Brunhes. Il dibattito tutt'ora in atto riguarda la possibilità per i primi ominidi di essersi stabiliti stabilmente in Europa prima di 1 Milione di anni fa. Tutti i siti Europei che presentano delle cronologie appropriate collocano la prima evidenza convincente di occupazione umana durante la porzione finale del crono a polarità inversa Matuyama che va dal tetto de subcrono a polarità normale Jaramillo (0.99 Ma) alla base del crono a polarità normale Brunhes (0.78 Ma). Sembra quindi plausibile che i primi ominidi stabilmente residenti in Europa siano arrivati nella porzione finale del crono a polarità inversa Matuyama. Questo periodo relativamente breve coincise con un importante cambiamento dei climi in Europa e altrove noto come Rivoluzione climatica del tardo Pleistocene Inferiore (EPR). L'EPR coincise con l'inizio delle grandi glaciazioni Pleistoceniche nell'emisfero Nord che innescarono la modifica dei modelli di drenaggio che portarono alla formazione dei moderni sistemi fluviali, specialmente quello del Danubio nell'Europa dell' Est e quello del Po in Italia. Questi cambiamenti portarono alla formazione di nuovi habitat caratterizzati da pianure colonizzate da praterie durante le transizioni fra i periodi glaciali e interglaciali, mentre steppe in cui veniva deposto il loess caratterizzavano gli apici dei periodi glaciali e foreste temperate i gli apici dei periodi interglaciali. L' EPR comportò anche un rinnovo delle faune come conseguenza dei cambiamenti climatici, le specie adatte ad ambienti di foresta fitta appartenenti alla così detta associazione faunistica Villafranchiana furono sostituite da specie più adatte agli ambienti neoformati pertinenti alla così detta associazione faunistica Galeriana. Sembra plausibile che l'apertura del passaggio fra il Danubio e il Po costituì un elemento fondamentale per la migrazione di questi animali e dei primi ominidi che arrivarono dall'Africa e il Levante, attraverso i Balcani, fino all'Europa meridionale a partire dal MIS 22.

Dopo aver fornito una revisione delle cronologie pertinenti ai siti a ominidi nell'area Mediterranea abbiamo investigato cinque nuovi siti allo scopo di fornire nuove prove che vadano a suffragare l'ipotesi di una colonizzazione dell'Europa da parte dei primi ominidi non antecedente l'EPR lungo il passaggio fra il Danubio e il Po. Il primo sito è la sequenza stratigrafica del torrente Arda in Nord Italia che fornisce un record continuo della transizione da sedimenti marini tipici del Pliocene e Pleistocene Inferiore fino al passaggio a sedimenti continentali tipici della tardo Pleistocene Inferiore e dell'Olocene. Nonostante non siano ancora state trovate prove di frequentazione umana in questa località, la scoperta di un livello a mammiferi contenente un'associazione mista di faune Villafranchiane e Galeriane appena antecedenti l'EPR prova il primo contatto avvenuto fra questi elementi faunistici. Il secondo sito indagato è Kostolac, in Serbia, nonostante non fornisca alcuna evidenza di occupazione umana questo sito supporta fortemente l'ipotesi "segui il branco" dal momento che ha fornito il reperto più

antico di *Mammuthus trogontherii* nel bacino Pannonico, appena antecedente il limite Brunhes-Matuyama, a letto di una sequenza di loess. Queste evidenze suggeriscono che questa specie sia giunta per la prima volta nella regione indagare subito l'EPR sfruttando il passaggio fra il Danubio e il Po. Il terzo sito presentato riguarda la sequenza stratigrafica della grotta di Kozarnika nel Nord della Bulgaria. Prove di occupazione umana della grotta sono presenti attraverso l'intera sequenza fino ai piedi di un deposito di loess posizionato fra il subcrone a polarità normale Jaramillo e il crone a polarità normale Brunhes. I dati ottenuti appoggiano fortemente l'idea che l'arrivo dei primi ominidi nella regione indagata sia avvenuta a partire dal MIS 22 risalendo lungo il sistema fluviale del Danubio partendo dal Mar Nero. Il Quarto sito indagato è Megalopolis, in Grecia, dove all'interno di un alternanza fra livelli di lignite e sedimenti terrigeni è presente un sito archeologico contenente un esemplare di *Elephas antiquus* con tracce di macellazione. Il limite Brunhes-Matuyama è stato riconosciuto nella porzione inferiore della sequenza stratigrafica, tuttavia non sono ancora presenti tracce di occupazione umana nell'area durante l'intervallo temporale critico ai fini di questo studio. Si è tuttavia osservata una forte correlazione fra la variazione delle facies deposte e le alternanze fra i periodo glaciali ed interglaciali che sono stati sfruttati per datare il sito archeologico a ~450 ka. L'ultimo sito indagato riguarda il deposito presente nella Grotta del Principe vicino Ventimiglia (Italia settentrionale) in cui è stato trovato un ilio umano preneanderataliano all'interno di un contesto stratigrafico complesso. La successione è stata attribuita al Pleistocene Medio in quanto lungo l'intera successione è stata riconosciuta solo polarità normale, interpretata come relativa al crono Brunhes. Evidenze provenienti dalle unità più antiche del deposito congiuntamente con l'osservazione dei tassi di uplift relativi all'area hanno suggerito che probabilmente la grotta era sommersa durante l'EPR e conseguentemente nessuna frequentazione umana fu possibile fino al MIS 7.

Con l'eccezione del deposito della Grotta del Principe, la cui età è risultata essere troppo recente, tutti gli altri siti indagati hanno prodotto evidenze a favore dell'ipotesi secondo cui la colonizzazione dell'Europa da parte dei primi ominidi non fu antecedente al MIS 22 e sia avvenuta risalendo il corridoio del Danubio e del Po. I dati raccolti vanno di conseguenza a suffragare il ruolo centrale che ha svolto l'EPR nel primo popolamento stabile del continente Europeo da parte dei primi ominidi.

1 - INTRODUCTION

Applying proper techniques to date stratigraphic sequences is a main issue in the determination of the age of any investigated site. This problem intensifies when it comes to hominin sites since the sediment holding the finds is deposited in continental environments where the correlation between different localities is complicated by the rapidly changing depositional facies even over short distances.

Absolute dating methods based on radioisotopes have large uncertainties that can constitute a real problem when it comes to the determination of the proper geochronology of a stratigraphic sequence in which, in a small window of time, several layers are present. A method like ESR calculates the absolute age of some quartz sediments from the moment they get buried. The problem with this kind of dating is that the entire system can be reset if the quartz sediments are exposed to sunlight again and tread a certain distance. If the quartz grains don't travel a sufficient distance it might occur that the system doesn't get reset completely before they get buried again, thus giving an overextimation of the absolute age of the investigated sediments.

A chronology based on biostratigraphy also has problems, the first one is that the dispersal of animal species might vary heavily based on local conditions and on geographical barriers that might prevent the colonization of certain areas by the migrants. Furthermore, the entire chronology based on mammal stratigraphy has been calibrated using magnetostratigraphy, thus, the use of biostratigraphy apart from this second discipline might bring to circular conclusions in the attribution of the age of the sequences.

A method that allows making robust correlations between stratigraphic series deposited in different environments all over the world is magnetostratigraphy. The magnetostratigraphic data allows to assign a sediment to a specific interval of time defined by the magnetic polarity signal this sediment has registered in the moment of its deposition. The combination of the data obtained from the samples collected in a stratigraphic sequence allows to define geological isochrons represented by the surface containing a dated magnetic polarity reversals, which represent a precise moment of geological time.

It is generally accepted in the paleoanthropological literature that the colonization of Europe by early hominins, intended as *Homo erectus* derived forms such as *Homo heidelbergensis,* occurred before the last magnetic polarity reversal that is dated back to 0.78 Ma and marks the transition form the Matuyama reversal polarity chron to the actual normal polarity chron known as Brunhes. Convincing evidences of a stable human occupation of this territory are given by human sites scattered all over the European continent, both in the Mediterranean region like in Spain (Carbonell et al., 1995, Parés et al., 1999) and Italy (Muttoni et al., 2011), but also in northern Europe (Parfitt et al., 2005) and central Europe (Muttoni et al. 2010 and references therein).

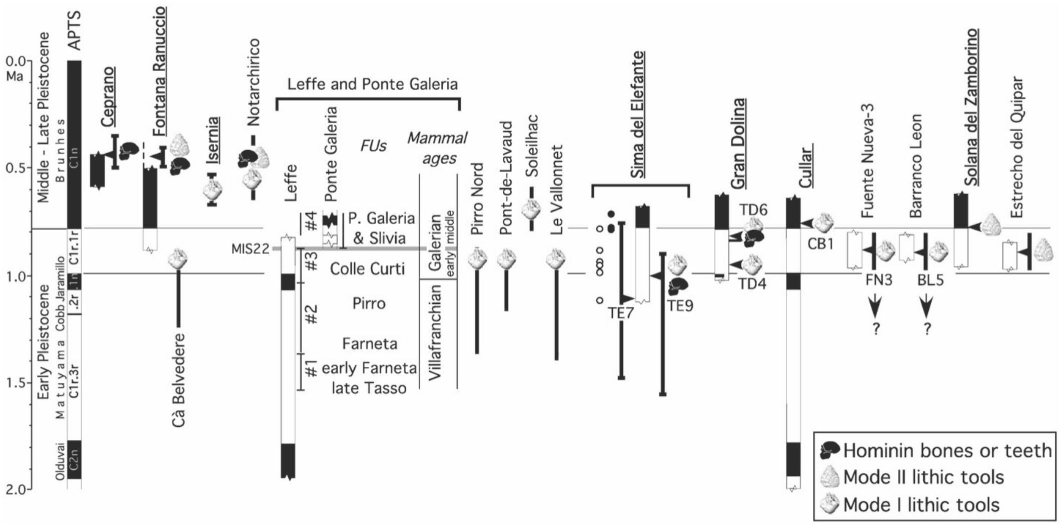

Figure 1 Chronologies based essentially on magnetostratigraphy and/or radiometric age data of key late Early–Middle Pleistocene sites from Italy, France and Spain bearing proof of hominin presence plotted against the astrochronological polarity time scale of the Pleistocene (black is normal geomagnetic 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 complessively attributed to Faunal Units (FU) from late Tasso–early Farneta (#1) to Slivia (#4), and of Ponte Galeria in central Italy. 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, 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 (After Muttoni et al., 2010).

The still ongoing debate concerns the possibility for early hominins to have firmly settled in Europe before 1 Million years ago (Antón et al., 2003; Antón et al., 2004; Baales, 2014; Bar-Yosef, et al., 2011; Ben-Dor, et al., 2011; Carbonell et al., 2008; Dennel, 2003; 2004; 2008; Dennel et al., 1996; Garcia et al., 2013; 2014; Gibert et al., 1998; Güleç et al., 1999; 2009; Landeck et al., 2014; Martínez-Navarro, 2010; Martínez et al., 2010; 2014; Monesi et al., 2016; Muttoni et al., 2011; 2011; 2013; 2014; 2015; Nomade et al., 2014; Palombo et al., 2006; Parés et al., 1999; 2006; 2013; Parfitt et al., 2010; Roebroeks, 2001; Roebroeks et al., 1994; Ron et al., 2001; Sirakov et al., 2010; Toro-Moyano et al., 2013; Made van der, 2011). Considering the Astrochronological Polarity Time Scale (APTS from now on) (Figure 1) it is evident that an age of exactly 1 Million years would put hominin sites during a short normal polarity period known as Jaramillo that lasted form 1.07 to 0.99 Ma, therefore the presence of this normal polarity period in the stratigraphic sequences assumes a very important role in the determination of the age of the hominin sites (Muttoni et al. 2015).

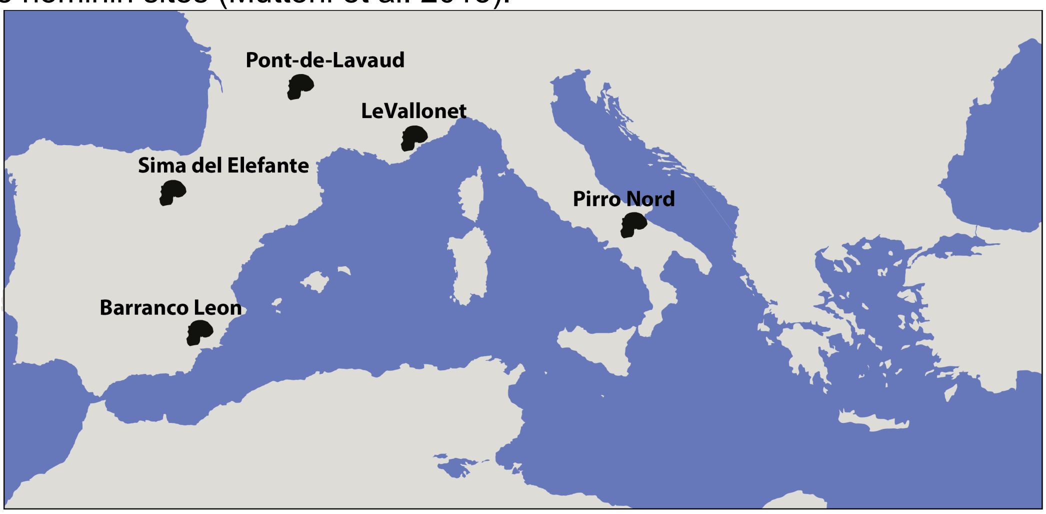

Figure 2 Map of the sites with claimed ages older than 1 Ma

A few sites in Europe seem to associate the evidence of human presence with ages older than 1 Million years, implying a human colonization of this region before the Jaramillo normal polarity period as seen in the western Asia sites such as Dmanisi, dated back to 1.7 Ma (Gabunia et al., 2000; Lorkdipanidze et al., 2007); still, no evidence of this subchron is shown in the european sites, as discussed below.

- The Spanish site of Sima del Elefante (Figure 2) in Atapuerca is a karst fissure filled with sediments (Figure 3) in which many lithic artifacts and a human mandible were found (Carbonell et al., 2008). A unit called Lower Red Unit from Trincera Elefante (TELRU from now on) is characterized with multiple archeological levels associated with two cosmogenic nuclide burial ages of 1.22 ± 0.16 Ma for the specimen coming from the level TE9, and 1.13 ± 0.18 Ma (Figure 1) for the specimen coming from level TE7(Carbonell et al., 2008). Both ages are expressed at 1σ (68%) level of confidence, but when they are expressed at 2σ level, implying a 95% of confidence, the age of the specimen coming from level TE9 would span from 0.9 to 1.54 Ma, and the specimen coming from level TE7 from 0.77 to 1.49 Ma, implying the possibility that both specimens are actually younger than the Jaramillo (Muttoni et al., 2010; Muttoni et al., 2013). This interpretation seems plausible since this section has been sampled for magnetostratigraphic investigation, and the Brunhes – Matuyama boundary (0.78 Ma) was found a few meters above level TE9, whereas there is no evidence of the Jaramillo in the whole sequence (Figure 2) (Parés et al., 2006; Carbonell et al., 2008).

Figure 3 View of the Sima del Elefante archeological site in Atapuerca

- The Italian site of Pirro Nord (Figure 2), located Apulia, southern Italy, is characterized by the finding of few lithic artifacts (Pavia et al., 2012) and was assigned to an age between 1.6 and 1.3 Ma (Figure 4). This hypothesis was based on a biostratigraphic association that assumes that the Pirro Nord faunal unit is older than the Colle Curti faunal unit tentatively associated to the Jaramillo normal polarity period (Coltorti et al., 1998). The Colle Curti type section (Coltorti et al., 1998) presents a normal polarity that has been suggested as an overprint due to a remagnetization as a consequence of diagenetic processes (Muttoni et

Figure 4 View ot the Pirro Nord site

al., 2010). As a consequence, there is no sound evidence for the Colle Curti faunal unit to be ascribed to the Jaramillo; more plausably, this unit would be associated with a reversal polarity attributed to the Matuyama, just as the Pirro Nord faunal unit, implying an age for both faunal units older than the Brunhes – Matuyama boundary (0.78 Ma), but with no elements to put them in a chronological position older than 1 Ma (Figure 1). In addition, the chronology based on micromammal biostratigraphy does not show a clear evidence for an age older than 1Ma for this site since it is based on an unprecise voles phylogeny. In Pirro Nord-13 the arvicolidae *Allophaiomys ruffoi* was found (Lopéz-García et al., 2014). This vole is characterized by undifferentiated enamel on the molars, which means that there is no difference on the thickness of the enamel between the frontal and the rear part of the angles of the teeth. In voles, a condition in which the thickness of the enamel in the rear part of the saltient angles of the teeth is larger than in the frontal part is defined as a "negative" or "mymomian" differentiation and is usually considered to be an archaic feature; on the other hand, a thicker enamel thickness in the frontal part of the saltient angles compared to the rear part is defined as a "positive" or "microtinian" differentiation and is considered to be a derived feature (Heinrich, 1990). The evolution of voles shows a trend that brought them to evolve from a mymomian feature to a microtinian feature, passing through a period characterized by the lack of differentiation in the thickness of the enamel. *A. ruffoi* was used in Pirro Nord-13 to prove that the site was older than TELRU at Atapuerca in Spain, dated to ~1.2 Ma, and where *Allophaiomys lavocati* was found (Cuenca-Bescós et al., 2013) . This second species is characterized by a microtinian differentiation, therefore, it is considered to be derived compared to *A. ruffoi* found in Pirro Nord, so, if the cosmogenic dating of TELRU is correct (~1.2 Ma) it would imply that also Pirro Nord is older than 1.2 Ma (Lopéz-García et al., 2014). The problem with the TELRU dating is that there is no evidence of the Jaramillo normal polarity subchron in the stratigraphic sequence and also the absolute dating obtained shows an error margin wide enough that it would not exclude the possibility for the dated specimen to be younger than the Jaramillo. Concerning the finding of *A. lavocati*, there is evidence of post Jaramillo sites where this species was found. Moreover, there is evidence in extant voles species to display all possible types of differentiation (Martin, 2014), therefore, voles enamel 'chronology' is considered unreliable at least in this case.

- The Barranco León site (Figure 5) in southern Spain is located in the intramontane Gaudix-Basa basin (Figure 2). Some lithic artifacts and a human tooth were found here. Four stratigraphic levels straddling the level from which the human tooth came from were dated through ESR on quartz grains giving an age of ~1.4 Ma (Figure 1) (Toro-Moyano et al., 2013). The inaccuracy of this method in this case is based on the fact that there is no evidence of a plausible source for the sediment far enough from the archeological site to enable the dated grains to be subject to sufficient transport in order to reset the ESR system before final deposition. It is therefore possible that the proposed ESR age overestimates the true age of the layer containing the human tooth (Muttoni et al., 2013). The magnetostratigraphic data show only reverse polarity in the entire section of 30 meters of thickness (Oms et al., 2000; Toro-Moyano et al., 2013). The four ESR dates covered in total 4 meters of the entire thickness of the sequence representing a time interval of 0.7 Ma. If the ESR dates were correct, the level containing the human tooth would be deposited in a reversal polarity period called Matuyama in which two normal polarity subchrons are present: the Olduvai that spans from 1.95 to 1.77 Ma and the Jaramillo that spans from 1.07 to 0.99 Ma. The time lapse occurring between the top of the Olduvai normal polarity period and the bottom of the Jaramillo is exactly 0.7 Ma, therefore, if the ESR dating were correct a magnetic normal polarity would be expected on the top and on the bottom of the dated interval but there is actually no evidence of either of these two normal polarity periods (Figure 1) (Muttoni et al., 2013). The reversal magnetic polarity observed through the entire stratigraphic sequence only allows to define the Barranco León site as older than the Brunhes – Matuyama boundary, but the probable untrustworthiness of the absolute dates obtained with the ESR does not exclude the possibility that also this site is actually ascribable as younger than the Jaramillo normal polarity subchron (Muttoni et al., 2013).

Figure 5 View of the Barranco Leon archeological site in Orce

- The Le Vallonet (Figure 6) site in southern France is situated in the Maritimes Alps and yielded various lithic tools (Bernal et al., 2004; Carbonell et al., 2008) and mammal remains (Figure 2). The faunal assemblage was attributed to the epivillafranchian faunal association and was dated between 0.98 and 0.91 Ma (De Lumley 1988). Two stalagmitic floors enclose the cave deposits; both were dated with ESR giving the ages of 0.91 ± 0.06 Ma for the upper floor and 1.37 ± 0.12 Ma for the lower floor (Figure 1) (Yokoyama et al., 1988). The level III of the cave stratigraphy was subjected to magnetic polarity analysis and a normal polarity was found. The attribution to a specific normal polarity period between the Brunhes, the Jaramillo or the Olduvai is still unclear (Figure 1), therefore the common attribution of the le Vallonet site to the Jaramillo normal polarity period may not be correct because of the lack of convincing magnetostratigraphic data (Yokoyama et al., 1988; Gagnepain, 1996, unpublished doctoral thesis) and more conventional radiometric age attribution.


Figure 6 View of the Le Vallonnet cave's interior

- The France site of Pont-de-Lavaud (Figure 2) in the Massif Central yielded some lithic tools (Despirée et al., 2003; Carbonell et al., 2008). This site was dated through ten ESR analyses on bleached sedimentary quartz that gave an age of 1.07 ± 0.09 Ma (Figure 1) (Despirée et al., 2006; Bahain et al., 2007). This dating would put the Pont-de-Lavaud site as older than the Brunhes-Matuyama boundary, straddling the Jaramillo subchron, but the sites lack magnetostratigraphic data (Figure 1) and more conventional radiometric ages.

As described above, the presence of the Jaramillo in the stratigraphic sequence plays a decisive role in the correct attribution of the age of site. However, the number of hominin sites that contains a record of the Jaramillo in Europe is very limited (Figure 1). These are:

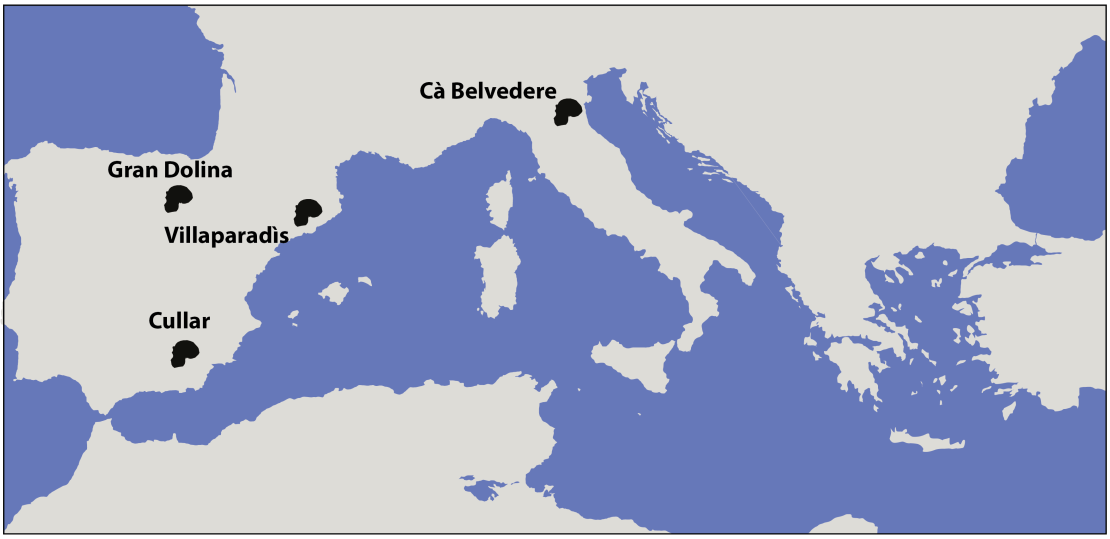

Figure 7 Map of European hominin sites that present a record of the Jaramillo in the chronology

- Cà Belvedere (Figure 7) is a lithic tool site of northern Italy close to Monte Poggiolo. The sequence is constituted of five different sections and a drilled core. The magnetostratigraphy has been correlated with the biostratigraphy through the use of nannofossils for the marine lower part of the sequence. In total two reversals were found, a normal polarity was recognized at the top of the sequence followed downwards by reverse polarity and then by another normal polarity interval. The reversal on top has been interpreted as the Brunhes – Matuyama boundary, while the one at the bottom as the Matuyama – Jaramillo (Figure 1). The sequence lacks the base of the Jaramillo subchron (Muttoni et al., 2011).

- The Cúllar site in Southern Spain (Figure 7) held some lithic tools. In this site, a 80 m thick sequence was sampled and five magnetic polarity reversals were recognized (Graces et al., 1997). Proceeding upwards along the sequence a reverse polarity interval was recorded at the bottom, followed by a normal polarity interval that was attributed to the Olduvai (1.95 - 1.77 Ma), then another reverse polarity interpreted as the middle Matuyama ended in another normal polarity period recognized as the Jaramillo (1.07 - 0.99 Ma) followed by a last reversal polarity interval attributed to the terminal part of the Matuyama followed then by a last normal polarity interval ascribed as the Brunhes (0.78 Ma) (Figure 1) (Graces et al., 1997). The lithic tools were found 2m above the Brunhes – Matuyama boundary implying a post 0.78 Ma age for the archeological site (Gibert et al., 2007).

- Lithic tools and hominin remains were retrieved from the Spanish section of Gran Dolina (Figure 8) at the Atapuerca site (Figure 7). The archeological layer was located just below the Brunhes – Matuyama boundary (Parés et al., 1999; 2013); paleomagnetic samples collected at the bottom of the stratigraphic sequence showed a thin (one sample-based) normal polarity interval that was tentatively attributed to the Jaramillo (Figure 1) (Parés et al., 1999).

Figure 8 View of the Gran Dolina site in Atapuerca

- At the Villaparadìs site in northern Spain near Barcelona (Figure 7) yielded lithic tools (Martínez et al., 2010) from unit EVT7 (Madurell-Malapeira et al., 2010). The magnetostratigraphy showed three clear reversals: a normal magnetic polarity interval at the bottom of the 14m-thick sequence is overlain by a reverse magnetic polarity interval and then by another normal magnetic polarity interval at the top. This polarity sequence was interpreted as a record of the Jaramillo followed upwards by the Matuyama and then by the Brunhes (Figure 1) (Madurell-Malapeira et al., 2010). The tool bearing levels in the EVT7 unit came from the reverse polarity period between the base of the Brunhes and the top of the Jaramillo implying an age in between 0.99 and 0.78 Ma for the layers containing the lithics (Figure 1) as confirmed also by an ESR age on quartz grains of 0.86 Ma (Martínez et al., 2010; 2014; Duval et al., 2014).

What seems clear then is that Europe was inhabited by early hominins before the Brunhes – Matuyama boundary, it is less likely that they were firmly present in Europe before or during the Jaramillo normal polarity subchron. It seems more plausible, from the chronology in our possess, that the first stable human residents came to Europe during the latter part of the Matuyama reverse polarity chron. This relatively brief period of time coincided with a major reorganization of the changing environmental conditions in Europe and elsewhere.

Considering the glacio-eustatic level curves obtained from the analysis of deep sea cores (Berger et al., 1993), it is possible to observe how the typical lower Pleistocene high frequency (~40 ka) and low amplitude oscillations changed to lower frequency (~100 ka) and higher amplitude cycles starting from the reverse polarity period between the top of the Jaramillo (0.99 Ma) and the base of the Brunhes (0.87 Ma) (Head et al., 2005; Lourens et al., 2014; Lisiecky et al., 2005). This time window seems also to correspond to the time lapse that includes the oldest and best dated hominin sites in Europe. MIS 22 (0.87 Ma) also corresponds to the onset of the first major Pleistocene glaciations in the northern hemisphere (Shackleton et al., 1976; Berger et al., 1993; Shackleton 1995; Head et al., 2005).

This major climate transition known as the late Early Pleistocene climate Revolution (EPR from now on) (Berger et al., 1993) implies a variation in the environment of northern Saharian habitats. Since before the EPR, a correlation has been observed between interglacial periods and Mediterranean sapropels, attributed to an increasing of the Nile runoff (Larrasoaña et al., 2013) during summer insolation maxima (Rossignol-Strick, 1983; Larrasoaña et al., 2013). On the African continent, these episodes are referred to as Green Sahara Periods (GSP from now on), which correspond to expansions of the savanna environment throughout the Sahara desert province. In the last 2 million years, there seems to have been more than sixty GSPs during which hominins and other animal species might have crossed the desert to occupy the northern Sahara region and expand eastwards in the middle East and then in Asia (Almogi-Labin, 2011; Zhu et al., 2004; Swisher et al., 1994). Three oxidized sapropels that might correspond to three GSP events, characterized by an increase in Sahara dust production, are present in the EPR age window (Larrasoaña et al., 2003; Trauth et al., 2009).

The EPR coincided also with glacio-eustatic lowstands that triggered the erosion of the Alpine-Dinaride mountain belt, which in turn brought the accumulation of large amounts of detritus in the surrounding plains. This led to the formation of large alluvial plains in the Pannonian-Dacian and Po basins in which thick loessic sequences started to deposit during glacial periods since the EPR. The onset of these major Pleistocene glaciations deeply modified the drainage patterns and consequently brought the formation of the modern fluvial systems especially the Danube in Eastern Europe (Winguth et al., 2000) and the Po in Italy (Muttoni et al., 2003; Scardia et al., 2010).

Before EPR, northern Italy was submerged as far west as the Milan area; with MIS 22, the increased erosional activity and runoff caused the infilling of the Padan marine gulf with sediments (Muttoni et al., 2003; 2010; 2011; Scardia et al., 2006; 2010; 2012). The onset of the modern Po river fluvial system saw a progradation of the Po delta eastwards (Kent et al., 2002; Muttoni et al., 2010; Scardia et al., 2006; 2012) and the formation of the present-day Po plain (Muttoni et al., 2010; 2011).

These environmental changes brought to the formation of new habitats characterized by lowlands colonized by grasslands during glacial/interglacial transitions, while steppic loess environments characterized full glacial periods and closed temperate forests full interglacial periods, as shown by the pollen records from several localities in Europe (Ravazzi et al., 1995; 2005; Tsedakis et al., 2006; de Balieu et al., 2006; 2013). The EPR caused also a faunal turnover as a consequence to the environmental changes. Species adapted to a closed forest environment such as bears and boars typical of the so-called Villafranchian faunal association were substituted with species more adapted to open landscapes such as grassland and savanna environments; these were for example the elephants coming from Africa and mammoths coming from Asia that together with other species define the so-called Galerian faunal association. The new comers were well adapted to the new habitats that appeared in Europe especially during glacial/interglacial transitions since MIS 22, and it seems probable that the opening of the Danube-Po getaway constituted a fundamental element for the migrations of these animals to take place from Africa/Levant across the Balkans into southern Europe since MIS 22 times (~0,87 Ma) (Muttoni et al., 2010; 2011).

The aim of this thesis is to provide new evidences that will substantiate the hypothesis of the colonization of Europe by early hominins not antecedent the EPR following the Danube-Po migration pathway. An initial review of the chronology presented for the sites manifesting human occupation of the Mediterranean area has been initially provided followed by the investigation of five key sites.

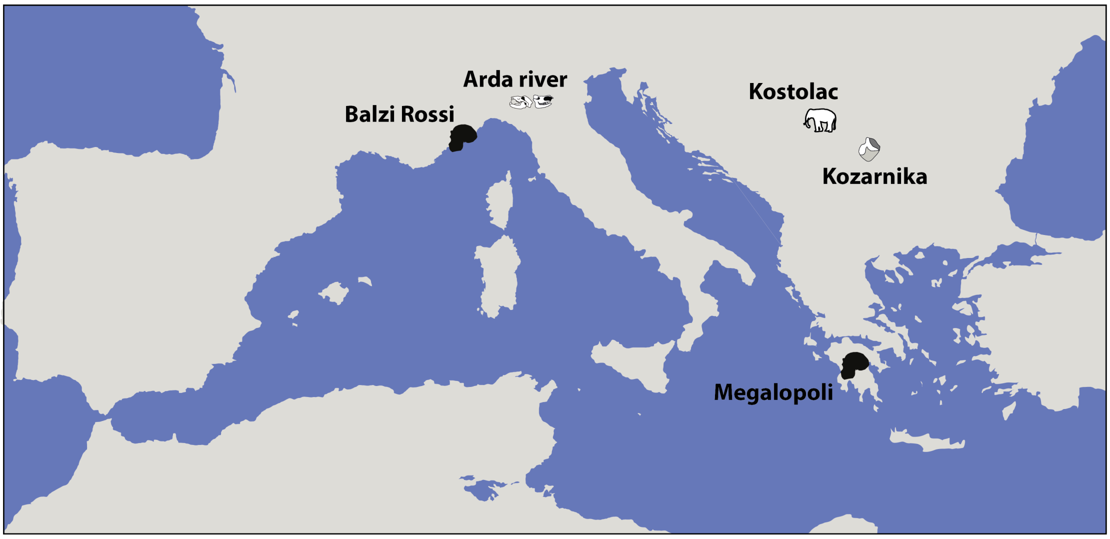

Figure 9 Map of the sites presented in this thesis

- The first site presented is the Arda river section, located in Northern Italy (Figure 9). The investigated series is a 300 m continuous record of the transition from marine sedimentation typical of the Pliocene-Early Pleistocene to late Early Pleistocene-Holocene continental sedimentation (Figure 10). The same stratigraphy was known from other more studied sequences known form the literature such as the nearby Stirone river (Gunderson et al., 2012; 2013; Mary et al., 1993) sequence and the Enza river (Gunderson et al., 2014). The discovery of a mammal layer with a mixed Villafranchian-Galerian faunal assemblage on the top of the sequence suggested moreover the Arda river to be an interesting site for the investigation of the environmental changes that occurred in conjunction with the EPR.

Figure 10 View of the Arda river stratigraphic section

- The second investigated site is Kostolac (Figure 11A) in Serbia (Figure 9). We chose to investigate this site because of the finding of a fully articulated *Mammuthus trogontherii* specimen (Figure 11C) occurred in 2009 (Lister et al., 2012) at the bottom of a loessic (Figure 11B) sequence. The interest aroused by this specimen derives from the fact

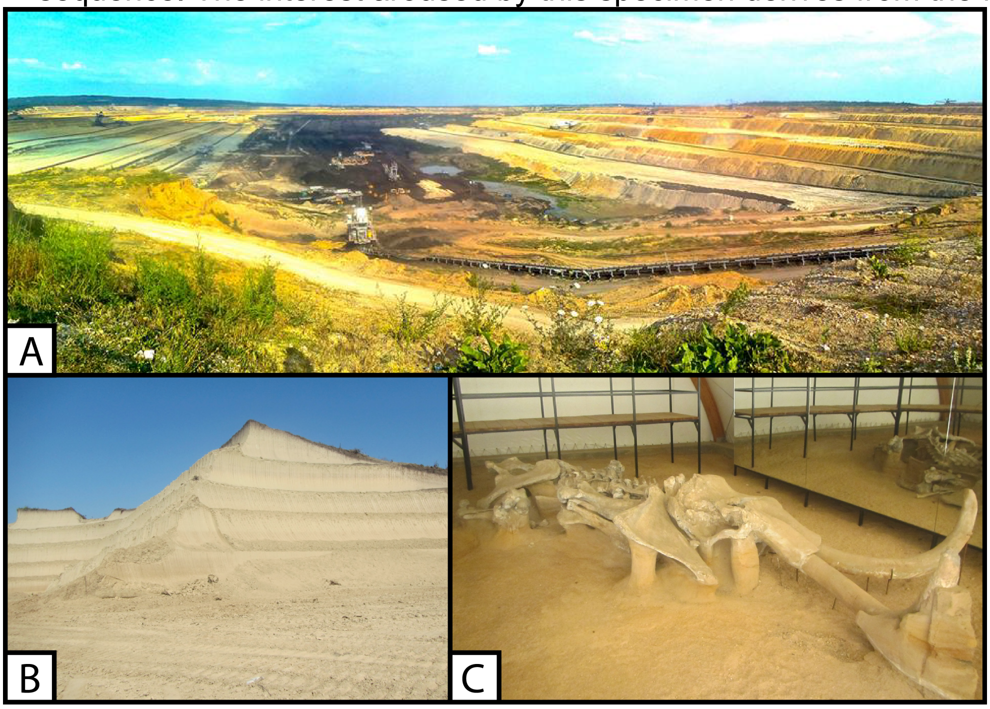

Figure 11 **A** View of the Kostolac site. **B** View of Kostolac's loessic sequence. **C** The *Mammuthus trogontherii* specimen found at the bottom of the loessic sequence in Kostolac.

that it is considered to be one of most ancient *M. trogontherii* found in the Pannonian basin, therefore his incoming in Europe seems to have followed the previously presented Danube-Po getaway hypothesis during the onset of the EPR.

- The third investigated locality is the Bulgarian site of Kozarnika (Figure 9) that consists in a stratigraphic sequence hold in a cave (Figure 12A-B) where archeological surveys (Figure 12B-C) go on since several years providing evidences of human occupation throughout the entire stratigraphic sequence (Sirakov et al., 2010). A previous and preliminary magnetostratigraphic study suggested the presence of magnetic polarity reversal attributed to the Brunhes – Matuyama boundary in the middle of the lithic sequence, but no magnetostratigraphic data were ever presented. These data, together with a chronology based on mammal fossils, would put the bottom of the sequence containing human lithic tools well before the Brunhes – Matuyama boundary and possibly before the EPR. We therefore decided to investigate this site in order to find evidences of the presumed magnetic polarity reversal and to provide a detailed magnetostratigraphic study of the entire sequence.

Figure 12 A External view of the Kozarnika cave. **B** Inner view of the Kozarnika cave and of the archeological site. **C** View of the archeological site in the Kozarnika cave.

- The fourth investigated site is the site of Megalopolis in the Peloponnese peninsula in Southern Greece (Figure 9). This site opens on an active lignite quarry where the stratigraphy is constituted by an alternation of lignite and sediment levels that constitutes the so called Marathousa Formation (Figure 13A). What brought our interest in this site is the finding of a human bone in the reworked material of the Marathousa Formation. A previous magnetostratigraphic study showed

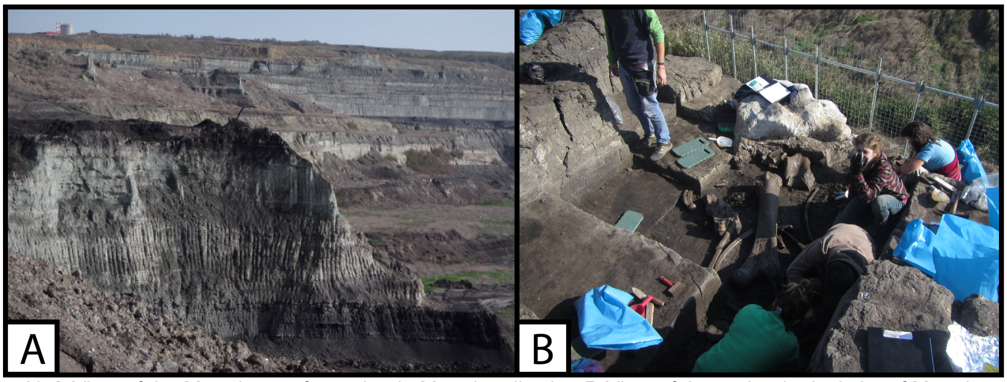

Figure 13 A View of the Marathousa formation in Megalopolis site. **B** View of the archeological site of Megalopolis

evidence of the Brunhes – Matuyama boundary at the bottom of the stratigraphic sequence (van Vugt et al., 2000). A correlation was made that linked the sediment – lignite alternations with the glacial – interglacial cycles but in a controversial and unclear way. An archeological survey (Figure 13B) has recently investigated the site providing evidence of human occupation of the area but no clear chronology was presented, therefore we opted to investigate the magnetic polarity stratigraphy of the sequence and clarify the correlation among the stratigraphic sequence and the climate fluctuations, as well as to try to assign a date to the archeological levels.

- The last presented site is the Prince's cave in the Balzi Rossi complex located in North Western Italy near Ventimiglia (Figure 9). The stratigraphic sequence that was sampled is a vertical cut of breccias inside a cave (Figure 14A) where a human iliac bone was found (Figure 14B) and was determined as *Homo heidelbergensis* (Barral et al., 1968; Lumley de, 1972a,b). The unit in which the find was recovered was attributed to MIS 7 based on an Gamma Ray spectrometry dating (Yokoyama, 1989) and mammal biostratigraphy (Barral et al., 1976; Simone, 2008) but since this chronology is based on magnetostratigraphy and no magnetostratigraphic analysis was ever held in this deposit we chose to go and make a preliminary study hoping eventually to find some reverse polarity that would prove the human frequentation of the area before the Brunhes-Matuyama boundary.

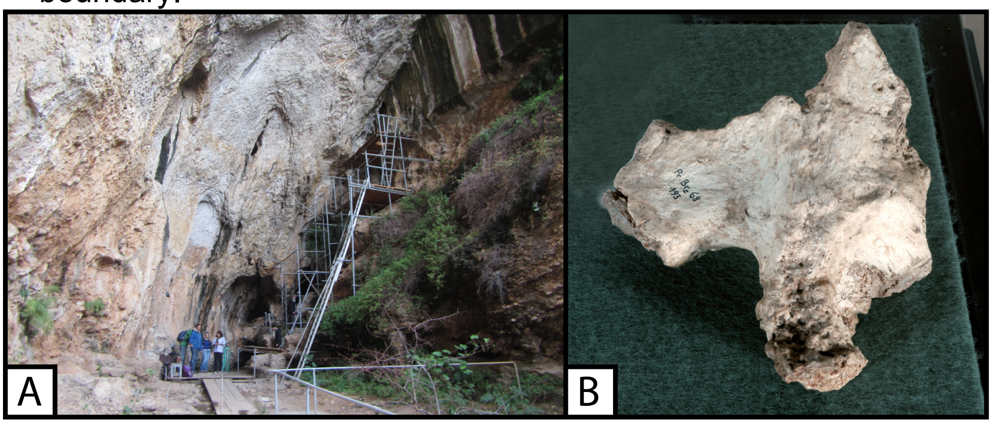

Figure 14 A View of the entrance of the Prince's Cave in the Balzi Rossi complex **B** The *Homo heilderbergensis* iliac bone collected in the breccias of the Prince's Cave stratigraphic sequence

2

MIGRATION OF HOMININS WITHIN MEGAHERBIVORES INTO EUROPE VIA THE DANUBE-PO GATEWAY IN THE LATE MATUYAMA CLIMATE REVOLUTION

My personal contribution in this work has consisted initially in the finding of part of the bibliographic material. Afterwards i focused in the creation of the figures and then i checked the completness and the correctness of the references.

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MIGRATION OF HOMININS WITH MEGAHERBIVORES INTO EUROPE VIA THE DANUBE-PO GATEWAY IN THE LATE MATUYAMA CLIMATE REVOLUTION

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Abstract. We update critical reviews of sites bearing hominin remains and/or tools from Europe (including the Balkans and Greece) and conclude that the only compelling evidence of hominin presence in these regions was after ~0.9 Ma (million-years-ago), bracketed by the end of the Jaramillo subchron (0.99 Ma) and the Brunhes/Matuyama boundary (0.78 Ma) and straddling the climatic late Early Pleistocene revolution (EPR) at the onset of enhanced glacial/interglacial activity that reverberated worldwide. Europe may have become initially populated during the EPR when, possibly for the first time in the Pleistocene, vast and exploitable ecosystems were generated along the Danube-Po Gateway. These newly formed settings, characterized by lowlands with open grasslands and reduced woody cover during glacial/interglacial transitions, represented the closest analogues to the savanna environment to which several large mammals linked with hominins in a common food web were adapted. It was only after stable and vast grassland-savanna environments opened that large mammals (e.g. megaherbivores) could expand into Europe along the Danube-Po Gateway in conjunction with the attached food web to which hominins belonged.

Introduction

The chronology of early hominin presence in Europe has been considerably improved in the last two decades. Proponents of a 'long' chronology (e.g., Bosinski 1992; Gibert et al. 1998; Toro-Moyano et al. 2013; Garcia et al. 2014) expect the earliest evidence from Europe to date to >1 Ma and correlate with the pre- or syn-Jaramillo portion of the Matuyama reverse geomagnetic polarity chron, and possibly be as old as the earliest dates claimed for Asia: ~1.7 Ma at Dmanisi in Georgia (e.g., Gabunia et al. 2000; Lordkipanidze et al. 2007), ~1.8 Ma in Java (Swisher et al. 1994), or ~1.66 Ma in China (Zhu et al. 2003; 2004). Those advocating a 'short' chronology claim instead that Europe was a peripheral peninsula of the Asian landmass, uninhabited for up to a million years after hominins first appeared in Asia. For example, Roebroeks and van Kolfschoten (1994) proposed that the first solid traces of hominin activities in Europe do not occur until around 0.5 Ma, which would lie well within the Brunhes normal geomagnetic polarity chron (<0.78 Ma). However, after new convincing findings from Spain (e.g., Carbonell et al. 1995), Dennell and Roebroeks (1996) and Roebroeks (2001) concluded that this short chronology applies only to Europe north of the Alps and the Pyrenees (although more recent findings at Happisburgh, England, definitely documented Europe colonization up to the boreal zone since the late Early Pleistocene [Parfitt et al. 2005, 2010]), whereas the Mediterranean region, and especially Spain, saw an earlier occupation starting around the end of the Early Pleistocene (late Matuyama Chron, >0.78 Ma). Dennell (2003) examined the archeological evidence and concluded that even if hominins occupied parts of Europe (as well as northern Africa and southern Asia) shortly after 2 Ma, there is little evidence of colonization and permanent settlement in these regions before the Middle Pleistocene (early Brunhes Chron, <0.78 Ma). Antón and Swisher (2004) reviewed multiple lines of evidence that support a long chronology of hominin presence outside of Africa in

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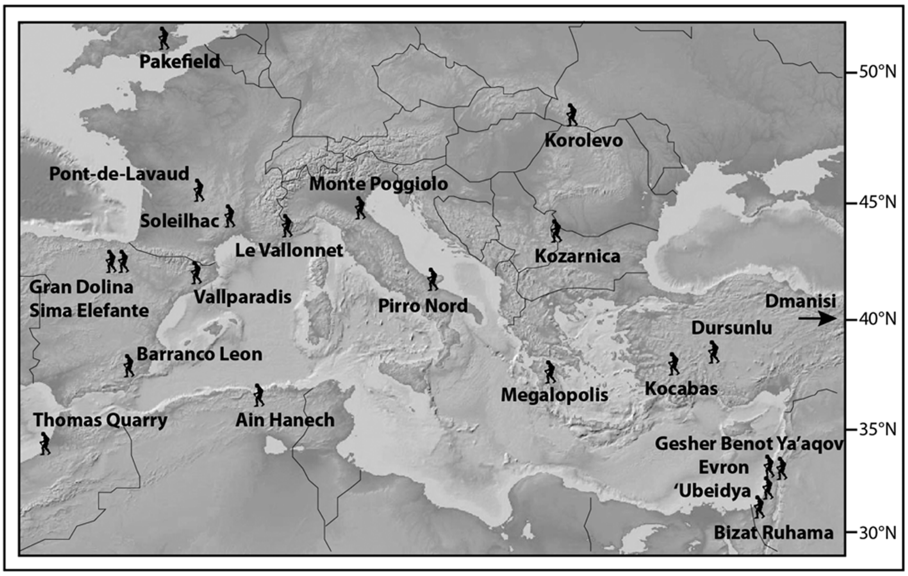

Fig. 1 - Geographic sketch map showing location of hominin sites discussed in the text.

western Asia and Indonesia at as far back as 1.8 Ma and a short (but not so short) chronology of earliest occupation of Europe (e.g., Spain) at ~0.8 Ma.

More recently reported cosmogenic burial dates from Sima del Elefante seem to indicate that hominin occupation in northern Spain was earlier, at around 1.2-1.1 Ma (Carbonell et al. 2008). Moreover, electron spin resonance (ESR) ages on quartz grains, coupled with magnetostratigraphic and biochronologic data, on a human tooth from the Barranco León site would seem to indicate that hominins were present in southern Spain as early as ~1.4 Ma (Toro-Moyano et al. 2013).

From a critique of the Barranco León evidence (Muttoni et al. 2013), we can agree that the precise chronology of earliest hominin presence in Europe remains a complicated and controversial issue especially because the age estimates of several key sites are still very uncertain (e.g., Villa 2001; Roebroeks 2001; Antón and Swisher 2004; Muttoni et al. 2009). In this paper, we expand our previous critical analyses of earliest hominin sites constrained in time by magnetostratigraphy and/or radiometric age data from the circum-Mediterranean region (Muttoni et al. 2010, 2011, 2013), discussing data from key sites bearing hominin remains and/or lithic industries from Europe and including a new critical review of data from the Balkan region, Greece, Turkey, and the Levant. We conclude that the first occurrence of hominins in Europe took place between the Jaramillo subchron and the Brunhes/Matuyama boundary (0.99-0.78 Ma), therefore in between the classic 'long' chronology of earliest peopling of Europe in the pre-Jaramillo Matuyama (>1 Ma; e.g., Garcia et al. 2014), and the classic 'short' chronology of earliest peopling after the Brunhes/Matuyama boundary in the Middle Pleistocene (<0.78 Ma; e.g., Roebroeks and van Kolfschoten 1994). We also improve our previous hypothesis (Muttoni et al. 2010, 2011) on possible paleoclimate causes of hominin migrations during the late Early Pleistocene climate revolution.

Magneto-chronology of early hominin presence in Europe

South and Central Europe

For the chronology of key hominin sites in South and Central Europe (either well-dated or less well-dated but highly cited in the mainstream literature) (Fig. 1), we summarize key elements of the critical review of Muttoni et al. (2010, 2011, 2013), including in the selective magnetochronology framework of Fig. 2 only sites with reliable and documented (and accessible) magnetostratigraphy.

Sites in Italy older than the Brunhes/Matuyama boundary are Cà Belvedere in northern Italy and Pirro Nord in southern Italy (Fig. 1). Cà Belvedere was dated to ~0.85 Ma, between the Jaramillo and the Brunhes, based on magnetostratigraphic data buttressed by marine biostratigraphic control from interfingering strata (Muttoni et al. 2011) (Fig. 2). Pirro Nord yielded only reverse magnetic polarity, indicating a pre-Brunhes age (>0.78 Ma) (Pavia et al. 2012); its current age attribution of ~1.7-1.3 Ma is based on mammal biostratigraphy (Pavia et al. 2012). The age of the Pirro faunal unit is strongly dependent on the assumption that it is older than the Colle Curti faunal unit attributed to the Jaramillo (Coltorti et al. 1998). However, the normal polarity interval in the Colle Curti section attributed to the Jaramillo occurs in a clayey interval rich in organic matter and iron sulphides, which are magnetically unstable and frequently of diagenetic origin (e.g., Roberts & Weaver 2005), whereas in the bracketing more sandy layers bearing magnetite, a normal polarity overprint had to be removed before higher unblocking temperature component directions of reverse polarity were revealed (Coltorti et al. 1998). This lithological and mineralogical dependence of magnetic polarity and the likely presence of diagenetic overprinting raise doubts that the purported Jaramillo is real and could instead represent a recent normal polarity overprint. Pending a reanalysis of the section (in progress), we maintain that in the absence of a clear Jaramillo, both the Colle Curti and the Pirro faunal units are, so to speak, 'lost in the Matuyama', without any meaningful numerical age attached other than older than 0.78 Ma.

In Spain, there is compelling magnetostratigraphic evidence of hominin presence before the Brunhes/Matuyama boundary, e.g., at Barranco León (Toro-Moyano et al. 2013), Gran Dolina (Pares and Perez-González 1999; Pares et al. 2013), Sima del Elefante (Carbonell et al. 2008), and Vallparadís (Martinez et al. 2010, 2014) (Fig. 1). At Vallparadís near Barcelona, lithic elements with claimed man-made 'Oldowan-like' features (see Garcia et al. 2013 for a description) have been retrieved from levels constrained to a time interval of reverse polarity comprised between the top of the Jaramillo (0.99 Ma) and the base of the Brunhes (0.78 Ma), and are associated with an average age of 0.83 Ma based on ESR-U/series dating of two equine molars and OSL dating of four quartz grain samples (Martinez et al. 2010, 2014). Martinez et al. (2014) attempted to apply vole clock chronology to assign an age of ~0.98-0.95 Ma to archeological level 10, which would then fall immediately after the Jaramillo. Martin (2014) illustrated that the vole clock method can hardly yield the level of accuracy implied by Martinez et al. (2014) at Vallparadís (and, for similar reasoning, at Fuente Nueva 3 and Barranco Lèon as implied by Lozano-Fernández et al. [2014]). In any case, the Vallparadís site remains at present probably the best magnetostratigraphically constrained site in Spain with the archeological levels falling between the top of the Jaramillo (0.99 Ma) and the base of the Brunhes (0.78 Ma) (Fig. 2). In the framework of a well-established pre-Brunhes and post-Jaramillo chronology of first hominin presence in Spain, there is in our opinion (see also Muttoni et al. 2010) no compelling evidence of hominin presence before (or even during) the Jaramillo, including the human tooth level from Barranco León, whose age attribution to ~1.4 Ma (Toro-Moyano et al. 2013) was recently criticized (Muttoni et al. 2013), and level TE9 from Sima del Elefante at Atapuerca (Carbonell et al. 2008) with cosmogenic burial age estimates that at 2s level (95% confidence) would not preclude that hominin occupation at Sima del Elefante occurred between the Brunhes/Matuyama boundary, which was found a few meters above level TE9, and the Jaramillo, which was not found in the section despite repeated and detailed sampling (Parès et al. 2006; Carbonell et al. 2008).

Hominin sites in France claimed to be older than 1 Ma (Soleilhac, Le Vallonnet, Pont-de-Lavaud, as well as additional sites in the Massif Central and Haute-Loire) typically lack convincing chronology (and sometimes even convincing evidence of human presence) (see critical review and discussion in Muttoni et al. 2010, 2011, 2013). The Le Vallonnet site (Fig. 1) deserves particular mention because it is frequently attributed to the Jaramillo (see for example Toro-Moyano et al. 2013), evidence of which is, however, very elusive. Yokoyama et al. (1988) reported normal polarity directions that they interpreted as pertaining to either the Brunhes or the Jaramillo or the Olduvai, whereas Gagnepain (1996) provided inconclusive paleomagnetic data, which did not allow establishing a clear magnetic polarity for the succession.

In the absence of convincing evidence of Untermassfeld as a Lower Paleolithic site (Baales 2014 vs. Landeck and Garcia 2014), the northernmost tool-bearing site in Europe is Happisburgh (UK; Fig. 1) where sediments are characterized by reverse magnetic polarity attributed, in conjunction with mammal biostratigraphic considerations, to the Matuyama after the Jaramillo and before the Brunhes (both not found), that is to say, to a time interval comprised between 0.99 and 0.78 Ma (Parfitt et al. 2010).

Southeastern Europe (Balkans and Greece)

The Balkan region is a key area for the exchanges between Europe and the Asian and African continents but none of the hereafter discussed sites are thus far provided with reliable and documented (and accessible) magnetostratigraphy that would make them part of the selective magnetochronology framework of Fig. 2.

Korolevo

This site is located in Ukraine along the Tisza River near the border between Hungary and Rumania (Fig. 1). The stratigraphy of the site, discovered in 1974 in a stone quarry, consists of 14 m of loess with seven different paleosols overlying fluvial deposits (Koulakovska et al. 2010). The Brunhes/Matuyama boundary was placed at the base of the loess sequence above the lowermost paleosol (Koulakovska et al. 2010; Stepanchuk et al. 2013), but we could not obtain information on the analytical data used to obtain polarity stratigraphy from the cited references in Russian. The earliest human presence there is testified by the recovery of Mode I (Oldowan) tools coming from two levels in the lower part of the succession, reportedly bearing normal overlying reverse polarity (Stepanchuk et al. 2013; Koulakovska et al. 2010).

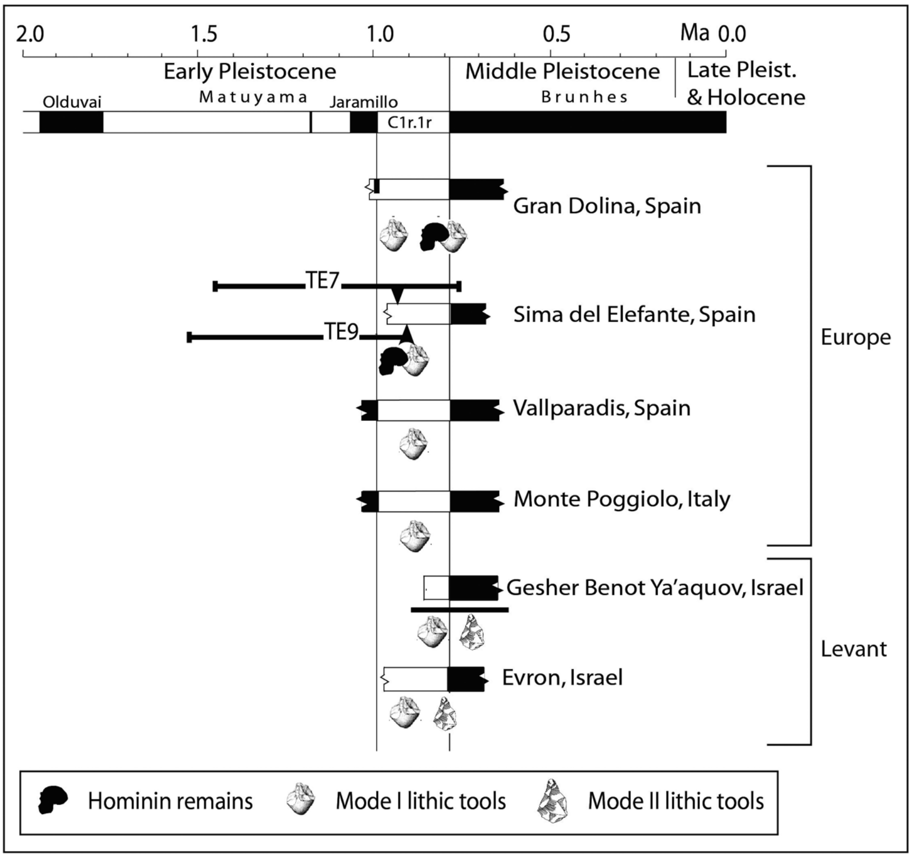

Fig. 2 - Our preferred interpretation of evidence for the earliest human occupation of Europe and at the gates of Europe in the Levant with respect to the astrochronological polarity time scale (APTS) (Lourens et al. 2004). Oldest key hominin sites with reliable magnetostratigraphy tend to occur within the reverse polarity interval between the Jaramillo and the Brunhes (0.99 to 0.78 Ma). Europe: Gran Dolina (Pares and Perez-González 1999; Pares et al. 2013), Sima del Elefante (Carbonell et al. 2008; with cosmogenic burial ages from levels TE7 and TE9 expressed at 2s level; Muttoni et al. 2013), Vallparadís (Martinez et al. 2010), Monte Poggiolo (Muttoni et al. 2011). Gates of Europe: Gesher Benot Ya'aqov (Goren-Inbar et al. 2000), Evron (Ron et al. 2003). Other sites with magnetostratigraphies that are debated or poorly documented or inaccessible that are discussed and referenced in the text (but not shown in the figure) include Soleilhac, Le Vallonnet, Pont-de-Lavaud in France, Kozarnica in Bulgaria, Korolevo in Ukraine, Megalopolis in Greece, Dursunlu in Turkey, and 'Ubeidyia in Israel, whereas Erk-el-Ahmar in Israel and Kocabas in Turkey are excluded because the hominin levels could not be securely traced into the magnetostratigraphic profiles. Other sites with valuable (and well illustrated) but incomplete (single polarity only) magnetostratigraphies are also provisionally excluded from this summary figure: Bizat Ruhama in Israel, Pirro Nord in Italy and Happisburgh in the U.K.; see text for references.

Kozarnica

This site is located in the northwestern part of the Lower Balkans, in the Danube plain of Bulgaria (Fig. 1). Human artifacts from different periods and industries were found inside a 210 m-long cave (Sirakov et al. 2010). The lower levels with lithic tools (from bottom to top, layers 13, 12, 11c and the basal part of 11b) were targeted for magnetostratigraphy. According to preliminary data, for which no analytical information was provided (Sirakov et al. 2010), sediments down to the middle part of layer 11b are characterized by normal polarity magnetization interpreted as a record of the Brunhes Chron; low magnetic inclination values in the lower part of layer 11b have been tentatively interpreted as indicating transition to reverse polarity of the Matuyama Chron but problems of consolidation of blocks from the lower part of the sequence (i.e., from underlying levels 11c-13) did not allow to retrieve a paleomagnetic signal (Sirakov et al. 2010).

Chronologic assessment was also supported by mammal biochronology. Using a statistical (probability) approach, the archeological layers were attributed to Mammal Neogene/Quaternary Zone (MNQ) 17 for layer 13, MNQ 18 for layer 12, and MNQ 19 for layers 11c and 11b (Sirakov et al. 2010). Sirakov et al. (2010) then concluded in favor of an age of 1.6-1.4 Ma for the earliest hominin evidence at Kozarnica. According to $^{40}Ar/^{39}Ar$ radiometric age assessments on key mammal sites in France, MNQ 17 is dated to well in excess of 2 Ma and MNQ 18 broadly corresponds to the Olduvai chron (1.95-1.78 Ma) (Nomade et al. 2014). Thus the MNQ 17-18 biochronologic attribution is in contrast with the (preliminary and partial) magnetostratigraphy and the 1.6-1.4 Ma age proposed by Sirakov et al. (2010). The Gelasian MNQ 17 age would make Kozarnica an outstanding outlier in hominin chronology with an age of > 2 Ma, i.e. older by as much as 1 Myr than any other dated site in Europe and, more in general, older than virtually all known hominin evidence outside Africa. Additional data are required in order to better assess the chronology of the Kozarnica cave infill and confirm if the lower archeological levels with lithic tools predate the Brunhes/Matuyama boundary.

Megalopolis

The Megalopolis basin is an intermontane depression located in the Peloponnesus, Greece (Fig. 1). A single human tooth was found in the early 1960's

(Harvati et al. 2009) in reworked material attributed to the Marathousa Member of the Choremi Formation, comprised of lacustrine muds intercalated with lignite seams (Okuda et al. 2002; Harvati et al. 2009; Tourloukis and Karkanas 2012 a, b). A magnetostratigraphic study was performed by Van Vught (2000) on outcropping sections of the Marathousa Member. The results showed an upward transition from reverse to normal polarity interpreted as the Brunhes/Matuyama boundary, in agreement with the biostratigraphic data based on micro- and macro-mammals such as *Hippopotamus antiquus*, *Praemegaceros verticornis*, *Pliomys* aff. *episcopalis*, *Mimomys* aff. *savini*, and *Mus spretus* (Tourloukis and Karkanas 2012 a, b). Unfortunately, it has not been possible to relocate the human tooth in the stratigraphic sequence studied by Van Vught (2000) (Tourloukis and Karkanas 2012 a, b); a new magnetostratigraphic investigation of the human tooth-bearing sequence is in order.

Summary of magneto-chronology of early hominin sites in Europe

Considering all the uncertainties and ongoing controversies (Muttoni et al. 2010, 2011, 2013, this study), we conclude that at present the best available data as summarized in Fig. 2 seem to indicate (or do not contradict) a vision of earliest hominin main presence in Europe between the top of the Jaramillo subchron (0.99 Ma) and the Brunhes/Matuyama boundary (0.78 Ma); that is to say, the European region, including the Balkans and Greece, was hominin-free prior to ~0.9 Ma. Although Turkey and the Levant could have been inhabited earlier (see below), our interpretation on the magnetochronology of earliest occupation of Europe starting at ~0.9 Ma lies in between the classic 'long' chronology of earliest peopling of Europe in the pre-Jaramillo Matuyama (>1 Ma; e.g., Garcia et al. 2014; see also Toro-Moyano et al. 2013 vs. Muttoni et al. 2013), and the classic 'short' chronology of earliest peopling after the Brunhes/Matuyama boundary in the Middle Pleistocene (<0.78 Ma; e.g., Roebroeks and van Kolfschoten 1994). We stress that within the broad magnetochronological framework indicated above, subtle age differences (on the order of ~100 ky) between sites in southern Europe and sites in central Europe could exist, but that these differences are at present difficult to resolve with the applied numerical age methods (e.g., magnetostratigraphic, ESR, cosmogenic isotopes).

We review now how this chronology of earliest hominin presence in Europe can be related to key climatic events that occurred globally in the late Early Pleistocene.

Pleistocene climate variability

Expanding previous considerations (Muttoni et al. 2010), the reasons hominins first migrated to Europe at ~0.9 Ma may be linked with Pleistocene climate variability and associated environmental and ecological changes. High frequency (~40 ky) and low amplitude glacio-eustatic (climatic) oscillations characterized the Early Pleistocene whereas lower frequency (~100 ky) and higher amplitude oscillations have dominated since the Middle Pleistocene (e.g., Berger et al. 1993). The transition to higher amplitude climate variability occurred in the late Early Pleistocene between the Jaramillo subchron (0.99 Ma) and the Brunhes/Matuyama boundary (0.78 Ma) (e.g., Head & Gibbard 2005; Lourens et al. 2004; Lisiecki & Raymo 2005) (Fig. 3A, B), the same magnetochronologic window that we believe includes the best-dated sites with evidence of earliest peopling of Europe (Fig. 2). Within the transition, marine isotope stage (MIS) 22 at ~0.9 Ma represents the first major northern hemisphere continental glaciation of the Pleistocene (Shackleton and Opdyke 1976; Berger et al. 1993; Shackleton 1995; Head and Gibbard 2005) (Fig. 3A, B). This major climatic transition is hereafter referred to as late Early Pleistocene Revolution (EPR) that substitutes for the often-used term Middle (or mid-) Pleistocene revolution (e.g., Berger et al. 1993) in deferrence to modern geologic time-scales in which the base of the Middle Pleistocene is placed at the Brunhes/Matuyama boundary at MIS 19 (Head and Gibbard 2005).

Larrasoaña et al. (2013) established a link between Mediterranean sapropels, traditionally attributed to increased Nile (or similar fluvial system) runoff during summer insolation maxima (Rossignol-Strick 1983), and recurrent humid episodes in North Africa – the so-called green Sahara periods (GSPs) – with savanna expansion throughout most of the desert. The sapropel-based GSP record was shown to be relatively continuous throughout the Pliocene and Pleistocene (Larrasoaña et al. 2013) (Fig. 3C), with only one apparent gap characterized by three oxidized sapropels/possible GSPs broadly occurring during the EPR from ~0.9 Ma to ~0.7 Ma (Larrasoaña, personal communication to GM; Fig. 3C), which temporally coincides with an a step-increase in Sahara dust production as revealed by data from Ocean Drilling Program (ODP) Site 967 (Larrasoaña et al. 2003; Trauth et al. 2009) (Fig. 3D). Our point here is that there seems to have existed as many as 63 GSPs since 2 Ma during which hominins and other mammals could have crossed the Sahara desert barrier and migrated back and forth from/to the Levant (Almogi-Labin 2011) as well as China (Zhu et al. 2004) and southeast Asia (Swisher et al. 1994), but

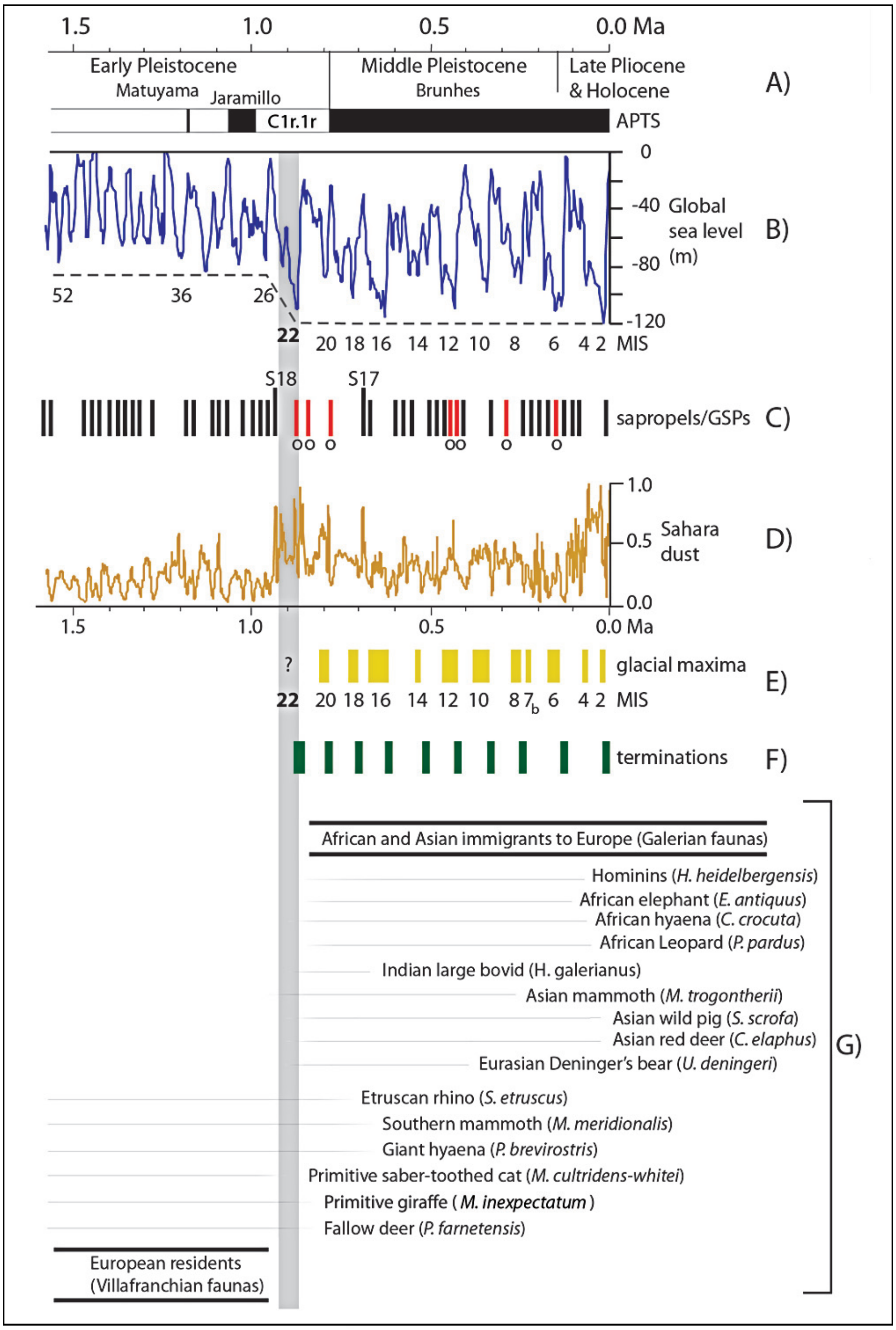

Fig. 3 - A) Astrochronological polarity time scale (APTS) (Lourens et al. 2004) as framework for correlation of B) Pleistocene climate variability as revealed by benthic oxygen isotope data (Shackleton 1995) scaled to the glacio-eustatic drop at the last glacial maximum time (Fairbanks 1989); C) the sapropel-based Green Sahara Period (GSP) record of Larrasoaña et al. (2013; "o" marks represent oxidized sapropels/possible GSPs); D) Sahara dust production as revealed by data from ODP Site 967 (Larrasoaña et al. 2003; Trauth et al. 2009); E) development of loess sequences with steppic vegetation associated with glacial maxima in Europe and the Black Sea area (Cremaschi 1987; Sartori et al. 1999; Dodonov et al. 2006; Fitzimmons et al. 2012; Ujvari et al. 2014; Jipa 2014), and F) main glacial/interglacial transitions characterized by the occurrence of grassland-savanna environments (grasslands or open woodlands; Leroy et al. 2011; de Beaulieu et al. 2013) in the Danube-Po Gateway, which we suggest were exploited for migrations into Europe by hominins and other mammals according to our revised migrate-with-the-herd hypothesis of first colonization of Europe during the Early Pleistocene climate revolution (EPR) centered at ~0.9 Ma (represented by vertical gray band). Panel G is range chart of large mammals in Europe showing the most representative Galerian taxa that entered Europe from Africa or Asia during the EPR at ~0.9 Ma that largely replaced Villafranchian (European resident) taxa (essentially from Van der Made 2011; Masini & Sala 2007).

apparently not according to our critical review until much later into Europe.

The Levant and Turkey: a staging area for hominin expansion into Europe at ~0.9 Ma?

The Levant and Turkey represent a natural staging area for the first hominins on the way to Europe at ~0.9 Ma and to Asia perhaps even earlier. In the Levant, the sites of Gesher Benot Ya'aqov and Evron in Israel (Fig. 1) yielded Mode II (Acheulean) lithic tools from levels just below a relatively well documented magnetic polarity transition interpreted as the Brunhes/Matuyama boundary (Goren-Inbar et al. 2000; Ron et al. 2003); these sites are included in our selective chronology of earliest hominin presence at the gates of Europe (Fig. 2). Additional celebrated sites discussed below ('Ubeidiya, Erk-el-Ahmar, and Bizat Ruhama in Israel; Kocabas and Dursunlu in Turkey) are provided with chronologies that would place them in the Early Pleistocene, well before the Brunhes/Matuyama boundary, but lack – in our opinion – sufficient numerical age estimates to place them relative to the Jaramillo or Olduvai subchrons.

The site of 'Ubeidiya in the Jordan Valley (Fig. 1) yielded Mode II (Acheulean) lithic tools from levels of reported reverse polarity attributed (although the magnetics data were not otherwise described) to the Matuyama Chron (Opdyke et al. 1983). Two short normal magnetic polarity intervals were later reported to be found in the Fi member and assigned to the Cobb Mountain and Gilsa subchrons (at 1.18 Ma and 1.57 Ma, respectively; Lourens et al. 2005; Singer 2014) but the results are

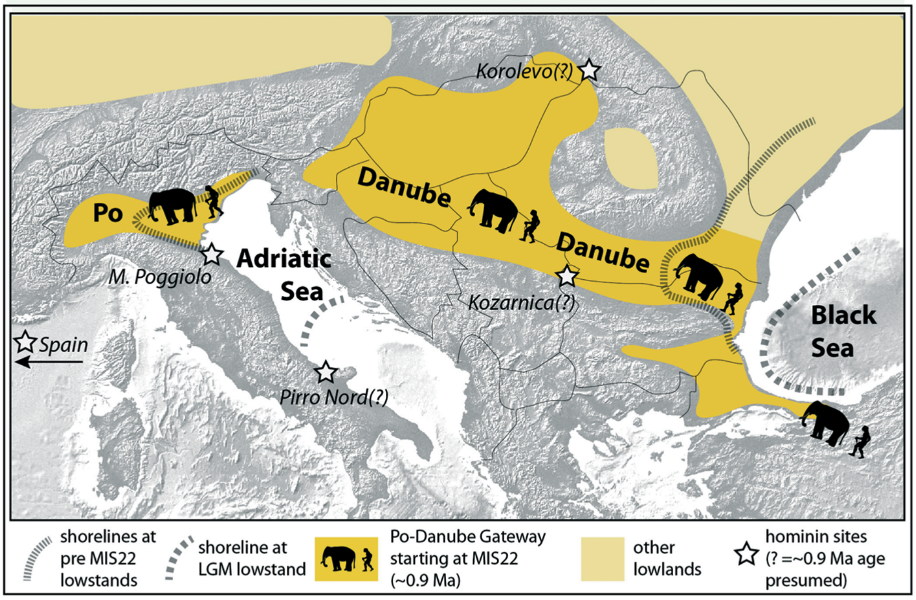

Fig. 4 - Paleogeographic scenario of our revised migrate-with-the-herd hypothesis of earliest expansion of hominins (and large mammals) from the Gates of Europe into Europe across the postulated Danube-Po Gateway during the EPR. Expansion occurred on stable lowlands developed as the Po and Danube deltas prograded over the Adriatic Sea and Black Sea, respectively, since MIS 22 (~0.9 Ma) (Muttoni et al. 2003; Scardia et al. 2006; Winguth et al. 2000). Coastlines at pre-MIS 22 lowstands and at the last glacial maximum (LGM) are tentatively depicted illustrating the advancement of the Po and Danube deltas. Colonization of these lowlands by grassland vegetation with reduced woody cover especially during the onset of glacial/interglacial transitions starting with MIS22/MIS21 provided the closest analogues in the temperate belt of the savanna ecosystems to which migrant mammals (e.g., megaherbivores) were adapted, and into which they expanded only since ~0.9 Ma together with hominins, which depended on them for food provision. Before MIS 22 (~0.9 Ma), these lowlands, reduced in size (see pre-MIS 22 coastlines), were colonized by more permanent closed forests, considered as unadapted to migrant African (or even Asian) large mammals (e.g., megaherbivores) and accompanying hominins.

in an unpublished Master's thesis (Bar-Yosef & Belmaker 2011 and reference therein). The current age attribution of the site to 1.6-1.2 Ma is based on long distance faunal correlations (Tchernov 1987; Martinez-Navarro et al. 2009; Bar-Yosef & Belmaker 2011). Discarding the site of Erk-el-Ahmar near 'Ubeidiya (Fig. 1), where levels with Mode I (Oldowan) lithic tools could not be correlated to the magnetostratigraphic profiles showing a reverse-normal-reverse polarity sequence (Braun et al. 1991; Ron & Levi 2001), we mention the Israel site of Bizat Ruhama in the northern Negev desert (Fig. 1), where Mode I (Oldowan) lithic tools were found in a reverse polarity interval attributed to the late Matuyama on the basis of integrated paleomagnetic and red thermoluminescence (RTL) data (Laukhin et al. 2001).

In south-central Turkey, the site of Dursunlu (Fig. 1) yielded levels with Mode I (Oldowan) lithic tools correlated to a normal-reverse-normal-reverse (bottom to top) polarity sequence retrieved from a drill core but no information on the procedures adopted to obtain the polarity stratigraphy was provided (Güleç et al. 1999, 2009), and hence this site is discarded from further consideration. The site of Kocabas in southwestern Turkey (Fig. 1) yielded a partial skull of *Homo erectus* s.l. from a travertine-fluvial sedimentary sequence (Lebatard et al. 2014). A well-described composite reverse-normal-reverse magnetic polarity profile was interpreted in conjunction with $^{26}Al/^{10}Be$ burial ages, as a record of the Matuyama-Cobb Mountain-Matuyama (or, alternatively, of the Matuyama-Jaramillo-Matuyama) polarity sequence comprised between ~1.5 Ma and 1.22 Ma (or ~1.5 Ma and ~1 Ma) (Lebatard et al. 2014). Unfortunately, the stratigraphic position of the skull is uncertain because it was not found directly within the magnetostratigraphic sequence but within a travertine block isolated earlier by quarry workers. The fossil is attributed an age of 1.3 Ma to 1.1 Ma (Lebatard et al. 2014) essentially because this is thought to be the minimum age of travertine deposition in the area.

From the magneto-chronologic framework illustrated above, hominins were clearly present in the Levant and Turkey before the Brunhes/Matuyama boundary (0.78 Ma). Provided the Kocabas hominin fossil has been correctly traced onto the composite magnetostratigraphic profile, and pending additional age constraints from sites in Israel (e.g., 'Ubeidiya, Erk-el-Ahmar), this would indicate hominin presence in Turkey and the Levant before the Jaramillo (i.e., before the EPR). This evidence would fit with the Early Pleistocene dispersal documented by Asian sites in the Caucasus, China and Java, and does not contradict our supposition based on the most reliable data that hominins apparently did not populate Europe until after the Jaramillo at ~0.9 Ma. We surmise that this late entry was due to the opening of a window of opportunity provided by exploitable ecosystems in the Danube-Po area (Balkans and northern Italy) that first started during the EPR.

Opening of the Danube-Po Gateway and first hominin expansion into Europe at ~0.9 Ma

Two main reasons lead us to speculate that hominins and some other mammals could enter the European realm through a postulated Danube-Po Gateway only starting at ~0.9 Ma during the EPR (Fig. 4):

1) Enhanced aridity and glacioeustatic lowstands associated with the EPR starting with MIS 22 (~0.9 Ma) fostered physical erosion in the Alpine-Dinaride mountain belt that promoted large fluxes of detritus that accumulated in peripheral plains. This triggered the formation and development of vast and stable lowlands (on which thick loess/paleosols sequences were deposited) such as the Pannonian Plain in Hungary and Serbia, Dacian Plain in Romania, and Po Plain in northern Italy.

2) Colonization of these lowlands by grassland vegetation with reduced woody cover occurred during onsets of glacial/interglacial transitions. These new environments represent the closest analogues in the temperate belt of the savanna ecosystem to which migrant mammals (and hominins with them) were already adapted.

Regarding the development of stable lowlands, the EPR was a time of profound reorganization of fluvial systems across Europe with the creation of the modern drainage systems of the Danube (Gábris & Nádor 2007) and Po rivers (Muttoni et al. 2003; Scardia et al. 2010), among other fluvial systems (Gibbard & Lewin 2009). The importance of the Po Valley Gateway during late Early Pleistocene mammal migrations was stressed by Muttoni et al. (2010, 2011). The northern Adriatic area was submerged as far west as the modern locality of Milan and as far north and south as the foothills of the Southern Alps and Apennines (Fig. 4) even during lowstands of the Early Pleistocene; it was only since immediately after MIS 22 at ~0.9 Ma that large stretches of the Po Plain started to become more persistently exposed due to enhanced fluvial detritus discharged into the Po Valley during what were becoming much lower glacioeustatic lowstands (Muttoni et al. 2003, 2010, 2011; Scardia et al. 2006, 2010, 2012). The detritus was redistributed as far east as Venice in the Adriatic Sea, promoting the strong progradation of the Po delta (Kent et al. 2002; Muttoni et al. 2010; Scardia et al. 2006, 2012). This may have opened possibly for the first time in the Pleistocene viable new migration routes for large mammals and hominins from the Danube corridor westward across northern Italy to southern France and Spain (Muttoni et al. 2010, 2011) (Fig. 4).

The Danube Gateway seems to have developed similarly and contemporaneously. Winguth et al. (2000) provided a seismo-stratigraphic model in which the Danube reached the Black Sea for the first time at ~0.9 Ma and subsequently built up the Danube fan (Fig. 4). The Dniepr fan started to form at about the same time, around 0.8 Ma (Winguth et al. 2002). These Danube-Po lowlands were covered since the late Early Pleistocene by thick loess sequences associated with enhanced glacial activity as revealed by several magnetostratigraphically dated land sections in Europe and the Black Sea area (e.g., Cremaschi 1987; Sartori et al. 1999; Dodonov et al. 2006; Fitzimmons et al. 2012; Ujvari et al. 2014; Jipa 2014) (Fig. 3E).

Regarding the development of persistent grassland-savanna ecosystems on these loessic lowlands (Fig. 4), the palynological record is relatively clear. Pollen data obtained from magnetostratigraphically calibrated deep cores drilled in the Po Valley and the bordering Southern Alps indicate that during the Early Pleistocene before the EPR (between the Olduvai subchron [1.95-1.78 Ma] and MIS 22 [~0.9 Ma]), climate was generally warm-temperate to cool but not cold, with abundant closed forests characterized by an alternation of deciduous broad-leaved species and conifers (Ravazzi & Rossignol-Strick 1995; Muttoni et al. 2003, 2007; Ravazzi et al. 2005). Even during the coldest spells of this climatic variability, no complete forest withdrawal was observed (Ravazzi et al. 2005).

During the EPR culminating with MIS 22, climate cooled, triggering forest withdrawal (Muttoni et al. 2003, 2007; Scardia et al. 2010). The long pollen record from Tenaghi Philippon in northern Greece (Tzedakis et al. 2006) reveals the vegetational (climate) variability (forest contractions/expansions) since 1.35 Ma across the EPR. This record shows high amplitude and low frequency oscillations with very pronounced expansions of steppe and grasslands during the glacial phases starting with MIS 22 (~0.9 Ma), in agreement with other records from France (e.g., Velay; de Beaulieu et al. 2006, 2013) and Italy (Magri 2010 and references therein).

The occurrence of persistent open vegetation phases only since MIS 22 (Magri 2010) is central to our revised (after Muttoni et al. 2010, 2011) migrate-with-the-herd hypothesis of first colonization of Europe during the EPR, considering that several large mammals on which hominins may have depended on for food provision (e.g., Ben-Dor et al. 2011) were adapted to open environments with limited woody cover (e.g., the African straight-tusked elephant and the Asian steppe mammoth; see Rivals et al. 2012 and discussion below). A recent analysis of faunal and pollen records at several early hominin sites in Europe coupled with climate simulations lead to the conclusion that the environmental context in which the first hominins entered into Europe and dispersed was characterized by the occurrence of open landscapes, essentially grasslands or open woodlands, typical of transitions from glacial to interglacial periods (the full glacials being too cold, and the interglacial to glacial transitions too forested) (Leroy et al. 2011). Well-defined open woodland phases become a persistent component of Pleistocene vegetational variability in southern and southeastern Europe only since ~0.9 Ma during glacial/interglacial transitions (de Beaulieu et al. 2006, 2013). We therefore regard the glacial/interglacial transitions starting from the end of MIS22 (Fig. 3F) as the main time windows of grassland-savanna environments in the Danube-Po Gateway exploited by hominins and other mammals for first migrations into Europe during the EPR starting at around 0.9 Ma (Fig. 4).

The elements outlined above lead us to a reformulation of the migrate-with-the-herd hypothesis of first peopling of Europe at ~0.9 Ma during the EPR.

A revised migrate-with-the-herd hypothesis of first hominin expansion into Europe at ~0.9 Ma

We previously hypothesized (Muttoni et al. 2010, 2011) that hominins seem to have entered Europe together with herds of large African (and Asian) herbivores because they were 'pushed out' of their homelands by enhanced aridity in the Sahara (Larrasoaña et al. 2003) and across Asia during the EPR, finding ultimate refuge in the more temperate Mediterranean realm. In fact, it appears that north subtropical Africa was quite often green (sustainable, traversable) well before and even during the harsh times of the EPR, providing numerous potential windows for mammal migrations in and out of Africa since at least 8 Ma (Larrasoaña et al. 2013).

Instead, we now believe that large mammals, and hominins with them, may have migrated to Europe starting at around 0.9 Ma because the EPR generated for the first time in the Pleistocene vast and exploitable ecosystems for African and Asian mammals especially along the conjunct Danube-Po Gateway (Fig. 4). These new environments were characterized by stable lowlands with open grassland vegetation and reduced woody cover during the onset of glacial/interglacial transitions (starting with MIS 22/MIS 21). The connection between savanna environments and mammal migrations is well established in the literature (e.g., Dennell 2004; but see Bar-Yosef & Belmaker 2011). In our view, the lack of grassland-savanna exploitable ecosystems before the EPR forestalled African and Asian large herbivores from expanding into Europe, should they have reached there. Animal fat from large herbivores (e.g., elephants) was apparently an essential food source for Pleistocene hominins in the Levant (Ben-Dor et al. 2011). It should not come as a surprise, therefore, that *H. erectus* expanded into the newly opened grassland-savanna ecosystems in conjunction with their migrating primary food source (Ben-Dor et al. 2011).

From the staging area in the Levant and Turkey, where hominins survived in diverse Mediterranean environments (Bar-Yosef & Belmaker 2011; Yeshurun et al. 2011), hominis seem to have expanded into Europe as part of a food web in conjunction with African and Asian mammals across the new grassland-savanna ecosystems of the Danube-Po Gateway. Megaherbivores requiring large dietary grass supply such as the African straight-tusked elephant (*Elephas antiquus*), the Asian steppe mammoth (*Mammuthus trogontherii*), the Asian red deer (*Cervus elaphus*), and the Indian large bovid (*Hemibos galerianus)* are among the most representative species of the Galerian mammal assemblage that entered Europe during the EPR at around 0.9 Ma and progressively replaced resident European species of the Villafranchian mammal assemblage, like the Etruscan rhino, the southern mammoth, and the fallow deer (Fig. 3G, essentially from Van der Made 2011, and Masini & Sala 2007; see also Palombo & Ferretti 2005; Palombo & Mussi 2006; Martinez-Navarro 2010; Van der Made 2013).

According to dental microwear analyses on proboscidean teeth (Rivals et al. 2012), the European resident *M. meridionalis* seems to have been more adapted to browsing, whereas immigrants *M. trogontherii* and *E. antiquus* were mixed browsers-grazers, and therefore more adapted to the persistent grassland-savanna ecosystems that developed during the EPR since MIS 22 or the immediately suceeding MIS 22/MIS 21 transition (~0.9 Ma). This dietary flexibility could have given *M. trogontherii* and *E. antiquus* an adaptive advantage relative to more forest-dependent *M. meridionalis*.

In this respect, the fossil record of large grassland-savanna-adapted herbivores may provide valuable clues to the migration routes and timing of hominins with their much more scanty traces. For example, the Serbian site of Kostolac east of Belgrade, located on our postulated Danube-Po Gateway, yielded a specimen of the steppe mammoth *M. trogontherii* from a level overlain by a thick loess-paleosol succession (Lister et al. 2012). *M. trogontherii* is an Asian immigrant that arrived in Europe just before the Brunhes/Matuyama boundary (Lister et al. 2012). We speculate that the level with *M. trogontherii* at Kostolac (for which magnetostratigraphic analyses are in progress by the writers) may represent a regional unconformity marking the EPR in the Danube Valley (similarly to the R surface in the Po Valley dated at ~0.9 Ma; Muttoni et al. 2003; Scardia et al. 2006) along which archeological surveys in search for early hominin sites might fruitfully focus.

Alternative migration scenarios: the North Africa-Gibraltar Strait connection

An alternative staging area for migration to Europe is represented by northern Africa. At Ain Hanech in northern Algeria (Fig. 1), Parès et al. (2014) obtained a convincing reverse-normal-reverse magnetic polarity sequence from the 29 m-thick type section of the Ain Hanech Formation, revising previous (but not illustrated) results (Sahnouni and de Heinzelin 1998 and references therein). Mode I (Oldowan) lithic tools were found in nearby ~3 m-thick sections at Ain Hanech (not to be confused with the Ain Hanech Formation type section) and El-Kherba (below a calcrete level sealing the Ain Hanech Formation and yielding Acheulean tools) in association with mammal remains, and were correlated by altimetric leveling to within the upper 5 m of the Ain Hanech Formation type section (Parès et al. 2014 and references therein) characterized by reverse magnetic polarity (Parès et al. 2014). After a long debate on the biochronological value of the recovered mammals (Sahnouni et al. 2002; Geraads et al. 2004; Sahnouni et al. 2004), the latest claims for the age of the Ain Hanech and El-Kherba tool-bearing sites are: 1) ~1.7 Ma based on magnetostratigraphy in conjunction with the chronology derived from the morphology of a tooth attributed to the suid *Kolpochoerus heseloni* and the recovery of a tooth fragment attributed to the proboscidean *Anancus* (Parès et al. 2014 and references therein); 2) ~1.5-1.2 Ma based on mammal biostratigraphy alone (Geraads 2010 and references therein), which – we notice – is an age that does not seem to openly violate the recent magnetostratigraphic data of Parès et al. (2014). The ongoing debate seems to still critically depend on the identification and chronological value of a tooth of *Kolpochoerus* and a tooth of *Anancus*, whose occurrences at Ain Hanech are in any case not well documented in the accessible literature.

At the site of Thomas Quarry 1 in the Atlantic Morocco (Fig. 1), Mode II (Acheulean) lithic tools have been found in level L (Raynal et al. 1995; Raynal et al. 2002; Geraads et al. 2004) attributed to the Matuyama Chron based on the presumed presence of reverse magnetic polarity, although no experimental data were illustrated (Raynal et al. 1995; Raynal et al. 1996; Sevket Sen, personal communication to G.M., 2014). Rhodes et al. (1996) reported an OSL-SAR (single aliquot regenerative) age estimate for level L of 0.99 ± 0.2 Ma associated with a 'surprisingly young' OSL-MAAD (multiple aliquot additive dose) age estimate of 0.26 ± 0.06 Ma (both quoted at 1s level). Sahnouni and Van der Made (2009) and Geraads (2010) seem to accept a late Early Pleistocene age for level L based on the available mammal biostratigraphy coupled with the OSL dates.

The relevance of the actual age(s) of the North Africa hominin sites is that they seem to have prompted Parès et al. (2014) to speculate anew about '*the likelihood of North Africa as a plausible routes* [sic] *for hominin expansion into Europe*', which seems to imply the crossing of the Gibraltar Strait into Spain. If so, we would point out (see also Muttoni et al. 2010) that the Gibraltar Strait has experienced Quaternary tectonic uplift as evidenced by a sequence of raised shorelines in Gibraltar as high as 210 m above present sea level (e.g., Rodrìguez-Vidal et al. 2004). This implies that even the lowest Early Pleistocene sea level lowstands (e.g., MIS 22) would have hardly affected the extent of the central channel, now ~5 km wide and ~300 m deep. More importantly, there is a fundamental difference between the Danube-Po Gateway route and a Gibraltar Strait crossing route. In our Danube-Po Gateway hypothesis, the opening of new, stable, and exploitable ecosystems provided a virtual ecological highway for the sustained expansion of mammals and hominins into Europe. On the other hand, a Gibraltar Strait crossing hypothesis inevitably implies a sporadic crossing of a significant barrier, which would be expected to act as a severe filter. In that respect, the Gibraltar Strait seems a much less obvious route, at least for establishing a stable and repeated physical and genetic exchange with Africa for continental-scale peopling of Europe accompanied by a wide variety of megaherbivores.

Summary and Conclusions

- As previously suggested, earliest hominin sites in Europe with reliable age control continue to indicate (or do not contradict) that the earliest peopling of Europe occurred within a narrow time window of the late Early Pleistocene comprised between the top of the Jaramillo subchron (0.99 Ma) and the Brunhes/Matuyama boundary (0.78 Ma). Our preferred late Early Pleistocene chronology (0.99-0.78 Ma) is 'not so short but not too long' as it lies between the classic 'long' chronology that expects the earliest hominin evidence from Europe to date before the Jaramillo (>1Ma) (e.g. Garcia et al. 2014; see also Toro-Moyano et al. 2013 vs. Muttoni et al. 2013), and the classic 'short' chronology claiming instead that Europe was largely uninhabited until after the Brunhes/Matuyama boundary in the Middle Pleistocene (<0.78 Ma) (e.g., Roebroeks & van Kolfschoten 1994). The timing of our preferred late Early Pleistocene (post-Jaramillo) chronology of earliest peopling of Europe may be related to the response of African and southern European climate to the inception of higher amplitude glacial oscillations of the late Early Pleistocene revolution (EPR) centered on MIS 22 (~0.9 Ma).
- We now suggest that hominins entered Europe for the first time during the EPR because it was when vast and exploitable lowlands with open vegetation developed along the conjunct Danube-Po Gateway, thus providing possibly for the first time in the Pleistocene an eco-space for migrations into Europe that grassland-savanna-adapted large mammals, and hominins with

them as part of a common and interlinked food web, could have expanded into (Fig. 4).

• We stress the importance of the opening of land coinduits during migrations of large mammals. A Danube-Po Gateway connecting the Levant and Turkey to Europe would have implied the crossing of only one (limited) waterway – the Bosphorus – which may have been at least intermittently exposed during the Pleistocene (making the Black Sea a freshwater lake; Ryan et al. 2003; but see also Yaltirak et al. 2002). The main point here is that linking the migrations of hominins with large herbivores makes the crossing of extended waterways (e.g. Gibraltar Strait) unlikely, whereas exposed and exploitable plains and lowlands seem more viable routes for the ensemble.

• Finally, the pathways of migration discussed above can be considered valid under the assumption that early Europeans came either accompanying *E. antiquus* from Africa (e.g., Antón 2003) or *M. trogontherii* from Asia (e.g., Dennell 2008), where the records of hominins seem to extend farther back in the Early Pleistocene than in Europe.

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3

INSIGHTS ON THE OPENING OF THE GALERIAN MAMMAL MIGRATION PATHWAY FROM MAGNETOSTRATIGRAPHY OF THE PLEISTOCENE MARINE-CONTINENTAL TRANSITION IN THE ARDA RIVER SECTION (NORTHERN ITALY)

My personal contribution in this work started in June 2011 with my master degree thesis. The entire sequence was measured, then described, and then sampled starting back then and finishing in September 2014. The measurment of the first samples occurred in August 2012 and the latest data were aquired at the beginning of 2015. After the field work and the measurment of all the samples in the Alpine Laboratory of Paleomagnetism of Peveragno (CN) my work consisted in the interpretation of the data and in the writing of the paper, as well as in the creation of the figures.

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Insights on the opening of the Galerian mammal migration pathway from magnetostratigraphy of the Pleistocene marine–continental transition in the Arda River section (northern Italy)

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A B S T R A C T

We investigated the magnetostratigraphy of the Arda River section (northern Italy) where the transition from marine to continental sedimentation occurring in the Po River basin during the Pleistocene is registered. Four magnetic polarity reversals were used to construct an age model of sedimentation aided by marine biostratigraphy and tied to a standard $\delta^{18}O$ curve from the literature. The section spans from the Olduvai subchron (1.94–1.78 Ma) across the Jaramillo subchron (1.07–0.99 Ma) up to the Brunhes–Matuyama boundary (0.78 Ma). The onset of continental deposition occurred during marine isotope stage (MIS) 30 at ~1.04 Ma. An association of Villafranchian and Early Galerian mammals, including *Sus strozzii* and *Ursus dolinensis*, has been found in the continental sediments dated to MIS 29–27 (~0.99 Ma). Above follows a prominent fluvial conglomerate attributed to the first major lowstand of the Pleistocene culminating with MIS 22 at ~0.9 Ma during the late Early Pleistocene climate turnover (EPT). These and other data from the literature are used to reconstruct the onset of continental deposition in the greater Po basin and shed light on the opening of the migration pathway that brought far-traveled Galerian mammal immigrants to enter Europe for the first time during the EPT.

Introduction

The Arda River section is located in northern Italy near the town of Castell'Arquato at the margin of the northern Apennines facing the Po River plain (Fig. 1). The section consists of a thick and continuous record of the transition from marine sedimentation typical of the Pliocene–Early Pleistocene to late Early Pleistocene–Holocene continental sedimentation, as documented in part also in the adjacent Stirone and Enza river sections (Mary et al., 1993; Gunderson et al., 2012, 2013; 2014).

Our main objective is to generate an age model of sedimentation for the Arda River section by integrating magnetostratigraphy (this study) with marine biostratigraphic data (Crippa et al., 2016; this study). In particular, we aim at dating the onset of continental deposition recorded in the upper part of the section where we also found a new mammal association (see also Bona and Sala, 2016). We use magnetostratigraphy to correlate the Arda River section to other sections from the literature (Muttoni et al., 2003, 2011; Scardia et al., 2006; Gunderson et al., 2012; Scardia et al., 2012; Gunderson et al., 2014; Pinti et al., 2001) with the objective of gauging how the onset of continental deposition evolved in space and time across the greater Po River basin. The timing of full continentalization of the Po basin is thought to coincide with the arrival in Europe of a renewed mammal fauna (Galerian) characterized by far-traveled immigrant species (Palombo and Mussi, 2006; Muttoni et al., 2014, 2015a; Palombo, 2014). We hypothesize that this was brought on by the formation of vast and exploitable ecosystems along a newly formed continental Po (and Danube) migration pathway, as recently described in Muttoni et al. (2014, 2015a) and further explored in this paper.

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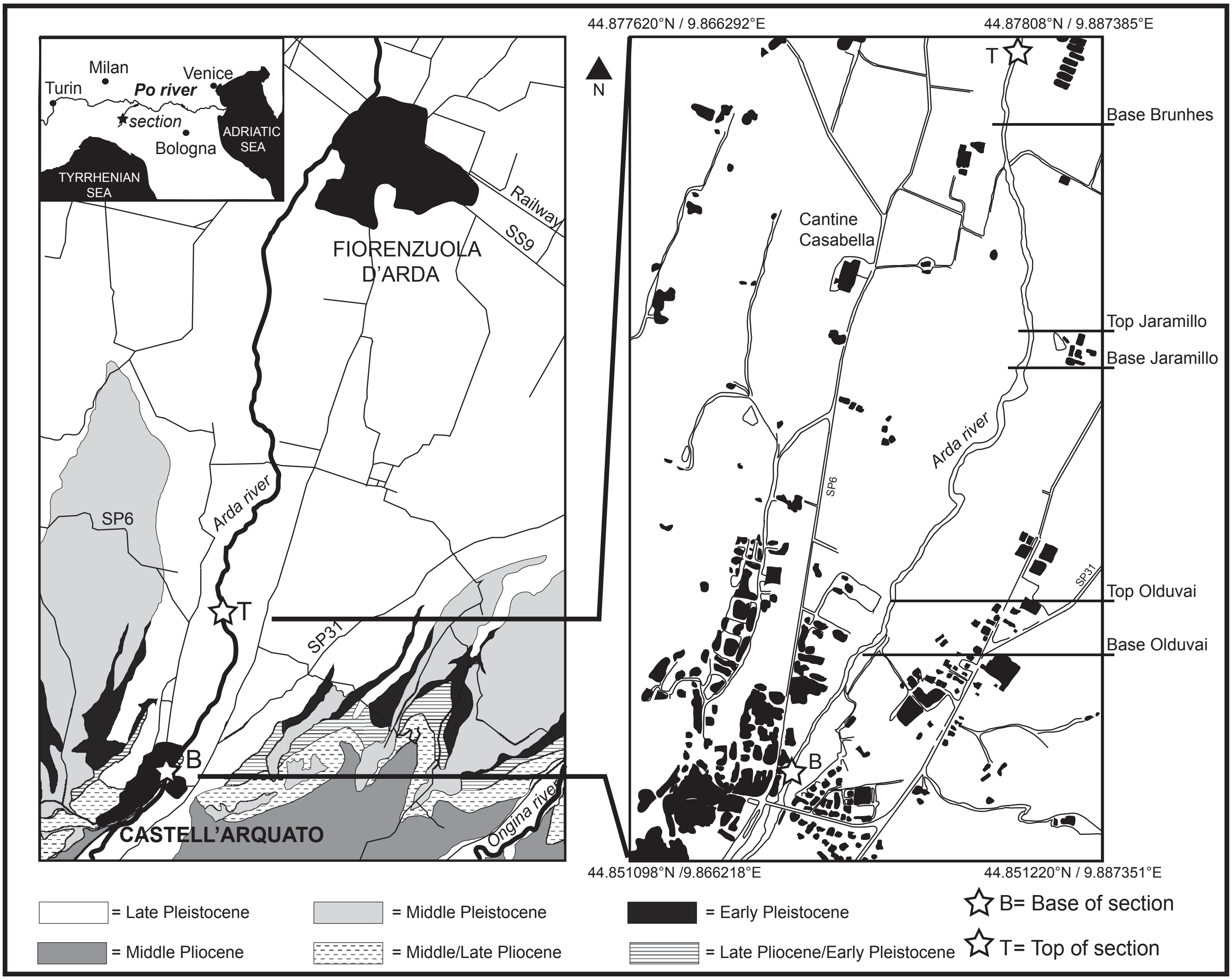

Figure 1. In left panel, geological map of the Castell'Arquato area in the northern Apennines with indication of the Arda River section. In right panel, planimetry of the sampled section with location of the main magnetic polarity reversals. Contour lines have been removed in both panels for clarity.

Stratigraphy and sedimentology

The Pleistocene Arda River section of this study lies stratigraphically above the Pliocene Castell'Arquato section of Channell et al. (1994), this latter comprised of marine claystones ('Argille Azzurre' *Auctorum*) correlated by biostratigraphy to the nearby Stirone section that was magnetostratigraphically dated from the Gilbert Chron at ~5 Ma to the Gauss Chron at ~2.5 Ma (Mary et al., 1993; Channell et al., 1994).

The Arda River section starts at the bridge immediately to the north of Castell'Arquato (base: 44.853619°N/9.873154°E) and extends northward along the banks of the Arda River for 300 stratigraphic meters (top: 44.877505°N/9.883693°E) (Fig. 1). The stratigraphic succession of marine-transitional–continental deposits therein exposed are attributed in the Italian Geological Map (Calabrese et al., 2009) to the Badagnano Synthem (mainly marine sandstones and claystones) and the Torrente Stirone and Costamezzana Synthems (mainly littoral sandstones, lagoonal/continental silty claystones, and fluvial conglomerates). Strata gently dip to the north by ~10° at the base and 5°–6° at the top. Faults have been observed in the lower part of the section up to ~50 m (Fig. 2A).

From bottom to top, five lithozones have been distinguished and interpreted in terms of depositional environment:

Lithozone 1 (0–220 m) consists of marine conglomerates and sandstones arranged in at least six, 5–25 m-thick fining upward cycles (labeled I–VI in Fig. 2A) interpreted as high-density turbidite flows (*sensu* Mutti et al., 2000). Each turbidite flow usually starts with massive to cross-bedded conglomerates with abundant shallow-water skeletal remains and intraclasts. Above follow sandstones that are either massive or with horizontal, hummocky, tabular or oblique cross stratification. Sharp-based, normally graded, tabular to lenticular lags of concave-down shells may occur at the base of the strata. Carbonaceous remains and wood fragments are also common within massive turbidite sandstones. Flaser and massive mudstone beds up to several cm-thick are often intercalated with these sandstones. Finally, above the turbidite sandstones follow resedimented, massive to laminated siltstones and mudstones arranged in thin couplets. Each of these turbidite events (I–VI) grade into hemipelagic siltstones and mudstones with marine bivalves in life position. The first occurrence of the foraminifera *Hyalinea baltica* and of the bivalve *Arctica islandica* were recorded at 98.3 m (Crippa et al., 2016) and 103 m, respectively.

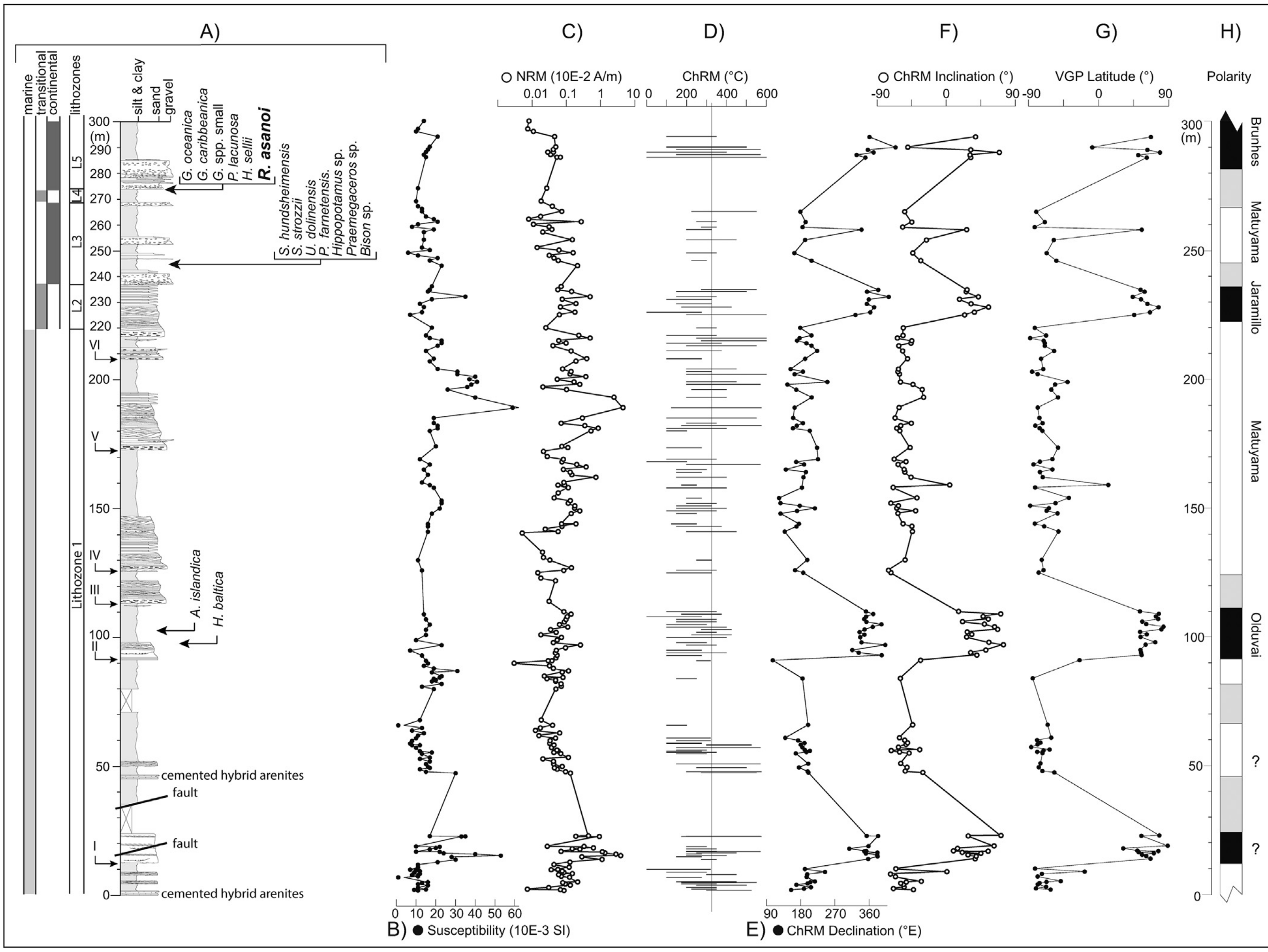

Figure 2. Stratigraphy and paleomagnetic data of the Arda River section. A) Stratigraphic sequence and key fossil occurrences; B) magnetic susceptibility; C) natural remanent magnetization (NRM); D) demagnetization window of the characteristic remanent magnetization (ChRM); E and F) declination and inclination of the ChRM; G) latitude of the virtual geomagnetic pole (VGP) of the ChRM; H) magnetic polarity, where black is normal and white is reverse polarity. L2 = lithozone 2; L3 = lithozone 3; L4 = lithozone 4; L5 = lithozone 5.

Lithozone 2 (220–237 m) is characterized by 0.3–1 m-thick beds of coarse-grained sandstones and matrix supported pebbly sandstones with low-angle ($\leq 20°$) cross-stratification trending asymptotically to the top and base of the beds, attributed to littoral (transitional) environments (Fig 2A). The top of lithozone 2 at 237 m represents the top of the section studied for biostratigraphy by Crippa et al. (2016) with an estimated age of ~1.1 Ma based on nannofossils.

Lithozone 3 (237–269 m) is comprised of continental sediments arranged in four main cycles, each characterized by 1–4 m-thick massive or crudely stratified, partially cemented fluvial gravel beds, passing rapidly upward to sandstones, siltstones and mudstones. Fossil roots and trunks in in-life position, together with calcium carbonate nodules and freshwater gastropods, are frequent in fine-grained beds, suggesting continental swamp environments. A level with mammal bones attributed to *Sus strozzii*, *Stephanorhinus hundsheimensis*, *Ursus dolinensis*, *Pseudodama farnetensis*, *Bison* sp., *Hippopotamus* sp., and *Praemegaceros* sp. has been found at 245 m (Fig. 2A; see also discussion below).

Lithozone 4 (269–275 m) consists of marine-transitional silty claystones bearing (mostly reworked) nannofossils with, among others, the useful marker *Reticulofenestra asanoi* (Fig. 2A; see discussion below). Finally, lithozone 5 follows above with persistent continental sedimentation consisting mainly of fluvial sands and gravels (Fig. 2A), which continues above our stratigraphic log with the deposition during the Middle–Late Pleistocene of the fluvial gravels of the Emilia Romagna Supersynthem (Calabrese et al., 2009).

Mammal fauna

The mammal fauna found at 245 m consists of 61 bone and teeth remains retrieved in 2006–2015 and housed at the geological museum "G. Cortesi" of Castell'Arquato. The fauna consists of seven taxa attributed using specific morphological features described hereafter and in a parallel paper (Bona and Sala, 2016): (I) *S. hundsheimensis* (Fortelius et al., 1993; Lacombat, 2006), attribution based on the overall morphology and dimensions of the skull and the teeth (Fig. 3, panel 1). (II) *Sus strozzii*, attribution based on the mandibular canines that present the typical '*Sus verrucosus*' section (Azzaroli, 1954) where buccal and lingual sides are similar in breadth while the distal side is less developed and the section of the teeth resembles an isosceles triangle (Fig. 3, panel 2). (III) *U. dolinensis*, attribution based on the skull and jaw that show strong speloid-like development while the teeth display very simple arctoid-like shapes and medium to large size dimensions (Fig. 3, panels 3–4). *U. dolinensis* was first described by García and Arsuaga (2001) at Atapuerca in Spain, while according to García (2004) and

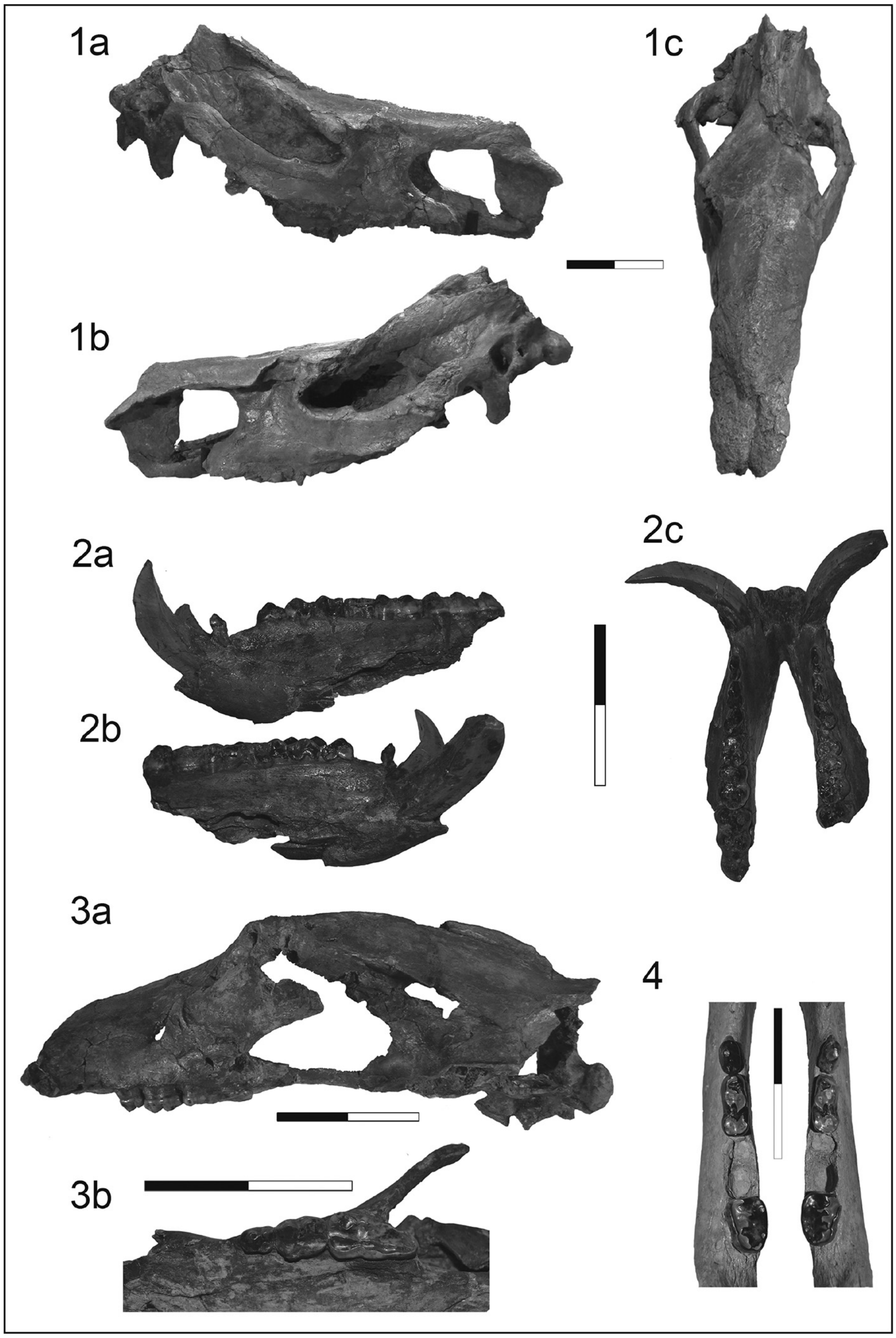

Figure 3. Key mammals from the Arda River section. 1) *Stephanorhinus hundsheimensis*: skull (Vt 088) a—right side, b—left side, c—dorsal view; 2) *Sus strozzii*: mandible (Vt 090) a—left side, b—right side, c—occlusal view; 3) *Ursus dolinensis*: half skull (Vt 081) a—left side, b—left cheek teeth; 4) *Ursus dolinensis*: mandible (Vt 034, Vt 035) occlusal view. Scale bar = 10 cm.

Kahlke (2007), *Ursus rodei* from Untermassfeld in Germany (Musil, 2001) should be considered a junior equivalent of *U. dolinensis*. (IV) *P. farnetensis*, attribution based on the overall morphology and dimensions of the teeth and the position of the brow tine close to the burr. (V) *Hippopotamus* sp., whose remains consist of only two large femur diaphyses with sub-square sections pertaining to two young individuals. (VI) *Praemegaceros* sp. indet., attribution based on the development direction of the peduncles observed in the frontal bones of a fragmentary skull, which forms a typical angle of about 90° (Kostopoulos, 1997; Azzaroli and Mazza, 1992). (VII) *Bison* sp., attribution based on the large dimensions of the bones and the degree of hypsodonty, as well as the slightly swollen base of the teeth crowns (Sala, 1986); the lack of a skull with horns and the fragmentary condition of the distal bones do not allow a more accurate species identification.

The Arda faunal assemblage comprises taxa included in the Villafranchian mammal age, such as *Pseudodama* and *Sus strozzii*, co-existing with the large cervid *Praemegaceros* and the bear *U. dolinensis* (= *U. rodei*), which are commonly considered post-Villafranchian and pertaining to the beginning of the Galerian mammal age (Gliozzi et al., 1997; Kahlke, 2007; Masini and Sala, 2007). *Bison* sp. and *Hippopotamus* sp. are not particularly

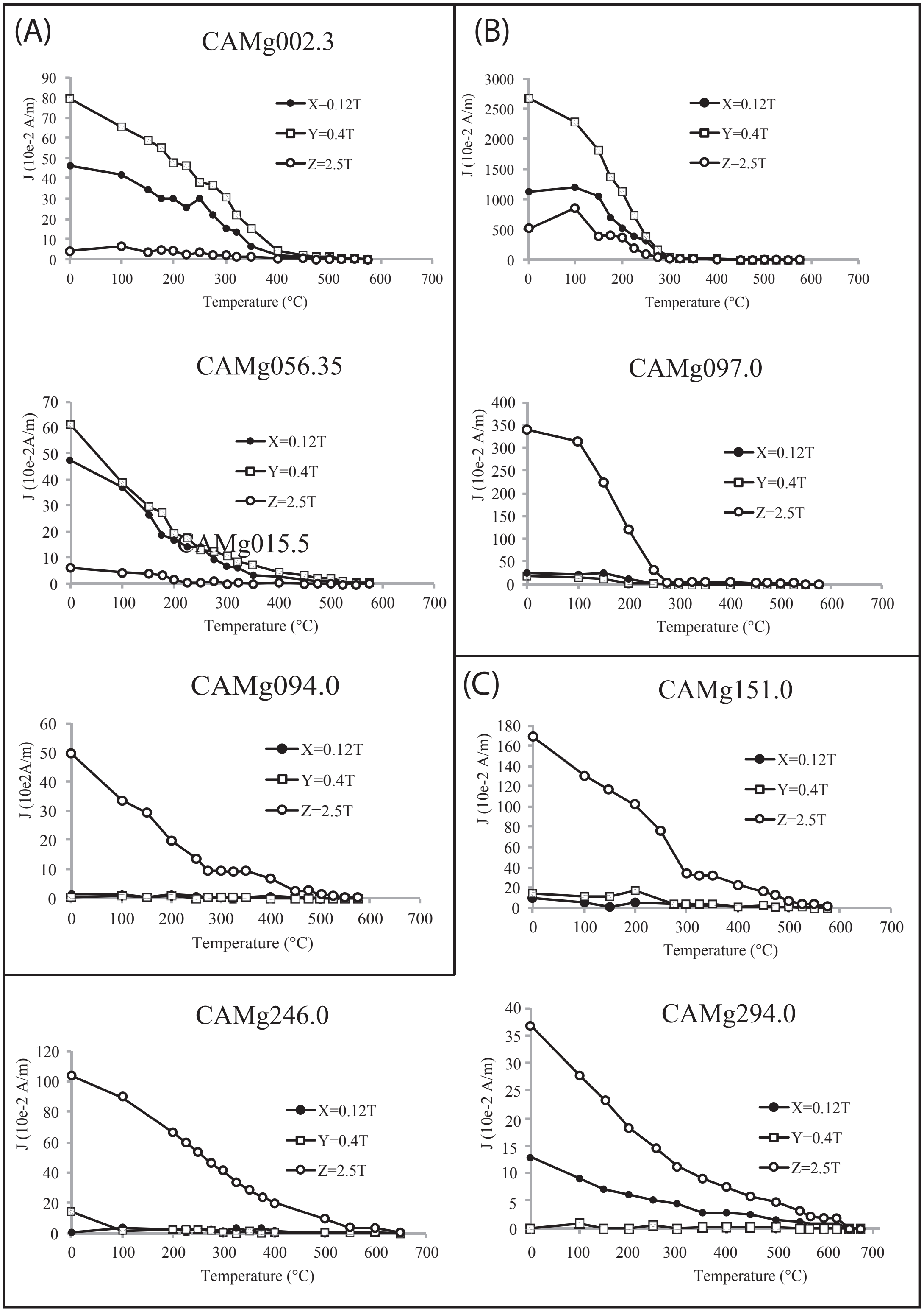

Figure 4. Isothermal remanent magnetization (IRM) diagrams of representative samples from the Arda River section bearing dominant (titano)magnetite (A), iron sulphides (B), and hematite (C); see text for discussion.

diagnostic in terms of mammal age attribution because the former could not been identified at sub-generic (*Eobison* or *Bison*) or specific level, and the latter belongs to a genus that has a wide temporal distribution (Gliozzi et al., 1997; Masini and Sala, 2007). In any case, according to the presence of the large-sized cervid *Praemegaceros* sp., the Arda fauna can be attributed to the Early Galerian Colle Curti faunal unit (FU) (Gliozzi et al., 1997; Coltorti et al., 1998; Masini and Sala, 2007). Elsewhere in Europe, a similar fauna was found at Untesmassfeld in Germany (Kahlke, 2006; Maul and Markova, 2007; Kahlke et al., 2011).

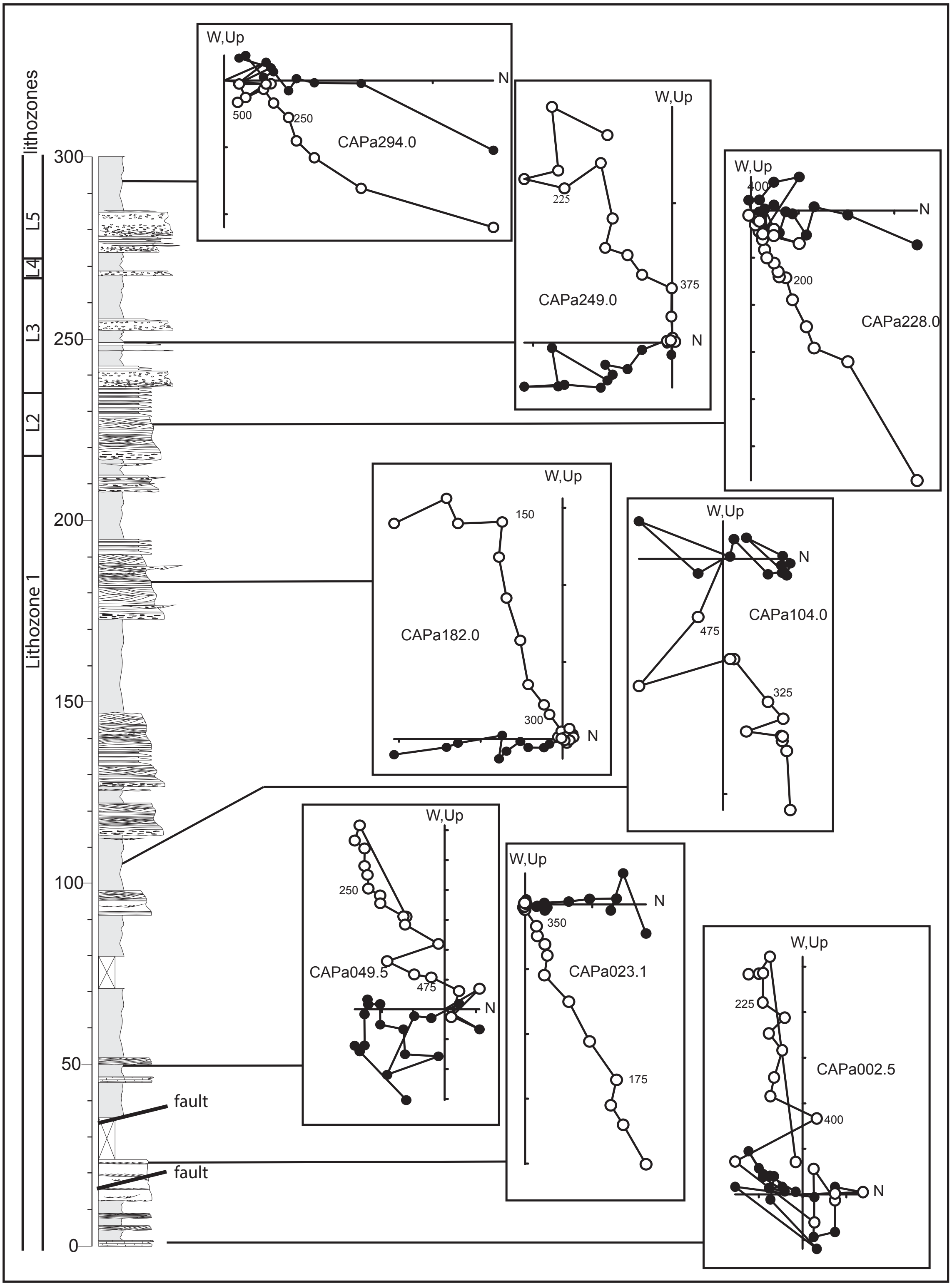

Figure 5. Vector end-point demagnetization diagrams of representative samples plotted aside the Arda stratigraphic sequence. Full symbols are projections on the horizontal plane and open symbols on the vertical plane. Demagnetization temperatures are expressed in °C. L2 = lithozone 2; L3 = lithozone 3; L4 = lithozone 4; L5 = lithozone 5.

Paleomagnetic methods

Paleomagnetic samples were cored in the field with an electric drill and oriented with a magnetic compass to obtain a total of 214 standard (10 cm^3) cylindrical specimens for paleomagnetic analyses. The initial magnetic susceptibility was measured on all samples at room temperature with a MS2 Bartington susceptibility bridge. A sub-set of 29 samples was subjected to rock magnetic analyses by means thermal demagnetization of a three-component isothermal remanent magnetization (IRM) imparted in fields of

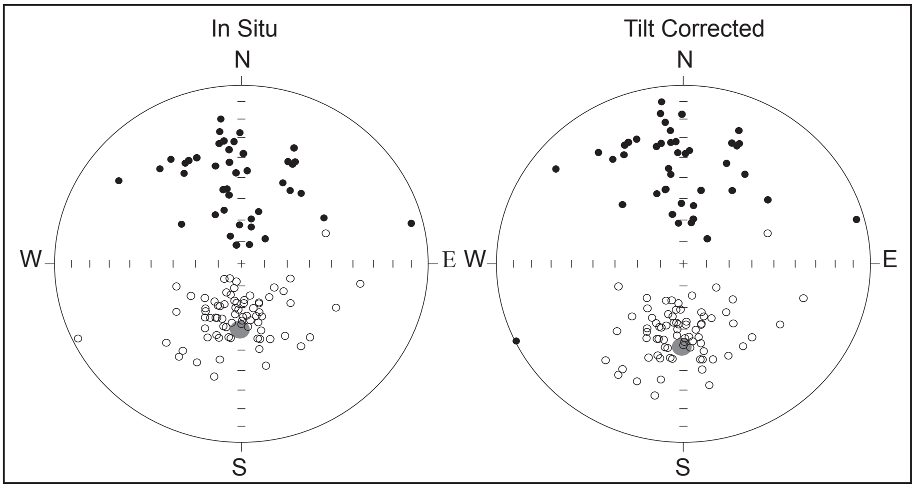

Figure 6. Equal area projection of the ChRM component directions in *in situ* and tilt corrected coordinates. Full symbols represent down-pointing vectors (normal polarity), open symbols represent up-pointing vectors (reverse polarity).

2.5 T, 0.4 T, and 0.12 T. The remaining 185 samples were subjected to thermal demagnetization in steps of 50 or 25°C from room temperature up to the Curie points of the magnetic minerals therein contained using a ASC TD48 furnace. The natural remanent magnetization (NRM) was measured after each demagnetization step with a 2G Enterprises DC-SQUID cryogenic magnetometer located in a shielded room. Standard least-square analysis was used to calculate magnetic component directions from vector end-point demagnetization diagrams, and standard Fisher statistical analysis was used to analyze the mean component directions. Magnetic measurements were carried out at the Alpine Laboratory of Paleomagnetism of Peveragno (Italy).

Paleomagnetic results

The magnetic susceptibility is characterized by values of ~$10–20*10^{-3}$ SI with two peaks of ~$50–60*10^{-3}$ SI at 17 m and 187 m (Fig. 2B). The intensity of the NRM shows average values of ~$0.07*10^{-2}$ A/m and two peaks of ~$4–5*10^{-2}$ A/m across the same stratigraphic levels as the susceptibility peaks (Fig. 2C).

Stepwise thermal demagnetization experiments of a three-component IRM show three types of behaviors: (I) the intermediate (0.4 T) and sometimes also the low (0.12 T) coercivity curves show maximum unblocking temperatures in excess of ~400°C and sometimes up to ~570°C, interpreted as signaling the presence of (titano)magnetite (Fig. 4A). (II) The intermediate (0.4 T) and sometimes also the low (0.12 T) and high (2.5 T) coercivity curves show a drastic drop in intensity at ~275–300°C interpreted as due to the presence of iron sulphides (Fig. 4B). (III) The high (2.5 T) coercivity curve shows maximum unblocking temperatures up to ~680°C interpreted as due to the presence of hematite (Fig. 4C).

Vector end-point demagnetization diagrams show the presence of characteristic remanent magnetization (ChRM) component directions oriented to the north and down (positive inclinations) or south and up (negative inclinations) that were isolated from ~100°C up to ~400–600°C (Fig. 5) in a total of 117 samples (detailed demagnetization temperature windows in Fig. 2D). These bipolar ChRM component directions, with mean angular deviation (MAD) values of usually less than 15°, are grouped in *in situ* (geographic) coordinates around a mean of declination = 1.1°E, inclination = 59.7° (k = 11.8, $\alpha95$ = 4.0°; Fig. 6) and in tilt corrected coordinates around a mean of declination = 0.9°E, inclination = 51.6° (k = 11.3, $\alpha95$ = 4.1°; Fig. 6).

The declination and inclination values of these ChRM component directions plotted *versus* stratigraphic depth (Fig. 2E and F) were used to calculate virtual geomagnetic pole (VGP) latitudes (Fig. 2G). VGP latitudes approaching +90° are interpreted as normal polarity and VGP latitudes approaching −90° as reverse polarity, thus defining a sequence of stratigraphically superposed normal and reverse magnetozones (Fig. 2H). The lower half of the section, from 0 to ~50 m, is characterized by reverse magnetic polarity interrupted by a normal polarity interval from 12 to 23 m (Fig. 2H). This part of the section is affected by faulting (Fig. 2A) that may have duplicated the stratigraphic record. The faulted levels comprising the lower normal polarity interval are moreover associated with high susceptibility and NRM intensity values (Fig. 2B and C) that could suggest chemical overprinting of the original magnetic signal. We therefore conservatively decided not to consider any further this lower part of the section. From ~50 to 92 m follows reverse polarity overlain by normal polarity up to 113 m, in turn overlain by reverse polarity up to 223 m, normal polarity up to about 235 m, then again reverse polarity up to about 267 m and, finally, normal polarity that continues to the section top (Fig. 2H).

We interpreted this sequence of magnetozones by means of correlation to the Lourens et al. (2004) astrochronological polarity time scale that we anchored to the $\delta^{18}O$ record of Shackleton (1995) (Fig. 7). The normal polarity interval found between 92 and 113 m is interpreted as a record of the Olduvai subchron (1.94–1.78 Ma; Fig. 7). This is supported by the first occurrence of *H. baltica* at 98.3 m (Crippa et al., 2016), which at the Calabrian GSSP at Vrica is dated to around the top of the Olduvai (Cita et al., 2012), and of *Arctica islandica* at 103 m. This latter has an extrapolated age of ~1.85 Ma in agreement with a radiometric (He/Th) age of 1.81 ± 0.1 Ma on corals from a level immediately above the first occurrence of *A. islandica* in the Santerno section (northern Apennines), as reported by Kukla et al. (1979) (see also Raffi, 1986).

The magnetochronologic interpretation of the reverse-normal-reverse-normal polarity sequence observed from 113 m (top Olduvai) to the section top, which represents the main focus of the paper, is achieved with the aid of nannofossil data from three samples collected in the uppermost transitional-marine level at 275 m (Figs. 2A and 7; Table 1), not sampled by Crippa et al. (2016). Samples are largely dominated by reworked Cretaceous, Paleogene, and Neogene taxa. The most recent taxa, such as *Helicosphaera sellii*, small *Gerphyrocapsa* spp., and *R. asanoi*, provide an upper age limit

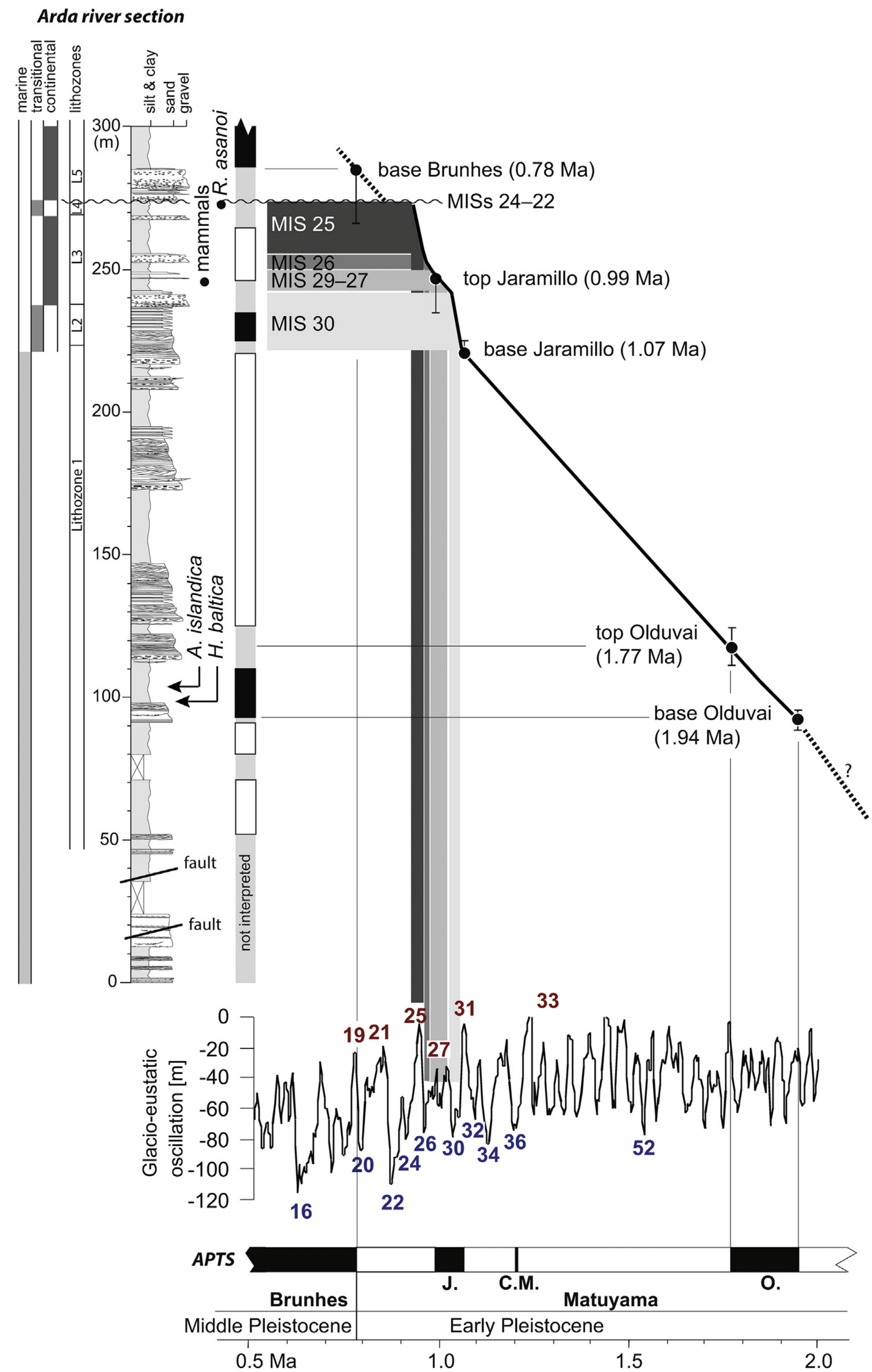

Figure 7. The Arda River section litho-magnetostratigraphy and key biostratigraphy correlated to the astrochronological polarity time scale (APTS) of Lourens et al. (2004) (J. = Jaramillo subchron, C.M. = Cobb Mountain subchron, O. = Olduvai subchron). The $\delta^{18}O$ record of Shackleton (1995), scaled to the glacio-eustatic drop at the last glacial maximum time (Fairbanks, 1989), is placed aside the APTS. Even numbers in red above the glacio-eustatic curve represent warm marine isotope stages (MISs), while odd numbers in blue below the curve represent cold stages. Key fossil occurrences are also indicated on the Arda lithostratigraphic log. L2 = lithozone 2; L3 = lithozone 3; L4 = lithozone 4; L5 = lithozone 5. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

for the sampled level; in particular, the presence of *R. asanoi*, the youngest taxon recovered in the reworked assemblage, indicates *terminus post quem* sedimentation between 1.14 and 0.91 Ma (Rio et al., 1990; Raffi, 2002). We therefore interpret the normal polarity interval from 223 to ~235 m as a record of the Jaramillo subchron (1.07–0.99 Ma), and the normal polarity interval at the section top as a (partial) record of the Brunhes Chron with a base at 0.78 Ma (Fig. 7), in agreement with previous studies indicating that

Table 1
Key species and number of occurrences of nannofossils from three samples (#1, #2, and #3) collected in the Arda River section in the uppermost transitional-marine level at 275 m.

Sample	*Calcidiscus leptoporus*	*Coccolithus pelagicus*	*Gephyrocapsa caribbeanica*	*Gephyrocapsa oceanica*	*Gephyrocapsa* spp.	*Gephyrocapsa* spp. small	*Helicosphaera carteri*	*Helicosphaera sellii*	*Pseudoemiliania lacunosa*	Reworked Cretaceous	Reworked Palaeogene	*Scapholithus fossilis*	*Syracosphaera pulchra*	*Umbilicosphaera sibogae*	Reworked Neogene	*Pontosphaera* spp.	***Reticulofenestra asanoi***
#1	3	24	2	2	2	5	12		2	874	384		1	1	332		2
#1	2	33	1	3	2	7	11		2	411	312		1		389	1	
#1	3	42	2	3	2	11	23	2	2	421	412	1	1	1	532		

full and persistent continental sedimentation similar to that observed in these levels occurred in the greater Po basin during the Brunhes Chron (e.g., Muttoni et al., 2003; Scardia et al., 2012). The intervening reverse polarity intervals are interpreted as records of the Matuyama Chron (Fig. 7).

Five magnetochronologic tie points have therefore been used to erect an age model of sedimentation for the Arda River section: the base and top of the Olduvai (1.94 and 1.78 Ma, respectively), the base and top of the Jaramillo (1.07 and 0.99 Ma, respectively), and the Matuyama–Brunhes boundary (0.78 Ma) (Fig. 7). As stated previously, the polarity stratigraphy below the base Olduvai has not been interpreted. According to the proposed age model, the long-term (average) sediment accumulation rate between the top of the Olduvai and the base of the Jaramillo is ~15 cm/ky (=150 m/Ma). The transition from marine to fully continental conditions, represented by the regressive sequence starting with littoral sandstones at 200 m and evolving into the first fluvial conglomerates at 237 m, may correspond to the MIS 30 regression and lowstand at ~1.04 Ma within the Jaramillo (Fig. 7).

The mammal bed at 245 m is approximately dated to the MIS 27–29 interval centered at ~0.99 Ma (Fig. 7). This finding revises the age of the Early Galerian Colle Curti faunal unit, to which these mammals pertain, that was previously dated to the base of the Jaramillo (Coltorti et al., 1998). As pointed out in Muttoni et al. (2010), the magnetostratigraphy of the Colle Curti type section is difficult to evaluate because of the presence of pervasive normal polarity remagnetizations associated with iron sulphides (Coltorti et al., 1998). Finally, the uppermost transitional-marine level with *R. asanoi* is attributed to MIS 25 (~0.95 Ma), while the fluvial conglomerate at 275 m immediately above was presumably deposited during the profound glacioeustatic lowstand culminating with MIS 22 at ~0.9 Ma, which marks the first most prominent continental glaciation of the Pleistocene in the Alpine-Po basin region (Muttoni et al., 2003; Scardia et al., 2006).

Discussion

We use data from the Arda River section in conjunction with data from the coeval Stirone River (Gunderson et al., 2013, 2014), Enza River (Gunderson et al., 2012) and Monte Poggiolo (Muttoni et al., 2011) sections to reconstruct the timing of the marine–continental transition in the southern part of the greater Po basin (Fig. 8A and B). We excluded from discussion data from the Stirone River section (Fig. 8B) because the critical stratigraphic interval between the Olduvai and the Jaramillo is substantially reduced (only 20 m-thick) probably due to the growth of the Salsomaggiore thrust between 1.8 and 1.0 Ma (Gunderson et al., 2012, 2013). Inspection of Figure 8A reveals that the marine–continental transition was slightly diachronic: while marine conditions persisted at Monte Poggiolo in the early part of the post-Jaramillo Matuyama, in the western part of the southern Po basin, at Arda and Enza, littoral sediments were accumulating during MIS 30 within the Jaramillo. Continental to transitional conditions were first established along the entire ~230 km-long studied transect only at the MIS 22 lowstand and persisted during the ensuing MIS 22/MIS 21 sea level rise and MIS 21 high-stand at ~0.85 Ma (Fig. 8A).

A similar situation has been observed in several deep cores taken by the geological survey of Region Lombardy (RL cores) across the northern part of the Po basin (Scardia et al., 2006, 2012) (Fig. 8B). As Figure 8C suggests, while the western cores displayed continental sedimentation since the pre-Jaramillo Matuyama (e.g., RL3), it is only at and after MIS 22–20 that continental sedimentation was established in the more eastern cores (e.g., RL2, RL1). It appears therefore that a first major jump eastward of the coastline

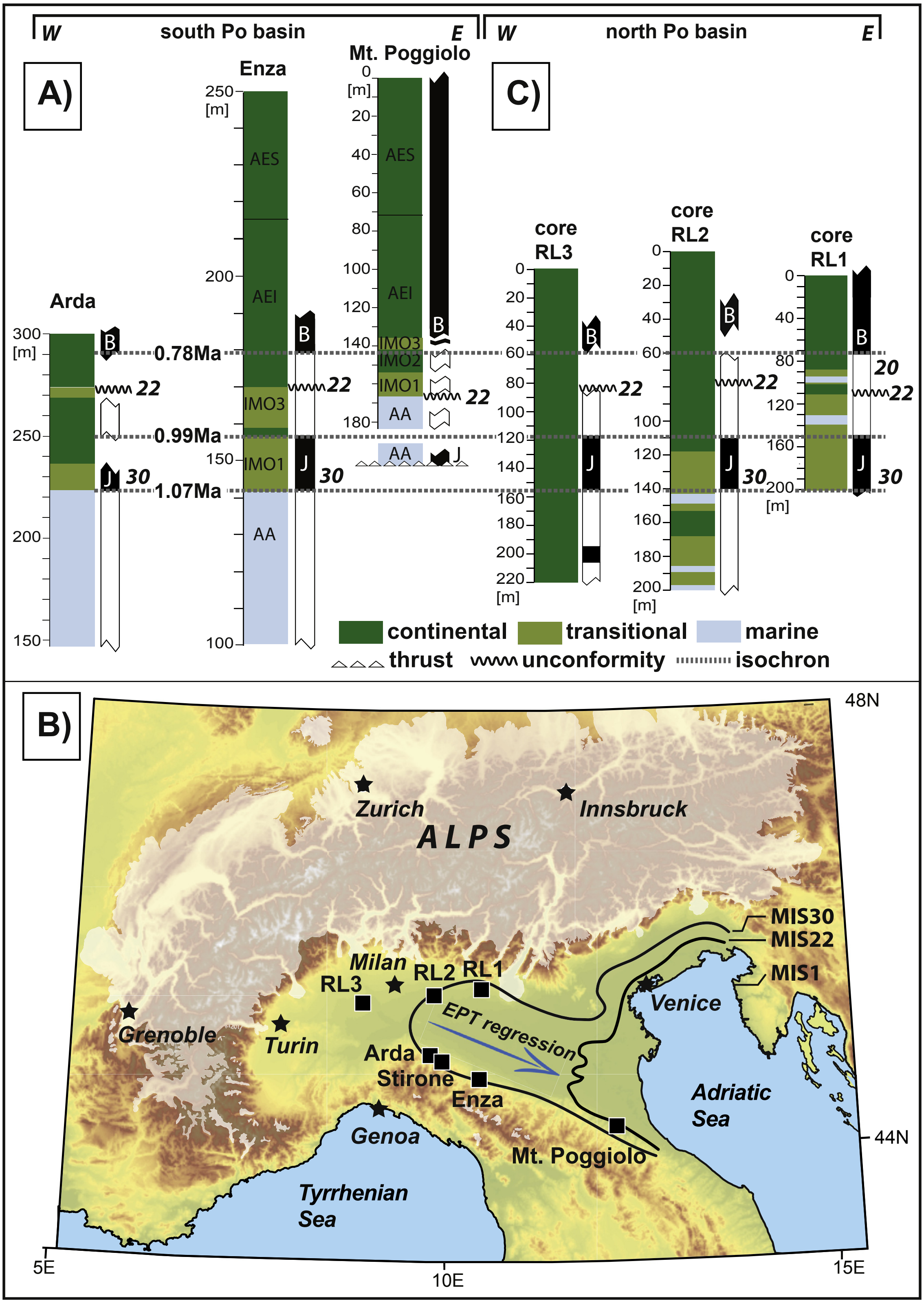

Figure 8. (A) Correlation of the litho-magnetostratigraphy of the Arda River section of this study with the Enza River (Gunderson et al., 2014) and Monte Poggiolo (Muttoni et al. (2011) litho-magnetostratigraphies from the southern part of the Po basin. (B) Paleogeography of the Po basin at the first major regression of the coastline in consequence of the MIS 22 lowstand during the late Early Pleistocene climate turnover (EPT). The EPT regression coincided with the full opening of the Po (and Danube) Galerian mammal migration pathway as described in Muttoni et al. (2014). (C) Correlation of the litho-magnetostratigraphies of selected deep cores (RL1, RL2, and RL3) from the northern part of the Po basin (Scardia et al., 2006, 2012). On magnetostratigraphic logs, black is normal polarity and white is reverse polarity; B = Brunhes Chron and J = Jaramillo subchron (reverse polarity intervals between Brunhes and Jaramillo and below Jaramillo are records of the Matuyama Chron); 30 = MIS30 (~1.05 Ma), 22 = MIS22 (~0.87 Ma); 20 = MIS20 (~0.80 Ma). AA = Argille Azzurre; IMO 1 = Imola sandstones member 1; IMO 2 = Imola sandstones member 2; IMO 3 = Imola sandstones member 3; AEI = Lower Emilia Romagna Synthem; AES = Upper Emilia Romagna Synthem (see Scardia et al., 2006, 2012; Calabrese et al., 2009 for further descriptions of these units).

was attained along the studied portion of the Po basin at the MIS 22 lowstand, which is represented in several cores by the so-called 'R' surface (or unconformity) that marks the progradation of high-energy alluvial fans from the southern Alps onto the Po basin (Muttoni et al., 2003; Scardia et al., 2006). MIS 22 represents the first major northern hemisphere continental glaciation of the Pleistocene (Shackleton and Opdyke, 1976; Berger et al., 1993; Shackleton, 1995; Head and Gibbard, 2005; Muttoni et al., 2003; Scardia et al., 2006, 2012) occurring during the so-called 'late Early Pleistocene climate turnover' (EPT, quoted in the literature also as 'late Early Pleistocene climate revolution' – EPR; Muttoni et al., 2014, 2015a).

The EPT coincided with a profound rejuvenation of the environment and the mammal fauna with the substitution of old Villafranchian by new Galerian elements (Palombo and Mussi, 2006; Manzi et al., 2011; Muttoni et al., 2014; Palombo, 2014). In particular, Muttoni et al. (2014) speculated that large mammals, and possibly hominins with them, may have migrated to Europe starting at around 0.9 Ma because the EPT generated for the first time in the Pleistocene vast and exploitable ecosystems for African and Asian mammals especially along a conjunct Po-Danube gateway connecting southern Europe with the Balkans (see Figure 4 in Muttoni et al., 2014). These new environments were characterized by stable continental lowlands with open grassland vegetation and reduced woody cover during the onset of glacial/interglacial transitions (starting with MIS 22/MIS 21) (see references to key pollen data and discussion in Muttoni et al., 2014). While the African and Asian immigrants may have exploited the Po-Danube gateway, other species may have migrated to southern Europe from north of the Alps or were simply redistributed across the continent; in that respect, there probably existed multiple entry points that collectively generated the Galerian turnover in the Italian peninsula (see also Palombo, 2014). In this respect, the hypothesis of the Po-Danube migration gateway (Muttoni et al., 2014) builds upon and complements earlier works on the mammal dispersal dynamics during the Pleistocene (Palombo and Mussi, 2006; Manzi et al., 2011; Palombo, 2014) because it provides the geological mechanism for the complex faunal turnover at the EPT.

The Arda mammal association, characterized by mixed Villafranchian and Early Galerian taxa attributed to MIS 27–29 at ~0.99 Ma, seems to conform to this scenario whereby it registers the beginning of the rapid Galerian replacement of older Villafranchian taxa. *Sus strozzii* is a typical Villafranchian taxon, present in the Italian peninsula up to the Early Pleistocene pre-Jaramillo Farneta faunal unit (Gliozzi et al., 1997; Masini and Sala, 2007), while our data indicates its presence up to ~0.99 Ma at the top of the Jaramillo. It co-existed with Galerian 'newcomers' like *Bison* sp., a more evolved form than previous *Eobison*, and with *U. dolinensis*, which may have immigrated from central Europe where it was found at Untermassfeld (Germany) in levels attributed to MIS 31 at the base of the Jaramillo (Kahlke, 2006; Kahlke et al., 2011; Maul and Markova, 2007). It is however only when fully continental conditions were established in the Po basin during (and after) the EPT regression that the Galerian faunal turnover could take place in its full extent with a total rejuvenation of the fauna. At that time is recorded the entrance in the Italian peninsula of megaherbivores requiring a large dietary supply such as the straight-tusked elephant (*Elephas antiquus*), the steppe mammoth (*Mammuthus trogontherii*) and the red deer (*Cervus elaphus acoronatus*). These are among the most representative species of the far-traveled Galerian elements that migrated from Africa-Levant and Asia into Europe since around 0.9 Ma (Muttoni et al., 2014, 2015a and references therein), shortly after the Arda fauna with its mixed Villafranchian-Early Galerian European elements.

Conclusions

Our data from the Arda River section confirms that the progressive infill of the Po basin driving the transition from marine to fully continental environments was established only during the EPT since MIS 22 (Fig. 8) in the same magnetochronologic window that is believed to include also some of the best-dated sites with evidence of the first entrance in Europe of far-traveled megaherbivore immigrants (e.g., Muttoni et al., 2015a). This is also the same magnetochronologic window of the earliest stable peopling of Europe according to the critical analysis of key fossil sites from Iberia and Italy of Muttoni et al. (2014 and references therein), albeit we acknowledge that the late Early–early Middle Pleistocene paleoanthropological record of Italy is still scanty, with only two well-dated sites at ~850 ka (Muttoni et al., 2011) and 600 ka (Coltorti et al., 2005). The ongoing debate, recently summarized in Muttoni et al. (2015b), is centered on the question of whether the first peopling occurred in post-Jaramillo (and pre-Brunhes) times as a direct consequence of the EPT (Muttoni et al., 2013, 2014, 2015a), or before the Jaramillo (e.g., Carbonell et al., 2008; Toro-Moyano et al., 2013) during times of no particular climatic or ecologic turnover.

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3

AGE OF *Mammuthus trogontherii* FROM KOSTOLAC, SERBIA, AND THE ENTRY OF MEGAHERBIVORES IN EUROPE DURING THE LATE MATUYAMA CLIMATE REVOLUTION

My personal contribution in this work started in July 2013 with week of fieldwork in the Kostolac site where my personal duty consisted in collecting all the samples subjected to AF demagnetization. Afterwards I did the entire analysis set on all the collected samples in the Alpine Laboratory of Paleomagnetism of Peveragno (Cuneo) and did the interpretation of the data. Afterwards I contributed to the creation of the figures and in the writing of the paper, as well as to check the completeness and the correctness of the references.

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Age of *Mammuthus trogontherii* from Kostolac, Serbia, and the entry of megaherbivores into Europe during the Late Matuyama climate revolution

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ABSTRACT

At the Drmno open-pit coal mine near Kostolac in Serbia, a nearly complete skeleton of *Mammuthus trogontherii* (nicknamed Vika) was discovered in a fluvial deposit overlain by a loess–paleosol sequence where a second paleontological level named Nosak with remains of *M. trogontherii* was found. We studied the magnetostratigraphy of the Kostolac sedimentary sequence and found that the Vika layer dates to ~0.8 Ma, shortly before the Brunhes–Matuyama boundary. In addition, according to our age model and previously reported optically stimulated luminescence and electron spin resonance dates, the Nosak fossils have an estimated age of 0.19 Ma and lived during the earliest part of Marine Isotope Stage 6. It appears therefore that at Kostolac, *M. trogontherii* is preserved both at its earliest occurrence at ~0.8 Ma and close to its latest occurrence at 0.19 Ma, and may well have been present in between, albeit not yet found. We speculate that megaherbivores such as *M. trogontherii* entered Europe along a conjunct Danube–Po River migration conduit connecting western Asia-Levant with central-southern Europe where vast and exploitable ecosystems, particularly suited for steppe- or savanna-adapted megaherbivores from Asia and Africa, developed during the late early Pleistocene climate revolution at around 0.8 Ma.

Introduction

The Drmno open-pit coal mine near Kostolac in Serbia (Fig. 1A, B) yielded a nearly complete and in situ skeleton of *Mammuthus trogontherii*, informally named Vika (Lister et al., 2012), from a fluvial sand interval (Fig. 2A) sealed by a thick loess–paleosol succession (Fig. 2B), itself containing a second paleontological layer, termed Nosak, with fossils of the same mammoth species (Marković et al., 2014; Dimitrijević et al., 2015).

M. trogontherii is an Asian immigrant that is commonly regarded to have reached the eastern fringes of Europe at ~1.0 Ma and central Europe just before the 0.78 Ma Brunhes–Matuyama boundary (Lister et al., 2005; Kahlke, 2014; see also discussion below). Muttoni et al. (2014) recently hypothesized that large mammals and hominins, interlinked in a common food web, expanded into Europe along a conjunct Danube–Po Gateway during the late Early Pleistocene (Late Matuyama) climate revolution (hereafter referred to as EPR) broadly starting at ~0.9 Ma (Muttoni et al., 2014). The level with the first occurrence of *M. trogontherii* at Kostolac might therefore represent a stratigraphic expression of the EPR in the Danube Valley (similar to the 'R surface' in the Po Valley dated at ~0.9 Ma; Muttoni et al., 2003; Scardia et al., 2006) along which paleontological and anthropological surveys in search for Asian and African mammal immigrants, including early hominins, could productively focus (Muttoni et al., 2014).

In this paper, we report the magnetostratigraphy of the Kostolac sedimentary record and find that the Vika layer dates to the Late Matuyama, shortly before the Brunhes–Matuyama boundary (0.78 Ma; time scale of Lourens et al., 2004). With a new estimated age of ~0.8 Ma, Vika, which was until recently only broadly constrained between 1.0 and 0.4 Ma (Lister et al., 2012), now represents one of the best-dated and oldest fossils of *M. trogontherii* in Europe. In addition, the Nosak *M. trogontherii* fossils, with an estimated age of 0.19 Ma (Dimitrijević et al., 2015), appear to be among the youngest of this taxon in Europe (Lister and Sher, 2001). Hence, it seems that Kostolac represents a remarkable paleontological site where *M. trogontherii* is preserved at the limits of its temporal range.

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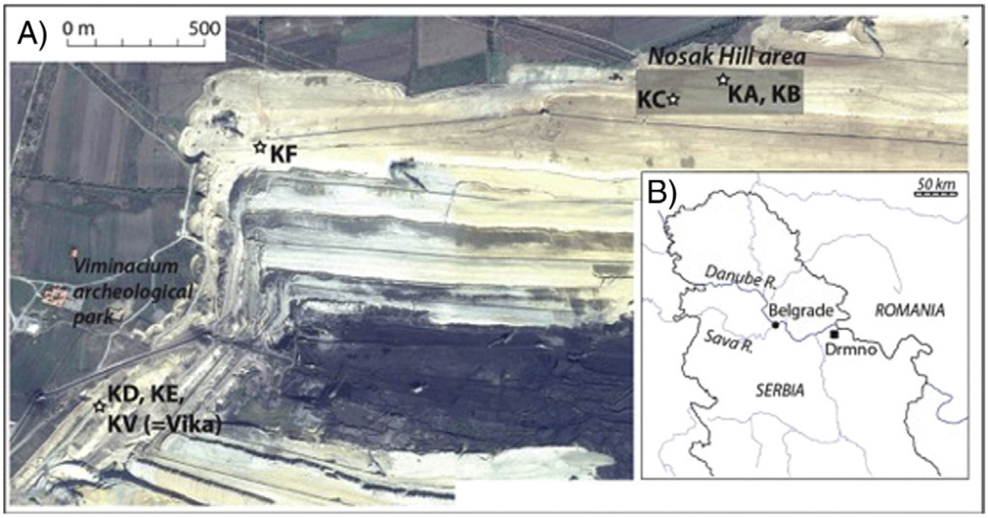

Figure. 1. (A) Google Earth map (2013) of the Drmno open-pit coal mine with location of the sampling sites of this study: sites KD–KV–KE (44°43′50″N, 21°14′21″E), site KF (44°44′17.85″ N, 21°14′23.85″E), and site KC (44°44′22.51″N, 21°15′27.18″E). Sites KA–KB (44°44′24.32″N, 21°15′34.70″E) are located in the same general area of the Nosak Hill site of Marković et al. (2014) (shaded rectangle); notice that because the quarry front is rapidly advancing due to extraction activity, these sites no longer exist. (B) The Drmno open-pit coal mine is located in Serbia, ~90 km southeast of Belgrade near the town of Kostolac.

Geological settings

The stratigraphy of the Kostolac basin is made available by extensive coal mining excavations. The strata consist of Pontian (= latest Miocene Paratethys stage, coeval with the Messinian) lacustrine deposits and deltaic sands, unconformably overlain by Pleistocene deposits divided into a lower complex of fluvial sediments and an upper complex of loess–paleosols (Lister et al., 2012; Marković et al., 2014; Dimitrijević et al., 2015).

The Pleistocene lower complex is composed of gravel, cross-bedded sands, and organic-rich silt interpreted as fluvial-channel deposits, interbedded with fine-grained, massive or laminated, organic-rich sediments interpreted as overbank deposits. The skeleton of Vika was unearthed in 2009 in the southwestern part of the open-pit mine (Fig. 1A, site KV) while a large excavation digger was removing the sediment overburden to access the underlying coal beds. The paleontological layer is located at the base of the lower complex at an elevation (above standard sea level) of approximately 58 m, about 5 m below the base of the loess–paleosol sequence (Lister et al., 2012) (Fig. 3, site KV). The digger destroyed the left side of the skull and damaged the bones of the left front leg. All other elements of the skeleton are present, including preserved counterparts on the right side. Vika is the first largely complete and anatomically articulated skeleton of this species found in the Balkan Peninsula and the Mediterranean area. Moreover, the skeleton is preserved in the animal's death posture, which is an exceptional taphonomic situation for any fossil specimen (Lister et al., 2012).

The upper complex comprises a succession of loess layers and paleosols. At the Nosak Hill site (Fig. 1A), Marković et al. (2014) reported the lithology and magnetic susceptibility of a 25.4-m-thick loess–paleosol sequence from 72.3 m to 97.7 m in elevation. Starting at the top, soil S0 is underlain by extended loess L1, then by soil S1, loess L2,

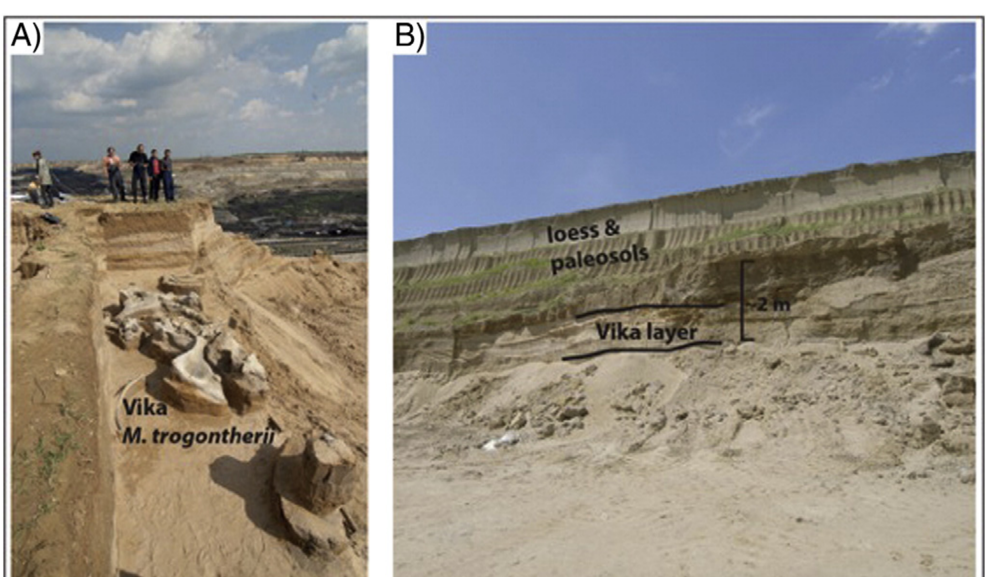

Figure. 2. The skeleton of Vika (*Mammuthus trogontherii*) unearthed in 2009 (A) in fluvial layers overlain by a loess–paleosol sequence (B).

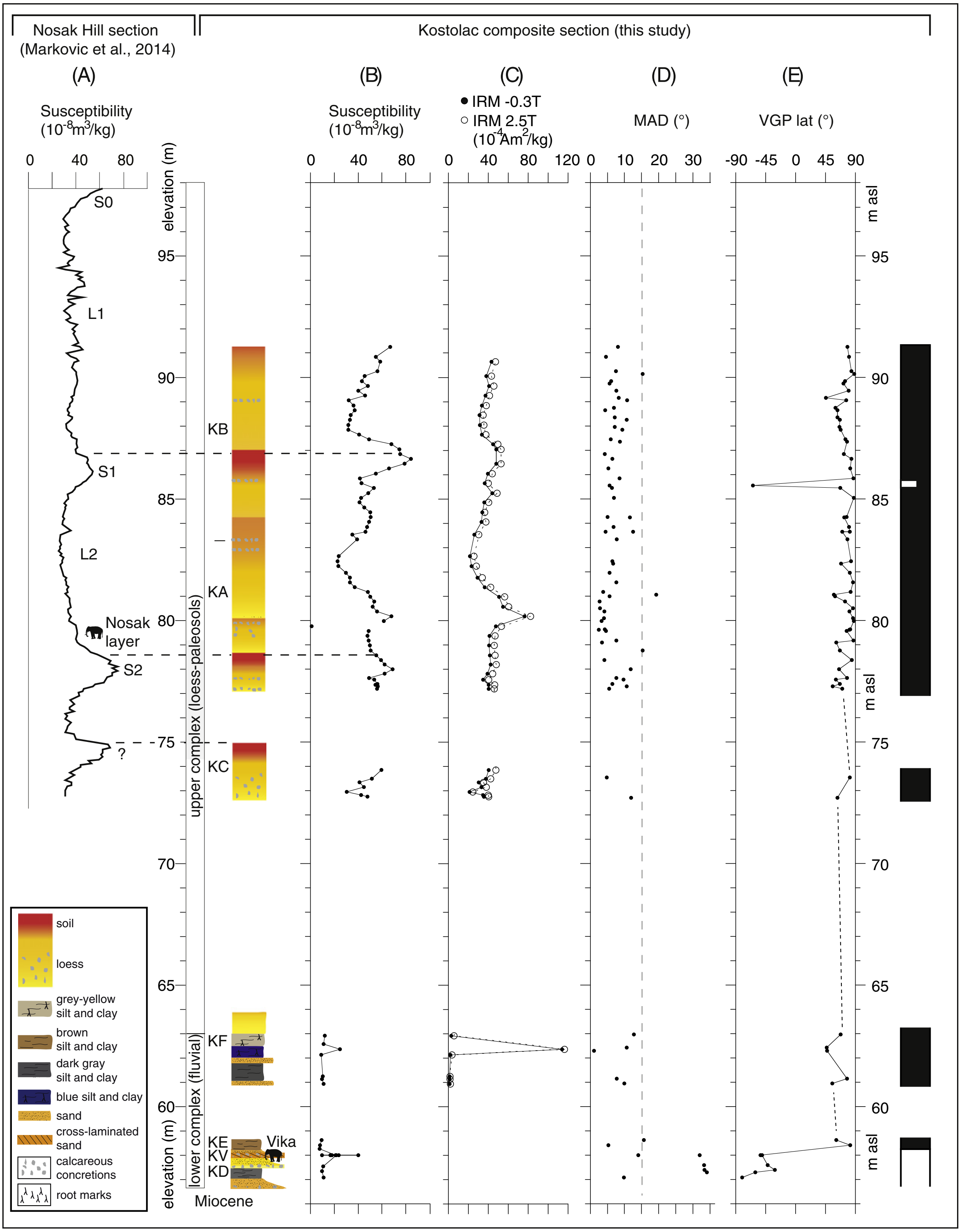

Figure. 3. From left to the right: the magnetic susceptibility profile of the Nosak Hill section of Marković et al. (2014) (A) correlated to the Kostolac composite section of this study (expressed in meters of elevation) with indication of sampling sites KD–KV–KE, KF, KC, and KA–KB, and the associated magnetic susceptibility (B) and $IRM_{-0.3T}$ and $IRM_{2.5T}$ (C) profiles. Characteristic magnetic component directions from thermally or AF demagnetized samples (maximum angular deviation [MAD values in D) have been used to calculate virtual geomagnetic pole (VGP) latitudes (E) and magnetic polarity for the Kostolac composite section (black is normal polarity, white is reverse polarity). See text for discussion.

and, finally, a basal couplet of soils labeled S2 and '?' (soil and loess nomenclature after Marković et al., 2014) (Fig. 3A). This sequence was attributed by Marković et al. (2014) to the last glacial–interglacial cycles of Marine Isotope Stage (MIS) 1 to MIS 7, using magnetic susceptibility correlations with sections from the literature and two preliminary post-IR infrared stimulated luminescence (post-IR IRSL) dates indicating minimum ages of 0.15 Ma for the base of L2 (Marković et al., 2014). This latter attribution has been recently confirmed by a new electronic spin resonance (ESR) date of 0.192 ± 0.005 Ma on a mammoth molar from the Nosak fossil layer located at the base of loess L2 (Dimitrijević et al., 2015; see also below). In addition, the couplet of cambisols S2 and '?' located below L2, and characterized by a well-developed B horizon, displays similarities with the Basaharc double soil complex at Paks, Hungary (Sartori et al., 1999), dated with the post-IR IRSL method to MIS 7 (Thiel et al., 2014). Therefore, key loess interval L2 should correspond to MIS 6 (see also age model below).

The Nosak fossil layer lies at ~79–80 m in elevation and ~20 m above the Vika layer, at the base of loess L2 (Fig. 3A). Skeletal remains, scattered over an area up to 10 m wide and 130 m long within this layer, were excavated in 2012; preliminary analyses indicate remains from at least four mammoths, a horse, and a cervid that, according to recent ESR analyses, lived 0.192 ± 0.005 Ma ago during the earliest part of MIS 6 (Dimitrijević et al., 2015).

Sites sampled for paleomagnetic analyses are (Fig. 1A): KD–KV–KE, consisting of three stratigraphically superposed sites encompassing the Vika layer (KV), site KF located 1 km to the NE of sites KD–KV–KE, site KC located 1.4 km to the ENE of site KF, and stratigraphically superposed sites KA–KB located 0.2 km to the ENE of site KC. Sites KC and KA–KB are in the same general area of the Nosak Hill site of Marković et al. (2014), which, however, no longer exists due to coal extraction activity (Fig. 1A). Altimetric leveling and visual lateral tracing of marker beds were used to construct a common stratigraphic scheme of the sites in a Kostolac composite section expressed in meters of elevation (Fig. 3).

Paleomagnetism and magnetostratigraphy

We conducted paleomagnetic analyses on a total of 152 stratigraphically superposed samples from the Kostolac composite section. The sample set consisted of 55 standard 10-cm^3 core samples that were drilled in the field with a cordless drill and oriented with a magnetic compass, and an additional 97 oriented samples that were obtained by inserting 10-cm^3 plastic boxes into outcrop sections. Thermal demagnetization was applied to the all 55 core samples, and alternating field (AF) demagnetization to 49 of the 97 plastic box samples, with the natural remanent magnetization (NRM) measured after each step on a 2G-Enterprises DC squid cryogenic magnetometer in a magnetically shielded room. Standard least-square analysis was used to calculate component directions from selected segments of vector end-point diagrams. Rock-magnetic properties were studied on 13 plastic box samples by means of isothermal remanent magnetization (IRM) backfield acquisition curves. Forty-eight plastic box samples were also given an IRM of 2.5 T in one direction ($IRM_{2.5T}$ = saturation IRM or SIRM) and of 0.3 T in the opposite direction ($IRM_{-0.3T}$). The initial magnetic susceptibility was measured on the 97 plastic box samples with an Agico Kappabridge KLY-2. IRM and susceptibility values were normalized by weight. All experiments were conducted at the Alpine Paleomagnetic Laboratory at Peveragno (Italy).

Samples from fluvial sediments below the loess–paleosol sequence (sites KD–KV–KE, and KF) are characterized by IRM acquisition curves that approach saturation by ~300 mT, but then continue to gently climb up to the highest applied fields of 2500 mT (Fig. 4); this behavior is interpreted as due to the presence of low coercivity magnetite in association with high coercivity hematite. Samples from the loess–paleosol sequence (sites KC and KA–KB) are dominated by a magnetic phase that shows tendency to saturate by ~300 mT (Fig. 4) interpreted as magnetite. Maximum unblocking temperatures of the natural remanent magnetization (NRM) on the order of 575°C confirm the presence of magnetite as main carrier of the magnetic remanence in the loess–paleosol sequence (see also below).

The initial susceptibility, normalized by sample weight, shows low values less than about 20×10^{-8} m^3/kg in the lower fluvial complex and higher values in the upper loess–paleosol complex, where peak values of ~90×10^{-8} m^3/kg are attained in the more developed paleosol intervals (Fig. 3B). The susceptibility profile coupled with elevation data were used to correlate our Kostolac composite section to the Nosak Hill section of Marković et al. (2014). High susceptibility values of Nosak Hill soil S1 were correlated to high susceptibility values of the soil at 86.5 m of the Kostolac composite section (Fig. 3A, B). The double cambisol pedocomplex in the lower part of the Nosak Hill section, termed S2 and '?' in Marković et al. (2014), is tentatively correlated to similar rubified paleosols with clay-rich B horizons located at 78.5 and 74.5 m of the Kostolac composite section (Fig. 3A, B). According to this correlation, the uppermost Nosak Hill soil S0 lies ~7 m above the top of the Kostolac composite section.

The $IRM_{2.5T}$ and $IRM_{-0.3T}$ values are similar (Fig. 3C) and tend to mimic the susceptibility trend with highest values in the pedogenized parts of the sequence related to higher concentrations of ferromagnetic minerals. The resulting 'S'-ratio, calculated as $IRM_{-0.3T}$/SIRM (not shown), is generally comprised between 0.8 and 0.9, except for the lowermost samples from the fluvial unit with S-ratios of 0.5–0.7.

Characteristic remanent magnetization (ChRM) component directions have been isolated in 70 samples with progressive demagnetization from room temperature or null up to a maximum of ~575°C or ~100 mT alternating field (AF)(Fig. 5A) and are characterized by maximum angular deviation (MAD) values of generally less than 15° except for the lowermost samples with MADs of ~30–35° (Fig. 3D). These ChRM directions have been found to be oriented either north and down (positive inclination) or south and up (negative inclination) (Fig. 5A) with an overall mean in common polarity of Dec. = 3.3°E, Inc. = 52.9° (Fig. 5B). The latitude of the virtual geomagnetic pole (VGP) derived from each ChRM direction relative to the mean paleomagnetic (north) pole axis was used for interpreting polarity stratigraphy (Fig. 3E). VGP latitudes approaching +90° or −90° are interpreted as recording normal or reverse polarity, respectively. The fluvial layers of the lower complex, including the layer hosting the Vika fossil, are characterized by relatively poorly defined reverse polarity. The overlying loess–paleosol sequence of the upper complex exhibits normal polarity. The reverse–normal polarity transition is placed at ~58.3 m, immediately above the Vika layer. A one-sample-based reverse polarity excursion is observed at level ~85.5 m (Fig. 3E).

The main polarity reversal at ~58.3 m most probably represents a record of the Brunhes–Matuyama boundary (0.78 Ma), which would imply substantial stratigraphic continuity throughout the studied sequence. Alternatively, it could represent a record of an older polarity reversal, such as the Jaramillo–Matuyama boundary (1.07 Ma), which would imply a hiatus of about 200 ka between the lower fluvial and the upper loess–paleosol sequences. Unconformities with lack of deposition may arise from reduction of accommodation space due to uplift, as in the case of the northern Po River basin in northern Italy, which, after a prolonged period of regional subsidence, experienced isostatic uplift during the middle Pleistocene becoming an area of bypass for sediments (Scardia et al., 2012). There is, however, no evidence to our knowledge of uplift of the Kostolac basin during the late early Pleistocene that could trigger the formation of such long-lasting unconformities. The presence of an erosional hiatus is even less viable considering that no paleosol has been observed at the top of the fluvial succession. Besides, loess deposition is a low-energy settling process hardly capable of eroding underlying sediments.

In conclusion, we infer that the observed polarity reversal represents a record of the Brunhes–Matuyama boundary (0.78 Ma) preserved within a substantially continuous stratigraphic sequence. This preferred interpretation is in substantial agreement with previous chronologies that place the onset of loess deposition in the Danube valley shortly below the Brunhes–Matuyama boundary (Sartori et al., 1999; Marković et al., 2011; Fitzsimmons et al., 2012; Marković et al., 2012, 2014).

Age model of sedimentation

Using magnetostratigraphy coupled with correlation of the extended loess–paleosol sequence of China (Ding et al., 2005) and Europe (Marković et al., 2011; Fitzsimmons et al., 2012; Marković et al., 2012,

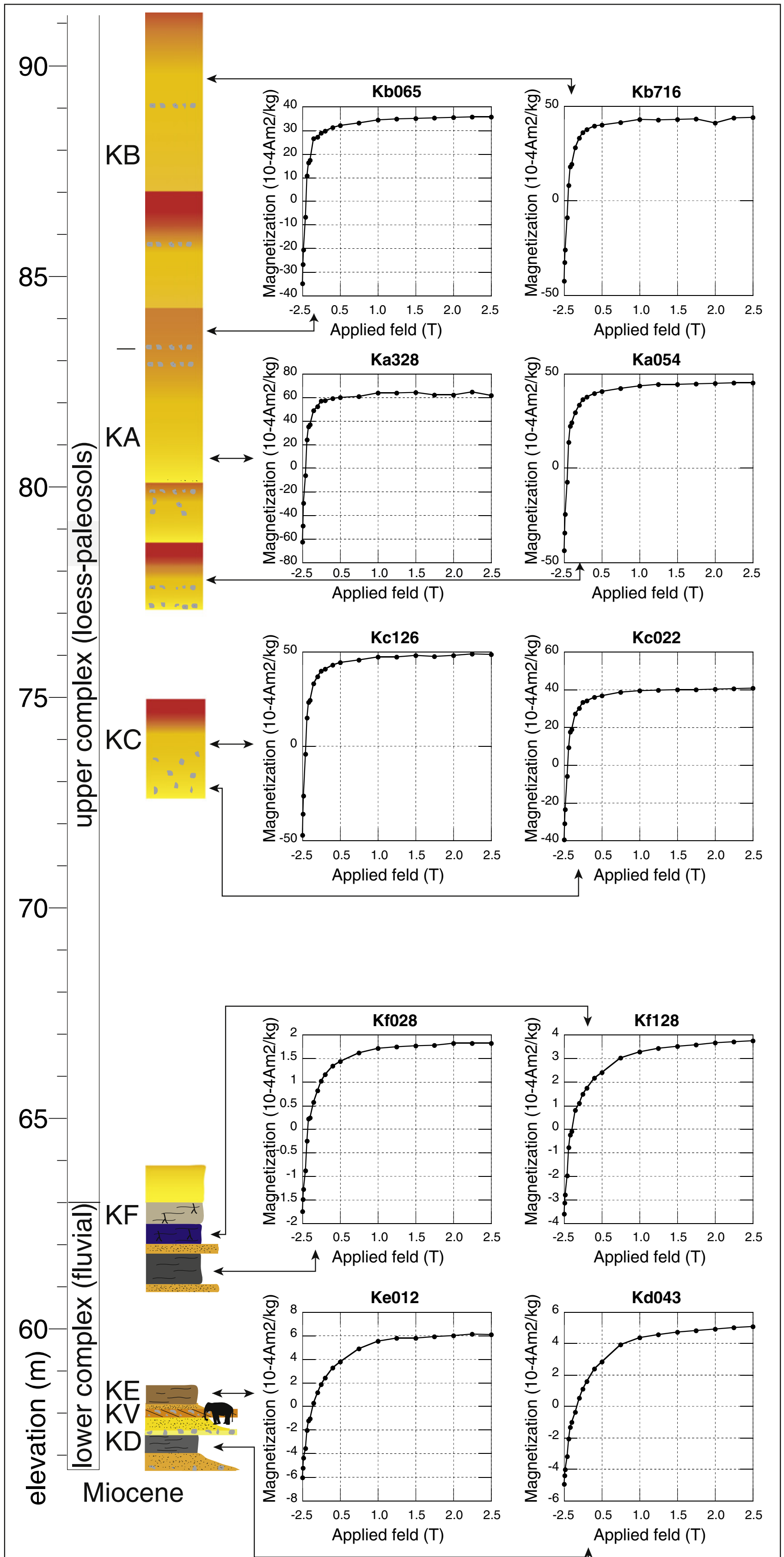

Figure. 4. Isothermal remanent magnetization (IRM) backfield acquisition curves on representative samples from the Kostolac sediments showing the presence of variable amounts of low- and high-coercivity magnetic components interpreted as magnetite and hematite, respectively. See text for discussion.

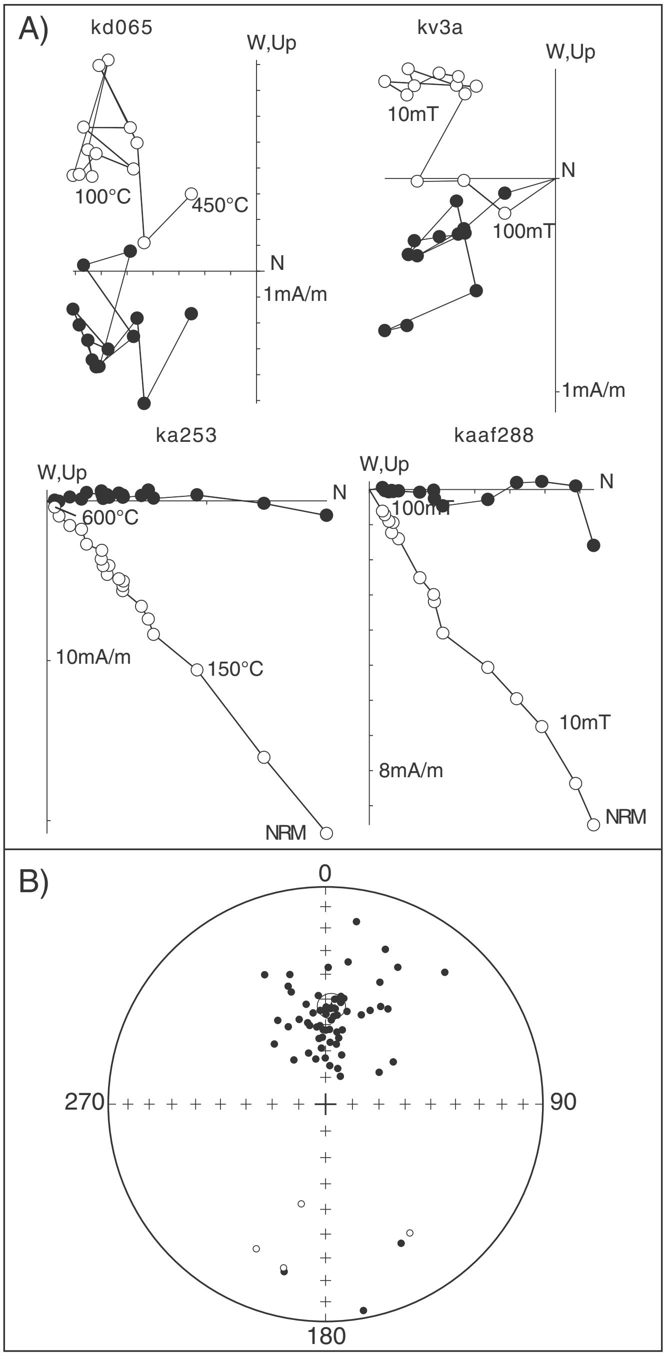

Figure. 5. (A) Vector end-point demagnetization diagrams of representative samples displaying characteristic magnetic component directions of reverse (Kd065, Kv3a) and normal (Ka253, Kaaf288) magnetic polarity. Closed symbols are projections onto the horizontal plane and open symbols onto the vertical plane. Demagnetization temperatures are expressed in °C or mT. (B) Equal-area projection of the characteristic remanent magnetization component directions and associated Fisher statistics mean direction (Dec. = 3.3°E, Inc. = 52.9°, k = 13, α95 = 4.9°, N = 70); closed (open) symbols represent down-pointing (up-pointing) directions.

2014) with the standard benthic δ^{18}O record (Lisiecki and Raymo, 2005), an age model of sedimentation has been constructed for the Kostolac composite section that takes into account the following tie points, from top to bottom (Fig. 6):

1) Soil S0 centered at ~98 m is attributed to MIS 1.
2) Soil S1 centered at ~86.5 m is attributed to MIS 5e; the reverse polarity excursion observed at ~85.5 m could represent a partial record of the Blake event, dated to ~0.115–0.120 Ma (Singer, 2014) and falling in the late Eemian (MIS 5e; Thouveny et al., 2008).
3) The Nosak level with *M. trogontherii* at the base of loess L2 is dated to 0.192 ± 0.005 Ma in the earliest part of MIS 6 according to (preliminary) ESR dating (Dimitrijević et al., 2015).
4) The cambisol couplets S2 and '?' centered at ~78.5 m and ~74.5 m are attributed to MIS 7a and MIS7e, respectively.
5) The Brunhes–Matuyama boundary at 0.78 Ma occurs at ~58.3 m.

According to this age model, the lowermost occurrence of *M. trogontherii* in the Vika layer has an extrapolated age of ~0.8 Ma and should fall within MIS 20 or at the MIS 20/MIS 19 termination, whereas the uppermost occurrence of *M. trogontherii* in the Nosak layer is dated to 0.19 Ma in the early part of MIS 6 (Fig. 6). The large stratigraphic gap between site KF and KC and the general lack of chronologic control points in the lower part of the Kostolac composite section (apart from the Brunhes–Matuyama boundary) makes it difficult to estimate the age of onset of loess deposition recorded in site KF, which presumably falls in the MIS 12–MIS 16 range (Fig. 6).

Discussion and conclusions

Although the dispersal of *M. trogontherii* from Asia into Europe is generally accepted to have occurred sometime before the Brunhes–Matuyama boundary (e.g., Lister et al., 2005; Palombo and Ferretti, 2005; Kahlke, 2014), there are in fact very few stratigraphic sections in Europe with remains of *M. trogontherii* that have reliable pre-Brunhes (>0.78 Ma) ages. Disregarding the molar fragment of *M. trogontherii* from Kärlich in Germany of insecure stratigraphic provenance (Lister et al., 2005), as well as the Kolkotova Balka site near Odessa at the gates of Europe for which we could not access and evaluate the original paleomagnetic data (Dodonov et al., 2006 and references therein), the only remaining European site that yielded *M. trogontherii* remains (molars) from levels that pre-date the Brunhes–Matuyama boundary is Dorn-Dürkheim 3 in Germany (Franzen et al., 2000; see also Lister et al., 2005; Kahlke, 2014). In this respect, the Kostolac sedimentary record appears to boast the remarkable characteristic of preserving in a continuous stratigraphy both the earliest occurrence in Europe of *M. trogontherii* at ~0.8 Ma in the latest Matuyama (Vika) and its last occurrence at 0.19 Ma at the onset of MIS 6 (Nosak), probably later than the commonly accepted last occurrence at ~0.2 Ma during MIS 7 (Lister and Sher, 2001; Lister et al., 2005).

M. trogontherii seems to have immigrated to Europe from Asia at broadly the same time (within a climatic cycle of typically 100 kyr) as *Elephas antiquus* came from Africa. The oldest remains in Europe of *E. antiquus* have been reported in the Torrent de Vallparadís section of northeastern Spain in levels of unit EVT7 (Martínez et al., 2010, 2014). Unit EVT7 yielded reverse magnetic polarity between the top of the Jaramillo (0.99 Ma) and the base of the Brunhes (0.78 Ma) (Madurell-Malapeira et al., 2010; see also Madurell-Malapeira et al., 2012 and Garcia et al., 2012), and is associated with an average age of 0.83 Ma based on ESR-U/series dating of two equine molars and OSL dating of four quartz grain samples (Martínez et al., 2010, 2014). This is virtually the same age as the weighted mean ESR age of 0.86 Ma obtained on quartz grains from level EVT7 (Duval et al., in press). Older age estimates of ~0.9 Ma based on micromammal analyses have been recently questioned by Martin (2014) and Muttoni et al. (2015).

In the Guadix-Baza basin of southeastern Spain, the ~30-m-thick Puerto Lobo section yielded a record of the Brunhes–Matuyama boundary (Gibert et al., 2007). The Huéscar-1 paleontological site with remains of *E. antiquus* (Gibert et al., 2007, table 1 and references therein; but see Lister, 2004), was traced ~10 m below the Brunhes–Matuyama boundary and presumably above the Jaramillo, which was not found in the section.

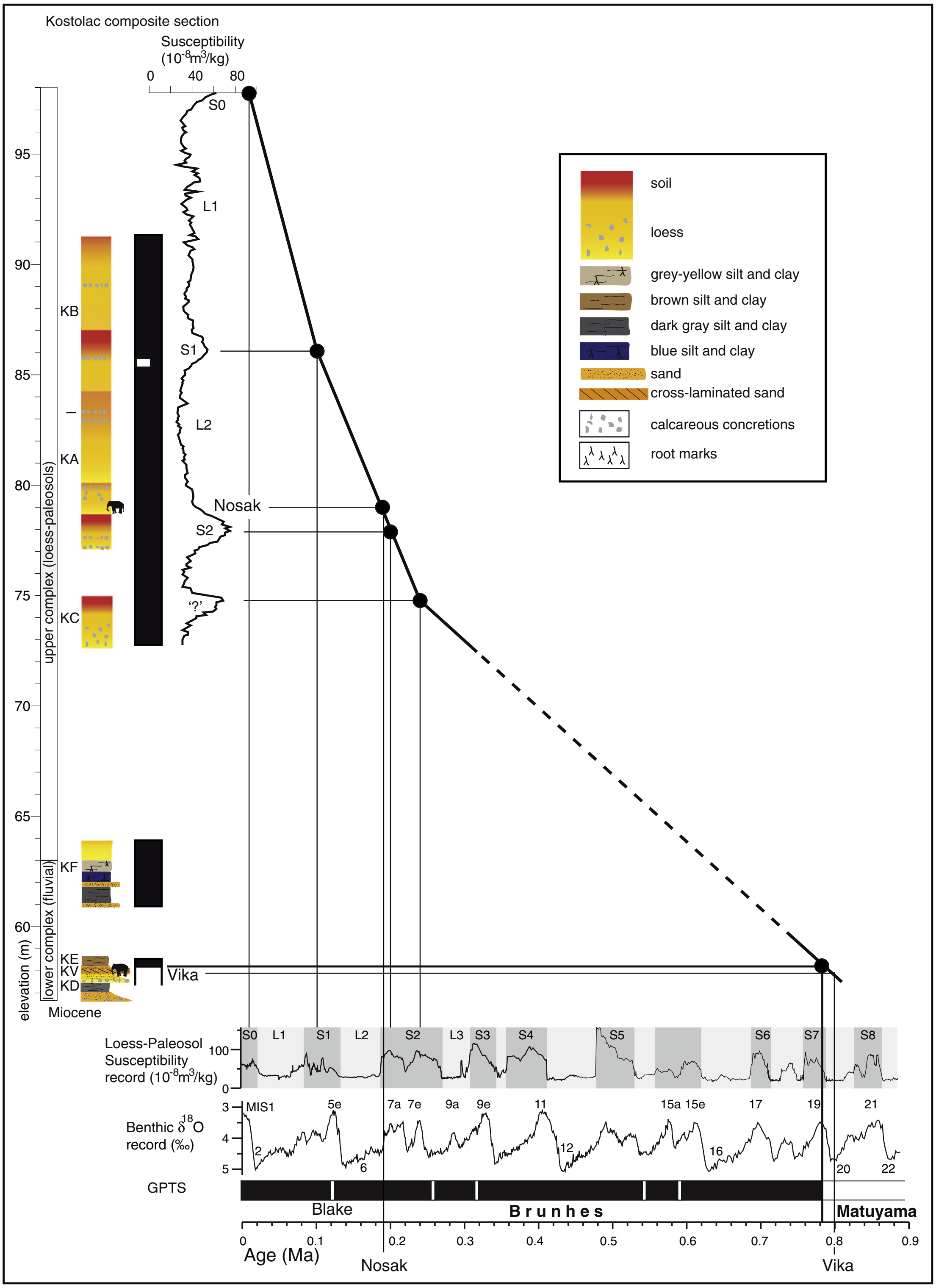

Figure. 6. Age model of sedimentation of the Kostolac composite sequence investigated in this study. On the horizontal axis is the geomagnetic polarity time scale (GPTS) of Lourens et al. (2004) placed aside the δ^{18}O record of Lisiecki and Raymo (2005) with indication of marine isotope stages (MISs) from MIS 1 to MIS 25, and the magnetic susceptibility expression of the loess (L)–paleosol (S) sequence of Ding et al. (2005). On the vertical axis is the Kostolac composite litho-magnetostratigraphy of this study correlated to the Nosak Hill magnetic susceptibility profile of Marković et al. (2014), arranged in meters of elevation. The Vika *M. trogontherii* has an extrapolated age of ~0.8 Ma and should fall within MIS 20 or the MIS 20/MIS 19 termination. The Nosak *M. trogontherii* is dated to 0.19 Ma in the earliest part of MIS 6. See text for discussion.

Muttoni et al. (2014) speculated that megaherbivores such as *M. trogontherii* and *E. antiquus* may have been 'pushed-and-pulled' into Europe in response to changes in African and southern European climate at the inception of higher amplitude glacial oscillations of the EPR centered on MIS 22 (~0.9 Ma) in the Late Matuyama. Megaherbivore expansion apparently occurred on stable lowlands developed as the Po and Danube deltas prograded into the Adriatic Sea and Black Sea, respectively, during the EPR (Muttoni et al., 2014 and references therein) (Fig. 7). Colonization of these lowlands by grassland vegetation with reduced woody cover, especially during the onset of

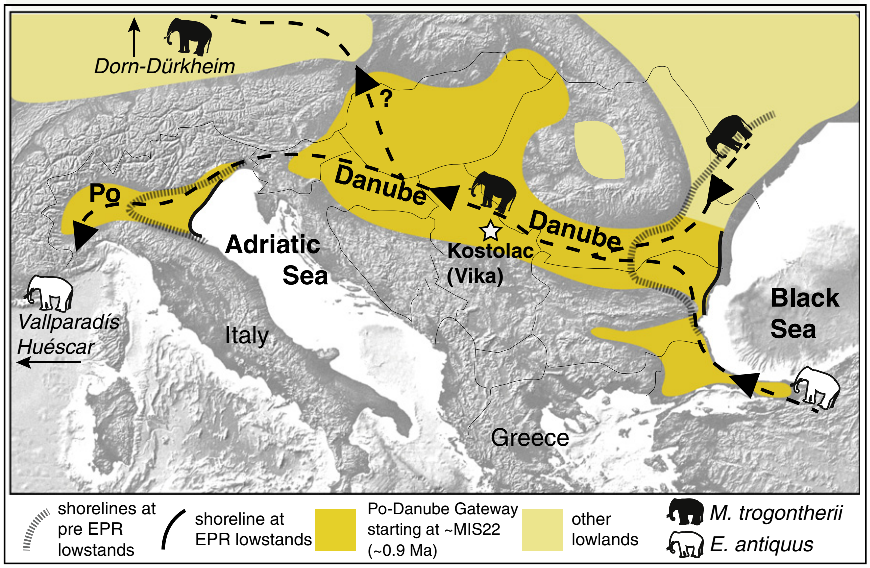

Figure. 7. Paleogeographic scenario of earliest expansion of *M. trogontherii* from Asia and *E. antiquus* from Africa-Levant into Europe across the postulated Danube–Po Gateway during the early Pleistocene climate revolution (EPR) (dashed lines). The gateway opened as the Po and Danube deltas prograded over the Adriatic Sea and Black Sea, respectively, during the EPR starting at MIS 22 (~0.9 Ma); coastlines at pre-EPR lowstands are tentatively depicted illustrating the advancement of the Po and Danube deltas. These new lowlands were characterized by grassland vegetation with reduced woody cover, especially during the onset of glacial/interglacial transitions staring with MIS 22/MIS 21, which provided the closest analogues in the temperate belt of the savanna ecosystems to which migrant megaherbivores (e.g., *M. trogontherii* and *E. antiquus*) were adapted. Redrawn from Muttoni et al. (2014).

glacial/interglacial transitions starting with MIS 22/MIS 21, provided the closest analogues in the temperate belt of the savanna-type ecosystems to which migrant megaherbivores such as the Asian steppe mammoth (*M. trogontherii*) and the straight-tusked elephant (*E. antiquus*), derived from the African savanna elephant (*E. recki*), were well adapted (Cerling et al., 2011), and into which they expanded only since ~0.9 Ma, possibly together with hominins interlinked in a common food web. Before MIS 22, these lowlands, smaller in extent (see pre-EPR coastlines in Fig. 7), were covered by more permanent closed forests, considered as less suitable to migrant African and Asian megaherbivores. Our findings hence support a model (Muttoni et al., 2014) wherein the stratigraphic level with Vika (*M. trogontherii*) at Kostolac rests upon a regional horizon marking the EPR in the Danube Valley, similar to the 'R surface' in the Po Valley also dated at ~0.9 Ma (Muttoni et al., 2003; Scardia et al., 2010, 2012).

The regional horizon marking the onset of loess deposition during the EPR could represent a prime target for surveys in search of sites in the Danube area with mammal immigrants from Asia and Africa, possibly including early hominins. Whether or not hominins arrived in Europe before the EPR (e.g., Carbonell et al., 2008; Toro-Moyano et al., 2013) remains a matter of debate (Muttoni et al., 2013, 2015), but we find it intriguing that the close association of large herbivores such as elephants and lithic artifacts, as revealed by the (still meager) fossil record, can be traced back almost to the emergence of humankind in Africa (Gaudzinski et al., 2005).

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INSIGHTS ON THE FIRST PEOPLING OF EUROPE FROM MAGNETOSTRATIGRAPHY OF THE PLEISTOCENE LITHIC TOOL-BEARING KOZARNIKA CAVE SEDIMENTS, BULGARIA.

My personal contribution in this work started with a week of fieldwork in July 2014 where my personal duty consisted in the measuring, description and sampling of the stratigraphic sequence. The following step consisted in the analysis of all the collected samples in the Alpine Laboratory of Paleomagnetism of Peveragno (Cuneo), and thus in the interpretation of the data. Afterward I took part to a second campaign between the end of July and the beginning of August 2015 in which my personal duty consisted again in the measuring, description and sampling of the stratigraphic sequence. Subsequently I provided the analysis of all the newly collected samples and merged the data acquired in the latter campaign with the ones obtained from the samples collected in 2014. Afterward I provided the interpretation of the entire dataset, contributed in the creation of the figures and in the writing of the paper, as well as to check the completeness and the correctness of the references.

INSIGHTS ON THE FIRST PEOPLING OF EUROPE FROM MAGNETOSTRATIGRAPHY OF THE PLEISTOCENE LITHIC TOOL-BEARING KOZARNIKA CAVE SEDIMENTS, BULGARIA.

Giovanni Muttoni, Edoardo Monesi, Nicholas Sirakov, Jean-Luc Guadelli, Dennis V. Kent, Giancarlo Scardia, Andrea Zerboni, Enzo Ferrara

Abstract

A 9 m-thick stratigraphic sequence containing archeological complexes spanning from the Neolithic to the Lower Paleolithic was found in the Kozarnika cave in northern Bulgaria. A magnetostratigraphic study of the section was attempted in previous years with limited success therefore the age of the section is still controversial. The chronology based on micromammals for the entire sequence spans from the Brunhes normal polarity chron across the entire upper part of the Matuyama reverse polarity chron (0.78-0.99 Ma) to the entire Jaramillo normal polarity subchron (0.99-1.07 Ma); in contrast the chronology based on large mammals continues across the entire Matuyama reverse polarity chron until the Matuyama-Gauss boundary (~2.5 Ma). We investigated the magnetic polarity of the entire section and found two magnetic polarity reversals in the lower part of the stratigraphic sequence, we interpreted the upper normal polarity as the Brunhes normal polarity chron and the lower one as the Jaramillo normal polarity subchron. The Kozarnika human tool site acquires a major role of interest in the debate about the first human colonization of Europe since the obtained data fits with the hypothesis suggesting that the first main hominin peopling of this region centered in a narrow chronological window between the top of the Jaramillo subchron (0.99 Ma) and the Brunhes–Matuyama boundary (0.78 Ma) as a consequence of the Early Pleistocene climate Revolution (EPR). This major climatic event started with MIS22 (~0.9 Ma) and brought in this region for the first time in the Pleistocene vast and exploitable ecosystems for African and Asian mammals along the conjunct Danube-Po migration Gateway. The incoming of these new species brought a profound

rejuvenation of the European faunas with the substitution of old Villafranchian species by new Galerian elements. It is inferred that hominins migrated to Europe from staging areas in the Levant in conjunction with African and Asian mammals as part of a common food web that expanded across the newly created grassland-savanna ecosystems of the Danube-Po Gateway, thus athwart the Kozarnika region.

1. Introduction

The Kozarnika Cave (43°39' N, 22°44'E) is situated in Bulgaria (district of Belogradchik), in the north-western part of the lower Balkans near the Danubian Plain (Popov, 1933; Sirakov et al., 2010) (Figure 1). The cave yielded a 9 m-thick stratigraphic sequence containing several lithological layers (from Layers 3-5 at the top to Layer 14 at the bottom) (Figure 2A) where various archaeological complexes, spanning from the Neolithic to the Lower Palaeolithic have been found (Sirakov et al., 2010 and references therein). The age of the section, in particular of the lower layers bearing Lower Palaeolithic tools, is however still controversial also because magnetostratigraphy was previously attempted, but with limited success (Sirakov et al., 2010).

Figure 1 Map of northwestern Bulgaria with location of the Kozarnika cave.

Small mammal associations provided a continuous record throughout the section organized, from top to bottom, in (Figure 2B) assemblage A1 (Layers 3a–9b) = "*Arvicola terrestris* Taxon Range zone", assemblage A2 (Layers 9c–10b) = upper part of "*Lagurus transiens-Arvicola cantianus* Assemblage zone", assemblage B1 (Layer 11a) = "*Mimomys savini-Lagurus transiens* Assemblage zone", and, finally, assemblage B2 (Layers 11b–13) = "*M. savini–M. pusillus* Assemblage zone" (Popov and Marinska, 2007). No significant gap seems to be present in this record, which according to standard small mammal bio-magnetochronology should span in relative continuity the last 1 million years, from virtually the entire Brunhes Chron across the Brunhes–Matuyama boundary (0.78 Ma; ages after Lourens et al., 2004) into the Jaramillo normal polarity subchron (0.99–1.07 Ma) (Popov and Marinska, 2007). This knowledge is used to erect an expected magnetochronology of the section based on small mammal distribution (Figure 2B).

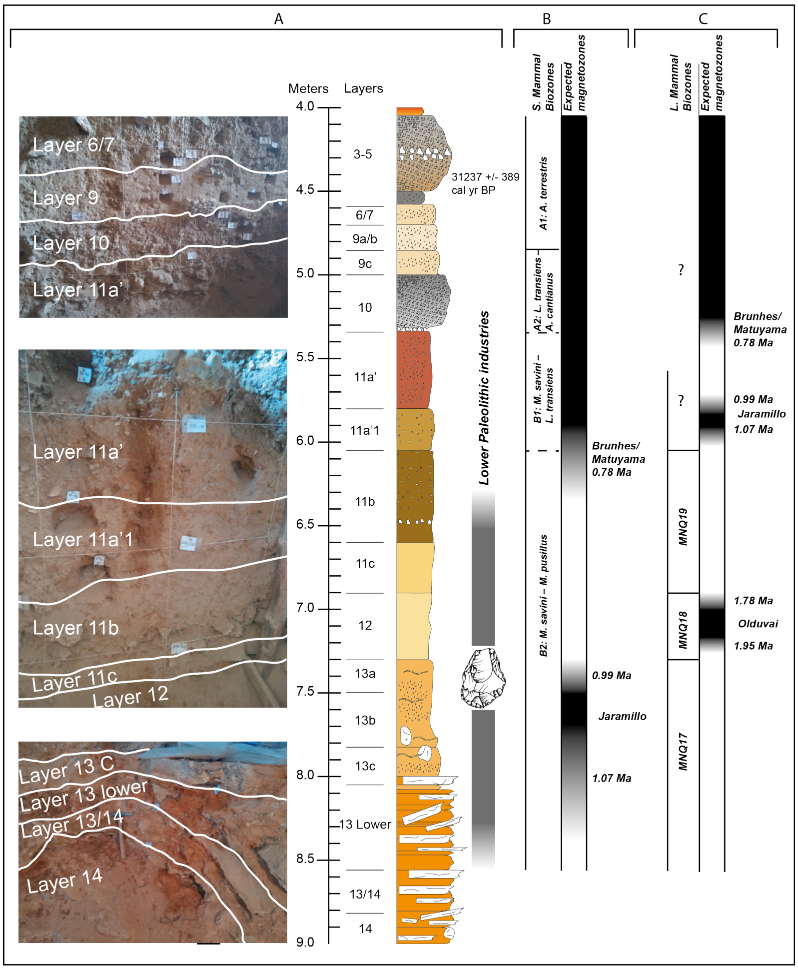

Figure 2 Lithologic log of the studied Kozarnika cave profile with photographs of the main sampled layers. Panels to the right are the magnetostratigraphies expected from small mammal (Popov and Marinska, 2007) and large mammal (Sirakov et al., 2010) biozonations of the cave sediments

In contrast, large mammals seem to indicate that the basal layers (11b–13) should belong to Mammal Neogene/Quaternary (MNQ) zones 19 to 17 (Sirakov et al., 2010), which, according to a recent radiometric (40Ar/39Ar) reassessment of classic mammalian localities from France, should correspond to a time interval broadly comprised between ~1.2 and ~2.6 Ma (Nomade et al., 2014). In terms of expected magnetochronology, this should straddle the Olduvai normal magnetic polarity subchron (1.78–1.95 Ma) down to the Matuyama–Gauss boundary (2.6 Ma) (Figure 2C).

Magnetostratigraphy coupled with a novel interpretation of the genesis of cave sediments offers therefore the possibility to contribute resolving this conundrum: according to the small mammal age option, we should find predominant normal magnetic polarity of the Brunhes Chron in the upper half of the cave stratigraphy and evidence for the Brunhes–Matuyama boundary in the lower half of the section, while according to the large mammal option, we should find predominantly reverse polarity of the Matuyama Chron possibly straddling the Olduvai normal polarity subchron in the lower half of the section, and normal polarity of the Brunhes Chron only in the upper layers. Here, we report on the magnetostratigraphy and sedimentology of the Kozarnika sediments and show that none of these options are strictly correct albeit our proposed solution is closer to the small mammal age option.

2. Site location and stratigraphy

The Kozarnika Cave opens to the south at an altitude of 481 m a.s.l., on a northern hillside of the valley of a tributary of the Skomlia River, which is part of the Danube drainage network. The valley is about 185 m deep and cuts several geological formations: Upper Jurassic grey limestone, Dogger yellow limestone, and Lias red conglomerates. Kozarnika Cave opens at ca. 85 m above the valley floor, in the upper limestone formation dating to the Upper Jurassic.

The cave stratigraphy is comprised of the following set of layers described from top to bottom (Figure 2A; see Sirakov et al., 2010 for details):

- Layers 3a to 4 are altogether 1–1.4 m-thick and composed of calcareous clasts (coming from the cave walls) in a light brown to whitish powdered silty matrix. These layers contain archaeological levels IVb-0I attributed to middle and recent stages of the Kozarnikien, which is a local blade industries containing backed pieces. Calibrated radiocarbon ages were obtained from Layers 3a and 3b spanning from 13,160 to 24,460 cal yr BP (REF).

• Layers 5a to 10a are altogether about 1.2-1.5 m-thick and are characterized by a finely powdered yellowish brown silty fraction. The coarse fraction (calcareous heterometric clasts and blocks) varies in abundance in the different layers, as a result of the fragmentation of the cave walls and roof. Layers 6 and 7 are almost identical (Layer 6 is light gray and Layer 7 light brown) and were grouped into Layer 6/7. Layer 8 was showed to be a subsequent den infill, and hence the stratigraphic sequence passes directly from Layer 6/7 to Layer 9. Layers 5a-c contains the archaeological levels V–VII attributed to the early stages of the Kozarnikien, and Layer 5b yielded a calibrated radiocarbon age of 31,237 ± 389 calibrated years before present (cal yr BP) (Sirakov et al., 2010). Layer 6/7 includes archaeological level VIII, which corresponds to an industry regarded as characteristic of the Middle Palaeolithic and the initial Late Palaeolithic, and uncalibrated, hence underestimated, radiocarbon ages ranging from 42,700 and 43,600 yr BP (Sirakov et al., 2010). Layers 9a-10a contain the archaeological levels IX-XIII of the Mousterian sequence.

• Layers 10b and 10c, varying in thickness from 15 to 50 cm, consist of non-compacted dark-brown loamy sand containing numerous gravels and calcareous pebbles that are more or less weathered. These layers contain the lower end of the Mousterian (Middle Paleolithic) sequence.

• Layers 11a to 13 have a total thickness of about 2.5 m and are composed of rather compact orange loamy sediments, blotched with dark manganese-bearing nodules and more or less rich in coarse rock blocks and pebbles (limestone blocks, flint pebbles from the cave walls, and more rarely rounded pebbles of quartz) with high degrees of alteration. These layers contain Lower Palaeolithic core-and-flake, non-Acheulian industries.

• Layer 14 represents the section base and is characterized by abundant limestone boulders with occasional orange, laminated sandy matrix in between.

Grain size analysis was performed to elucidate the origin of the sediments (Gale and Hoare, 1991). Sediment samples, 25 to 40 g in weight, were treated with 10 ml of 30% H_2O_2 in order to remove the organic matter content. This treatment was repeated twice. After drying in an oven at 50°C, samples were gently disaggregated in an agate mortar and sieved at 1000 and 500 mm. Samples were always weighted after each step. The fine fraction was then dispersed in 0.05% sodium metaphosphate solution, disaggregated in an ultrasonic bath for 15 sec, and then passed through a Malvern Mastersizer (mod. 2000) for grain analysis.

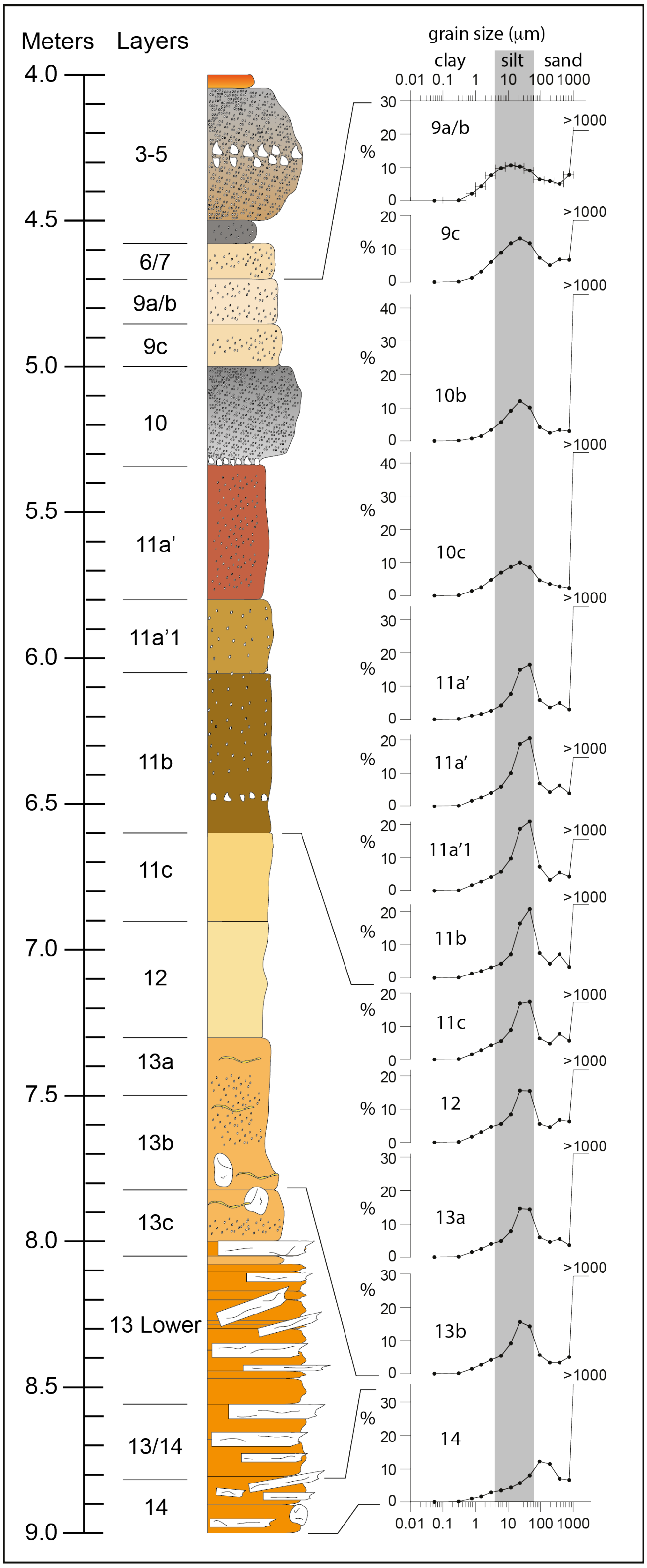

Figure 3 Grain size distribution curves. See text for discussion.

Curves of grain size distribution are reported in Figure 3 and described hereafter from top to bottom.

• The uppermost Layers 9a/b to 10c display a bimodal distribution of particles, with the clay content progressively decreasing downsection (i.e., samples become progressively more sorted).

• Curves of Layers from 11a to 13b are very similar and moderately sorted; they present a bimodal distribution of particles (less evident in sample 13b) and very low clay content. A main peak is related to the silty fraction (ca. 20–60 μm), whereas the second peak is related to fine and medium sand (ca. 120–140 μm).

- The lowermost Layer 14 is poorly sorted with high silt and sand content.

3. Paleomagnetism

Previous paleomagnetic sampling resulted unsuccessful essentially because of the unconsolidated nature of the sediments (Sirakov et al., 2010).

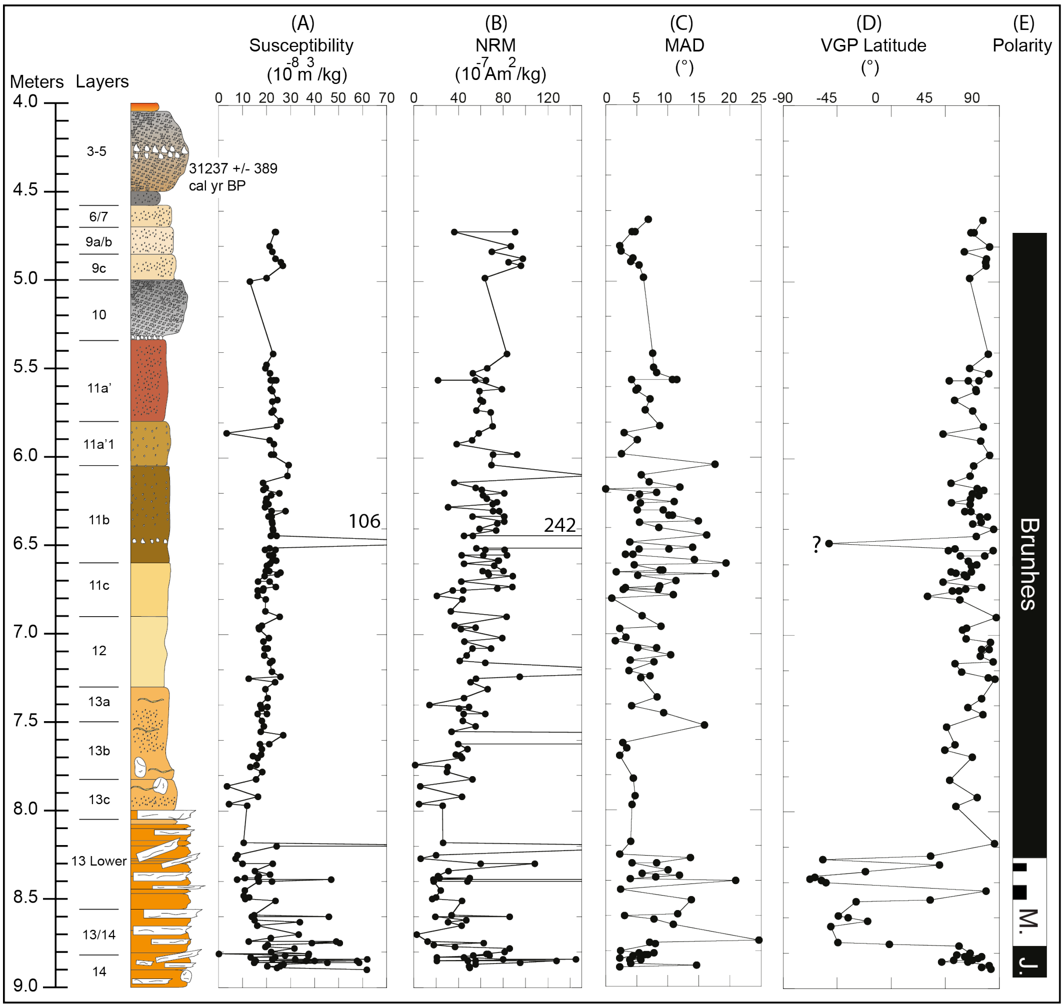

Figure 4 The Kozarnika stratigraphic section correlated from left to right with: (A) Magnetic susceptibility and (B) NRM. Characteristic magnetic component directions from thermally or AF demagnetized samples (maximum angular deviation (MAD) values in (C) have been used to calculate virtual geomagnetic pole (VGP) latitudes (D) and magnetic polarity for the Kozarnika composite section (black is normal polarity) (E). See text for discussion.

We avoided this issue by carefully inserting ~5cc plastic cylinders into oriented sediment walls obtaining a total of 173 specimens for paleomagnetic analyses from Layer 6/7 at the top to Layer 14 at the base (Figure 4). The initial magnetic susceptibility was measured on all weighted samples at room temperature with a KLY-2 Kappabridge. A sub-set of 10 samples was subjected to rock magnetic analyses by means isothermal remanent magnetization (IRM) acquisition imparted at -2.5 T along the horizontal axis in one direction (-z) and then progressively increasing from +0.025 T up to + 2.5 T in the opposite direction (+z).

All samples were subjected to alternating field (AF) demagnetization in steps of up to 80 mT with the natural remanent magnetization (NRM) measured after each demagnetization step with a 2G Enterprises DC-SQUID cryogenic magnetometer located in a shielded room. Standard least-square analysis was used to calculate magnetic component directions from vector end-point demagnetization diagrams, and standard Fisher statistical analysis was used to analyze the mean component directions. Magnetic measurements were carried out at the Alpine Laboratory of Paleomagnetism of Peveragno and INRIM Turin (Italy).

The magnetic susceptibility fluctuates around a mean value of ~$20*10^{-8}$ m^3/kg throughout most of the section (with one isolated peak value at 6.48 m), while the section base is characterized by higher values of ~$40–60*10^{-8}$ m^3/kg (Figure 4A). The intensity of the natural remanent magnetization (NRM) is comprised between $20*10^{-7}$ Am^2/kg and $120*10^{-7}$ Am^2/kg and is punctuated by an isolated peak value of $242*10^{-7}$ Am^2/kg again at 6.48 m (Figure 4B).

IRM acquisition curves reveal the presence of a soft coercivity ferromagnetic mineral that tends to saturate in fields of 0.06 T (60 mT) variably associated with a higher coercivity mineral that shows no tendency to saturate up to 2.5 T fields (Figure 5A). The proportion of soft/hard minerals varies throughout the section whereby the hard coercivity fraction is confined to 5–10% of the total IRM from the section top down to Layer 13b to then increase to values of up to 20% in Layers 13 Lower and Layer 13/14 (Figure 5B).

The soft coercivity mineral is interpreted as a magnetite phase whereas the hard coercivity mineral as hematite and/or ghoetite.

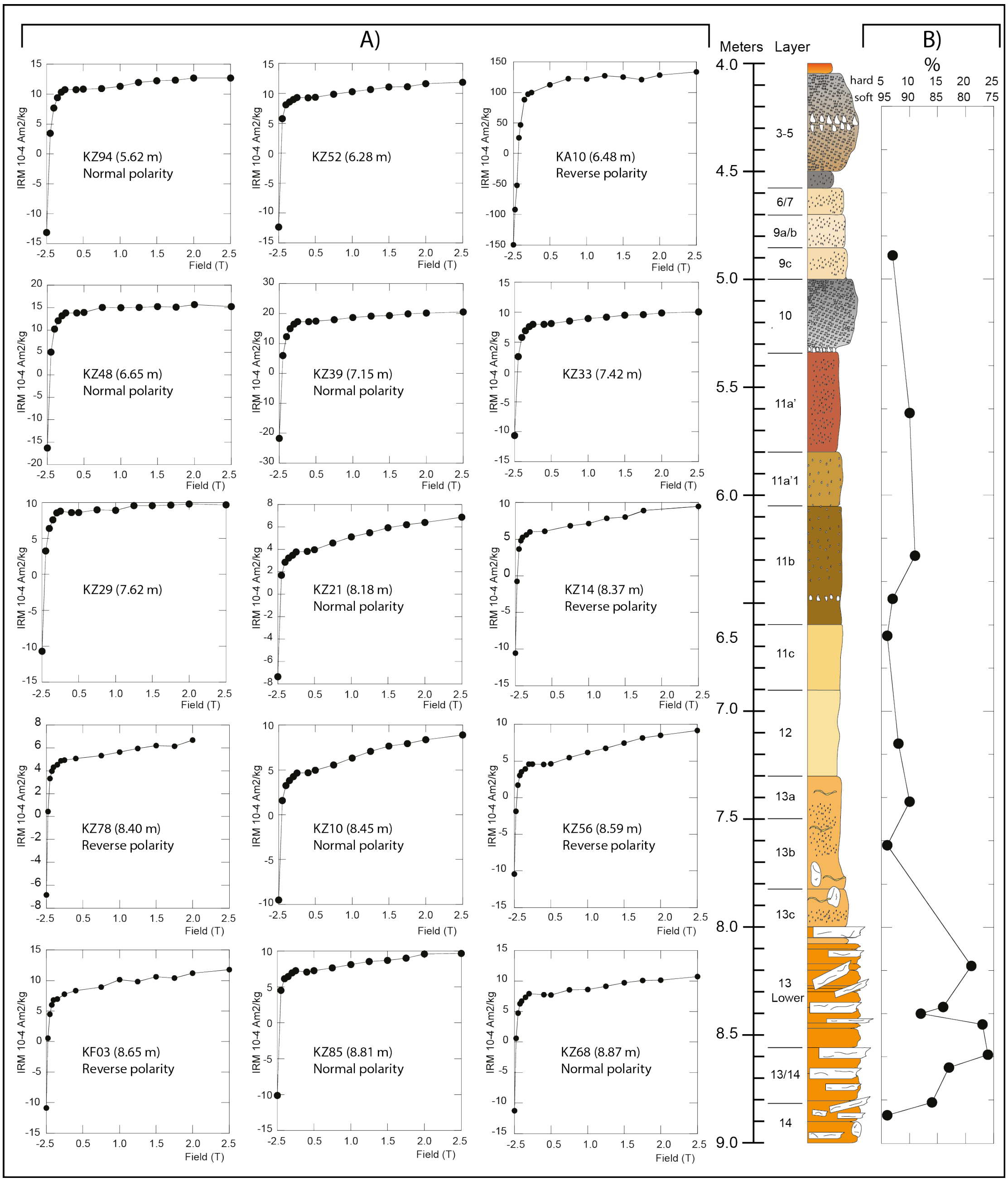

Figure 5 (A) Isothermal remanent magnetization (IRM) backfield acquisition curves on representative samples from the Kozarnika sediments. (B) The proportion of soft/hard minerals varies throughout the section. See text for discussion.

Vector end-point demagnetization diagrams show the presence of soft magnetic component directions termed A that are easily removed between 0 mT and 10–20 mT (Figure 6). These directions are oriented downward (positive inclinations) with scattered, generally northerly declinations (Figure 6, 7). At higher AF demagnetization steps, the natural magnetic remanence becomes harder to unblock, and a characteristic remanent magnetization component, termed C, was isolated in 119 samples up to a maximum of 80 mT (Figure 7). These C component directions are either oriented northerly and down, and hence they constitute a sort of a prosecution at higher AF values of the A component, or show a tendency to turn to southerly declinations and upward (negative) inclinations (Figure 6, 7). These bipolar C component directions, with mean angular deviation (MAD) values of usually less than 10° (Figure 4C), are grouped around a mean of declination = 358.3°E, inclination = 62.5° (n = 119, k = 9.8, a95 = 4.4°; Figure 7).

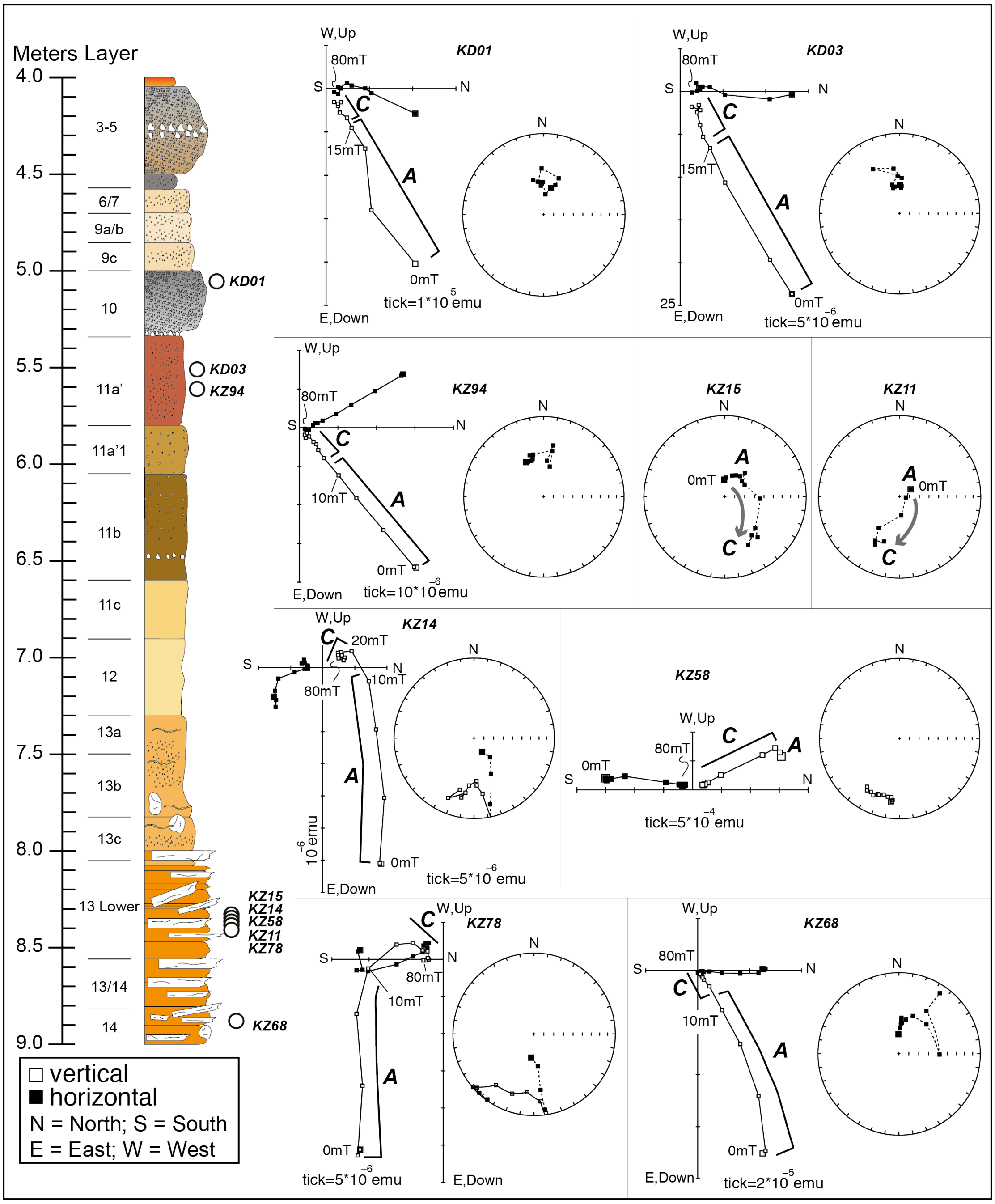

Figure 6 Vector end-point demagnetization diagrams of representative samples displaying the soft magnetic component (A) and the characteristic magnetic component (C) directions of normal (KD01, KD03, KZ94, KZ68) and reverse (KZ15, KZ11, KZ14, KZ58, KZ78) magnetic polarity. Closed symbols are projections onto the horizontal plane and open symbols onto the vertical plane. Demagnetization temperatures are expressed in mT.

Both the A and C components constituting the NRM are unblocked in AF fields that reside well within the IRM acquisition spectrum of the soft coercivity ferromagnetic mineral interpreted as a magnetite/maghemite phase (Figure 5). The hard coercivity phase (hematite and/or ghoetite), which is evident in the IRM acquisition experiments in fields above 100 mT, does not seem to carry any sizable portion of the NRM, which is unblocked virtually completely in fields of 80 mT. This suggests that the C component directions and the normal and reverse magnetic polarities that they define are carried by a same ferromagnetic (magnetite/maghemite) phase, irrespective of polarity, which supports the primary nature of these magnetic components.

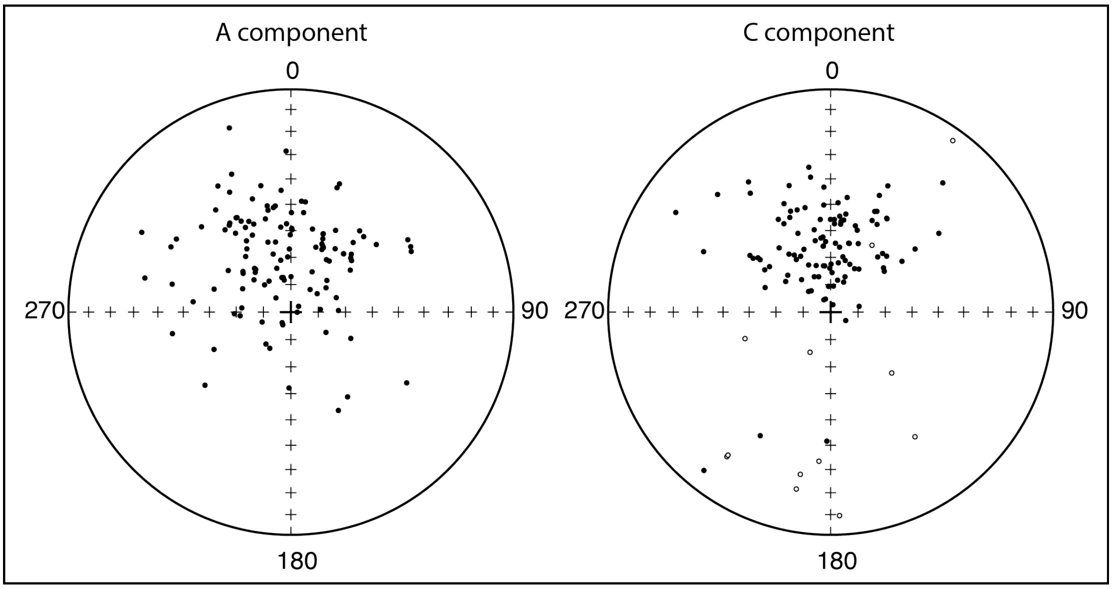

Figure 7 Equal-area projection of the soft magnetic component (A) (left) and of the characteristic remanent magnetization component (C) (right) directions. Closed (open) symbols represent down-pointing (up-pointing) directions.

The declination and inclination values of the C component directions were used to calculate virtual geomagnetic pole (VGP) latitudes and plotted *versus* stratigraphic depth (Figure 4D). VGP latitudes approaching +90° are interpreted as normal polarity and VGP latitudes approaching -90° as reverse polarity, thus defining a sequence of stratigraphically superposed normal (black) and reverse (white) magnetozones (Figure 4E). The section is characterized by consistent normal magnetic polarity from upper Layers 9a/b at 4.7 m down to 8.28 m within Layer 13 Lower. This relatively thick normal polarity interval is interrupted by a single sample at 6.48 m in the lower part of Layer 11b displaying a southerly-and-up C component direction that is associated with high NRM and susceptibility values (Figure 4D, E); this sample resulted also highly anisotropic during IRM experiments whereby the induced magnetization lied at high angle relative to the applied fields. Below meter level 8.28, and still within Layer 13 Lower, as well as in underlying Layer 13/14, reverse polarity C component directions have been observed after removal of a pervasive initial overprint component of normal polarity. At the section bottom, Layer 14 is characterized by C component directions of normal magnetic polarity (Figure 4D, E).

4. Data interpretation

The origin of the cave sediments

According to grain size distribution curves (Figure 3), the poor sorting of the samples from the uppermost Layers 9a/b and 9c suggest a colluvial origin (Krumbein and Sloss, 1963; Ricci Lucchi, 1980). Grain size curves of samples from the basal layers also suggest a colluvial origin of sediments; moreover, at the macro-scale these layers present laminated patterns typical of water transport. Samples from Layers 10b to 13b) have a characteristic bimodal distribution, typical of loess deposited into caves. In fact, the main mode of these curves corresponds to the typical grain size distribution of loess (Pye, 1987, 1995; Coudé-Gaussen, 1990; Assallay et al., 1998), whereas the second peak reflects the presence of sandy to coarser rock fragments from the cryogenic dismantling of the cave walls and roof (Figure 3). A similar bimodal grain size distribution of loess layers has been found in cave-entrance and rock shelter contexts at the margin of the Po Plain Loess Basin of northern Italy (Cremaschi, 1987; Castiglioni et al., 1990; Ferraris et al., 1990; Zerboni et al., 2015). The attribution of most of the analyzed samples to loess trapped at the entrance of the cave fits well with the geographic position of the Kozarnika Cave, which is located at the south-western margin of the Bulgarian lower Danube loess belt (Buggle et al., 2009, 2013; Fitzsimmons et al., 2012; Markovic et al., 2015) of eastern Europe (Haase et al., .

Loess deposition in the middle and lower Danube valley is a Lower and Middle Pleistocene environmental process (Fitzsimmons et al., 2012;

Markovic et al., 2015); moreover, loess deposits in the Pannonian basin possibly extends to the base of the Pleistocene (Fitzsimmons et al., 2012). Considering the several loess sequences and related magnetostratigraphic profiles from Hungary, Serbia, and Romania, we conclude that loess sedimentation generally started in these regions shortly below the Brunhes–Matuyama boundary (Sartori et al., 1999; Jordanova et al., 2008; Fitzsimmons et al., 2012; Markovic et al., 2015; Muttoni et al., 2015a). Thus it seems that loess accumulation in the Kozarnika Cave should not be older than the Brunhes–Matuyama boundary.

Magnetostratigraphy and age of the cave sediments

We interpret the upper and thick normal magnetic polarity as a record of the Brunhes Chron (Figure 4D, E). This interpretation agrees with three independent lines of evidence: (i) the calibrated radiocarbon age of 31237 ± 389 cal yr BP in Layer 6/7 clearly indicates that the section top is latest Pleistocene (= latest Brunhes) in age (Sirakov et al., 2010) (Figure 4); (ii) the small mammal associations indicate that the upper half of the section, from Layers 3a–9b to Layer 11a, should be attributed to the Brunhes Chron (Popov and Marinska, 2007) (Figure 2). (iii) the silt fraction of the tool-bearing layers is of loess origin, and as stated above, the onset of loess deposition in the Danube valley occurred shortly below the Brunhes–Matuyama boundary.

Assuming no substantial gaps in Layers 11-13, we placed the Brunhes–Matuyama boundary (0.78 Ma) at 8.28 m within Layer 13 Lower in correspondence of the first sample displaying a C component direction of reverse magnetic polarity (Figure 4D, E). The lower normal magnetic polarity observed in Layer 14 could be a partial record of the Jaramillo subchron (lasting altogether from 0.99 to 1.07 Ma) for which, however, we lack the base. The scattered normal polarity directions embedded in reverse polarity within Layer 13 Lower (half bars in Figure 4E) could be pre-Brunhes polarity excursions or could represent records of the Brunhes Chron in pre-Brunhes sediments due to retarded lock-in of the NRM; it cannot also be excluded the presence in sedimentologically complex Layer 13 Lower, whose internal stratification/lamination if very hard to trace laterally, of downward infiltrations (sedimentary dikes/undulated erosional surfaces) of upper (Brunhes) sediments.

Our magnetostratigraphic interpretation does not strictly fit with either of the two working hypotheses shown in Figure 2, albeit it lies much closer to the small mammal hypothesis that implies an age of the section base of about 1 Ma (Popov and Marinska, 2007). In particular, the small mammal hypothesis predicts a position for the Brunhes/Matuyama boundary about within Layer 11b instead of Layer 13 Lower where we found it (compare Figure 2 with Figure 4). According to previous magnetostratigraphic analyses reported in Sirakov et al. (2010), the analytical details of which were however not illustrated or discussed, *"the sedimentation of layers 10a to the middle part of 11b took place in a period of normal magnetic polarity (Brunhes) (...) However the low values of the paleo-latitude in the lower part of layer 11b has been affected by a magnetic transition of inverted polarity (Matuyama) towards normal polarity. Unfortunately, some problems of consolidation of the blocks from the bottom part did not allow continuation of this study*". Based on this initial report, we played particular attention to Layer 11b where paleomagnetic sampling resolution was particularly high; indeed, we found one sample at 6.48 m in the lower part of Layer 11b, associated with high NRM values and yielding an anisotropic response to IRM experiments (see above), displaying reverse polarity, however, there is no evidence in this densely sampled interval of a clear and persistent normal-to-reverse polarity transition (Figure 4D, E). Considering our data in conjunction with the virtually continuous small mammal associations as well as the ordered temporal sequence of stone artifacts throughout the section, we see no evidence for substantial stratigraphic gaps and maintain confidence in a Brunhes–Matuyama boundary placed at ~8.28 m or thereabout within Layer 13 Lower (Figure 4D, E).

Regarding the discrepancy with the large mammal hypothesis, which predicts the section base to be older than the Olduvai subchron, we stress that the large mammal fragments attributed by Sirakov et al. (2010) to MNQ18 in the Early Villafranchian (Early Pleistocene) could in fact lie somewhat closer to the beginning of the Epivillafranchian (see also Kahlke, 2011).

5. Kozarnika in the context of the first peopling of Europe

Our data from Kozarnika, with lithic tools from post-Jaramillo and pre-Brunhes levels, fits well with a recent hypothesis of first main hominin peopling of Europe centered in a narrow chronological window between the top of the Jaramillo subchron (0.99 Ma) and the Brunhes–Matuyama boundary (0.78 Ma) (Muttoni et al., 2014; 2015a,b). Inspection of Figure 8 reveals that sites in Europe with reliable magnetochronologic constraints occurring in this time interval are, apart from Kozarnika, Gran Dolina in Spain (Pares and Perez-González, 1999; Pares et al., 2013), Sima del Elefante in Spain (Carbonell et al., 2008; with cosmogenic burial ages from levels TE7 and TE9 expressed at 2sigma level; see discussion in Muttoni et al., 2014;

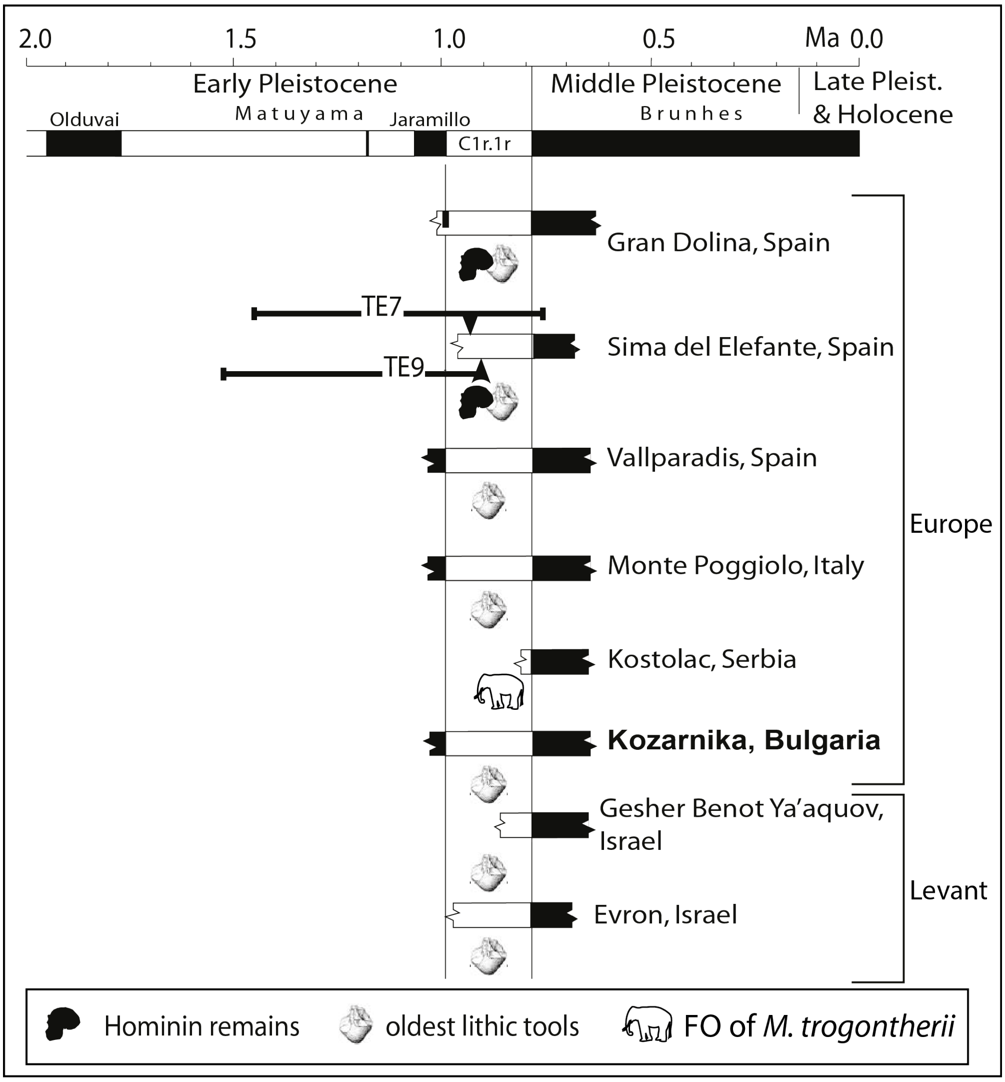

Figure 8 Paleogeographic scenario of our revised migrate-with-the-herd hypothesis of earliest expansion of hominins (and large mammals) from the Gates of Europe into Europe across the postulated Danube-Po Gateway during the EPR (dashed lines). Expansion occurred on stable lowlands developed as the Po and Danube deltas prograded over the Adriatic Sea and Black Sea, respectively, since MIS 22 (~0.9 Ma). Coastlines at pre-MIS 22 lowstands and at the last glacial maximum (LGM) are tentatively depicted illustrating the advancement of the Po and Danube deltas. See text for discussion.

2015a), Vallparadís in Spain (Martinez et al., 2010), and Monte Poggiolo in northern Italy (Muttoni et al., 2011). Hominin occupation is documented at approximately the same times at the gates of Europe in Israel, such as at Gesher Benot Ya'aqov (Goren-Inbar et al., 2000) and Evron (Ron et al., 2003) (Figure 8). Several other sites with proof of early hominin presence are excluded from this summary figure either because of poor or poorly documented age constraints (e.g., Soleilhac, Le Vallonnet, Pont-de-Lavaud in France; Korolevo in Ukraine; Dursunlu in Turkey, and 'Ubeidiya in Israel), or because hominin levels could not be securely traced into the magnetostratigraphic profiles (e.g., Kocabas in Turkey) or finally because their magnetostratigraphies are incomplete (single polarity only; e.g., Bizat Ruhama in Israel; Pirro Nord in Italy; Happisburgh in the U.K) (see Muttoni et al., 2014; 2015a,b for further details and references).

The oldest peopling of Europe as revealed by these best-dated sites appear broadly coeval with the timing of the transition in global climate variability from lower to higher amplitude (=intensity) cycles that occurred in the late Early Pleistocene between the Jaramillo subchron (0.99 Ma) and the Brunhes–Matuyama boundary (0.78 Ma) (e.g., Head and Gibbard, 2005; Lourens et al., 2004; Lisiecki and Raymo, 2005). Within this transition, variably referred in the literature to as late Early Pleistocene Revolution (EPR) or late Early Pleistocene Transition (EPT), marine isotope stage (MIS) 22 at ~0.9 Ma represents the first major northern hemisphere continental glaciation of the Pleistocene (Shackleton and Opdyke, 1976; Berger et al., 1993; Shackleton, 1995; Head and Gibbard, 2005). It has been illustrated and discussed in a number of recent papers (Muttoni et al., 2014; 2015a,b) that the EPR is believed to have generated for the first time in the Pleistocene vast and exploitable ecosystems for African and Asian mammals especially along a conjunct Danube-Po migration Gateway (Figure 9). Enhanced erosion of the Alpine chain by valley glacier carving starting with the MIS 22 ice advance and redistribution of these glacial sediments by fluvioglacial systems from the glaciated mountain areas towards the peripheral plains (e.g., Po, Danube) generated new stable lowland areas that were colonized by open grassland vegetation and reduced woody cover during the onset of glacial/interglacial transitions starting with MIS 22/MIS 21 (Muttoni et al., 2003; 2010; 2014;

2015a; Scardia et al., 2010; 2012; Monesi et al., 2016). The EPR coincided also with a profound rejuvenation of the faunas with the substitution of old Villafranchian species by new Galerian elements (Palombo and Mussi, 2006; Palombo, 2014; Muttoni et al., 2014; Monesi et al., 2016).

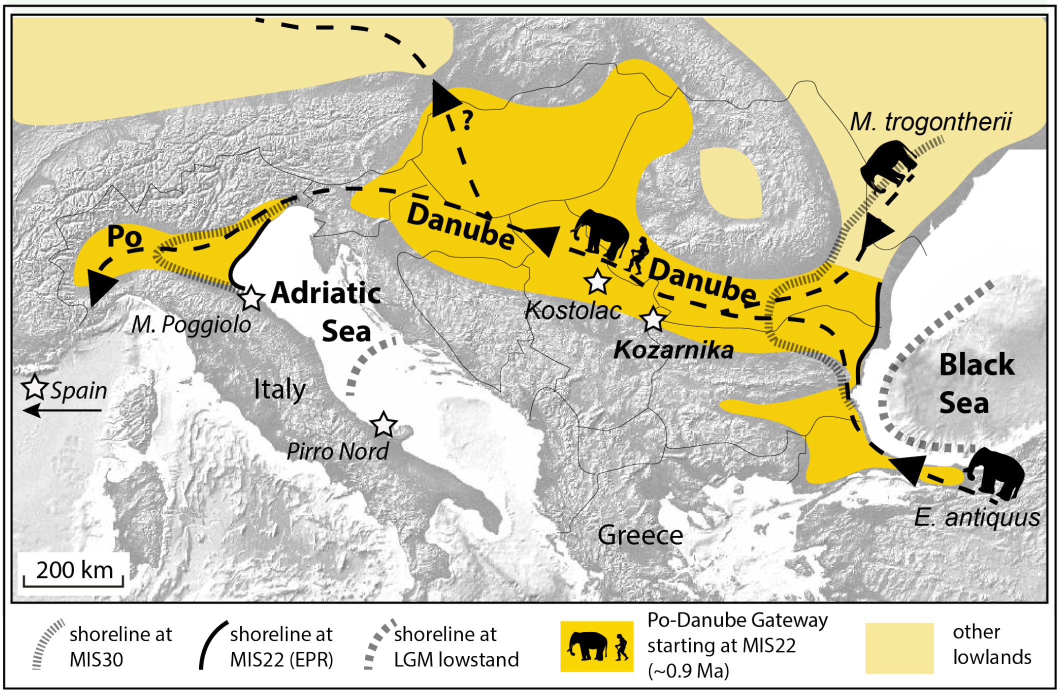

Figure 9 Our preferred interpretation of evidence for the earliest human occupation of Europe and at the gates of Europe in the Levant with respect to the astrochronological geomagnetic polarity time scale (APTS) (Lourens et al., 2004). Oldest key hominin sites with reliable magnetostratigraphy tend to occur within the reverse polarity interval between the Jaramillo and the Brunhes (0.99 to 0.78 Ma). Europe: Gran Dolina (Pares and Perez-González, 1999; Pares et al., 2013), Sima del Elefante (Carbonell et al., 2008; with cosmogenic burial ages from levels TE7 and TE9 expressed at 2s level; Muttoni et al., 2013), Vallparadís (Martinez et al., 2010), Monte Poggiolo (Muttoni et al., 2011), Kozarnika, Bulgaria (this study). Also shown is the site of Kostolac in Serbia that yielded remains of *M. trogontherii* (but no hominin remains) in pre-Brunhes levels (Muttoni et al., 2015a). Gates of Europe: Gesher Benot Ya'aqov (Goren-Inbar et al., 2000), Evron (Ron et al., 2003). See text for discussion.

Putting these and additional elements together, it is inferred that hominins migrated to Europe from staging areas in the Levant in conjunction with African and Asian mammals as part of a common food web that expanded across the newly created grassland-savanna ecosystems of the Danube-Po Gateway, which provided the closest analogues in the temperate belt of the savanna-type ecosystems to which migrant megaherbivores such as the Asian steppe mammoth (*M. trogontherii*) and the straight-tusked elephant (*E. antiquus)* were already well adapted. Before MIS 22, these lowlands were less suitable to migrant African and Asian megaherbivores because much smaller in extent, as episodically inundated by shallow continental seas, and covered by more permanent closed forests (for further details, see Muttoni et al., 2014; 2015a,b; Monesi et al., 2016). This EPR migration scenario is supported also by magnetostratigraphic data from Kostolac in Serbia where the first occurrence in Europe of *M. trogontherii* was traced in levels immediately older than the Brunhes–Matuyama boundary (Muttoni et al., 2015a).

Our data from Kozarnika seems therefore to support the 'follow-the-herd' hypothesis of hominin migration into Europe as part of an ecosystem expanding across a Danube-Po Gateway that was first created in the Pleistocene at ~0.9 Ma during the EPR. Whether hominins occasionally entered Europe already before the Jaramillo (e.g., Carbonell et al., 2008; Toro-Moyano et al., 2013) during times of no particular climatic or ecologic turnover is still a matter of debate (Muttoni et al., 2013; 2015a). In any case, as stressed elsewhere, the regional horizon marking the EPR could represent a prime target for surveys in search of additional sites in the Danube area with mammal immigrants from Asia and Africa (e.g., Kostolac; Muttoni et al., 2015a) possibly including early hominins, like Kozarnika.

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6

MAGNETOSTRATIGRAPHY OF THE PLEISTOCENE CONTINENTAL SEDIMENTS OF THE MEGALOPOLIS BASIN, GREECE: CONSTRAINTS ON THE AGE OF THE MARATHOUSA-1 ARCHEOLOGICAL LEVELS.

My personal contribution in this work started with a week of fieldwork in June 2014 where my personal duty consisted in the measuring, description and sampling of the stratigraphic sequence of the Marathousa mine. The following step consisted in the analysis of all the collected samples in the Alpine Laboratory of Paleomagnetism of Peveragno (Cuneo), and thus in the interpretation of the data. Afterward I took part to a second campaign in October 2014 where the stratigraphy of the Choremi mine was investigated in addition to a new complete profile of the Marathousa mine. In this second campaign my personal duty consisted strictly in the sampling. Afterward I did the analysis of all the collected samples in the Alpine Laboratory of Paleomagnetism of Peveragno (Cuneo) and I merged the data of the samples collected in both campaigns in the Marathousa mine in order to give an univocal interpretation for this site. In the end I contributed in the creation of the figures and in the writing of the paper, as well as to check the completeness and the correctness of the references.

MAGNETOSTRATIGRAPHY OF THE PLEISTOCENE CONTINENTAL SEDIMENTS OF THE MEGALOPOLIS BASIN, GREECE: CONSTRAINTS ON THE AGE OF THE MARATHOUSA-1 ARCHEOLOGICAL LEVELS.

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Abstract
We investigated the magnetostratigraphy of the Megalopolis Basin in central Peloponnese, Greece, which encompasses a record of Pleistocene lacustrine and coal-bearing sedimentation where lithic tools stratigraphically associated with remnants of a virtually complete skeleton of *Elephas (Palaeoloxodon) antiquus* were recently found at the Marathousa-1 site. A magnetic polarity reversal was observed within a ~10 m-thick coal seam at the base of the (exposed) stratigraphic sequence, and it was interpreted as a record of the Brunhes/Matuyama (B/M) boundary (0.78 Ma), in agreement with previous results. Assuming that coal seams were deposited generally under warm and humid climate conditions, this finding is in agreement with data from the literature indicating that the B/M boundary occurs within warm Marine Isotope Stage (MIS) 19. We then attempted to correlate the reminder of the lacustrine and coal-bearing intervals above the B/M boundary to a standard isotope

record of Pleistocene climate variability. Two age models of sedimentation were generated: according to preferred option #1, lithic tool-bearing Layer 4 of the Marathousa-1 site should have an age comprised between ~0.48 Ma and ~0.42 Ma, while according to alternative option #2, the archeological Layer 4 would have an age comprised between ~0.565 Ma and ~0.54 Ma. Option #1 is at present considered the preferred option as it is in closer agreement with preliminary ESR dates from the Marathousa-1 site. This age model has been exported to other areas of the Megalopolis Basin, where additional archeological/paleontological sites could be present, by means of correlations to lithostratigraphic logs derived from commercial drill cores taken in 1958-1960 for coal exploration.

Keywords

Megalopolis; Greece; Pleistocene; magnetostratigraphy; lithic tools; *Elephas antiquus*

1. Introduction

The Megalopolis Basin is a tectonic half-graben filled with Neogene to Holocene mainly continental sediments (Vinken 1965) located in central Peloponnese, Greece (Fig. 1A). The Pleistocene portion of this sequence, which is the object of this study, is comprised of the Marathousa Member of the Choremi Formation, characterized by lacustrine clay, silt and sand intervals alternating with lignite seams (Fig. 1B) (Vinken 1965; Nickel et al., 1996; Sakorafa and Michailidis, 1997; Siavalas et al., 2009; van Vugt et al., 2000). The Marathousa Member comprises the recently discovered Marathousa-1 Lower Palaeolithic site with remains of *Elephas (Palaeoloxodon) antiquus* in association with a rich lithic tool assemblage (Panagopoulou et al., 2015). The aim of this paper is to place constraints on the age of the Marathousa-1 site by means of magnetostratigraphy and correlations with Pleistocene climatic variability as revealed by a standard $\delta^{18}O$ curve from the literature (Lisiecki and Raymo, 2005) under the assumption that lignites deposited during interglacial periods while detrital intervals during glacial periods (Nickel et al. 1996; van Vugt et al. 2000;

Okuda et al., 2002; see below).

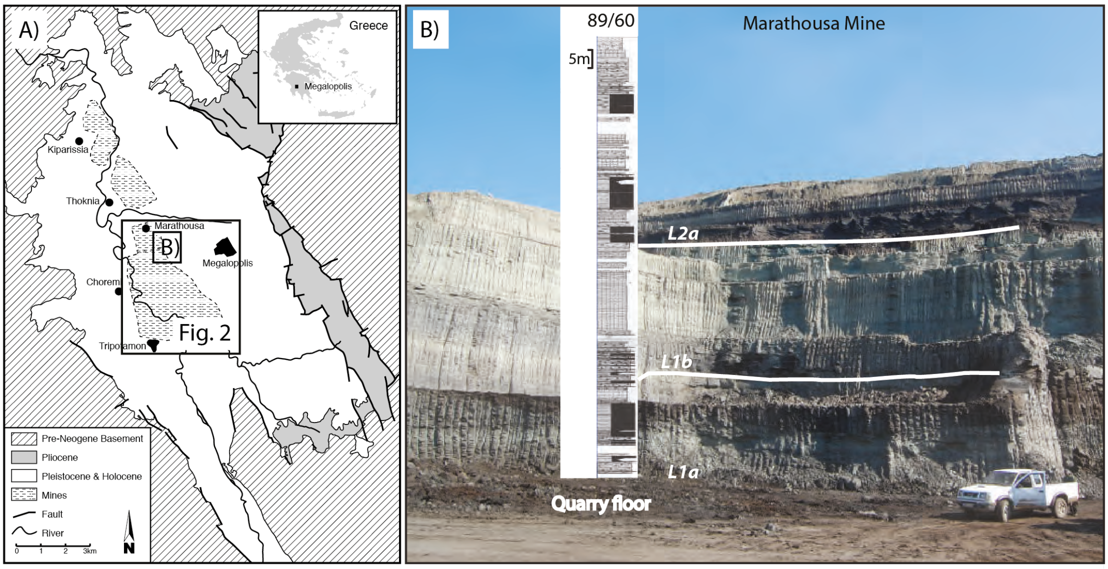

Figure 1 (A) geologic map of the Megalopolis Basin in central Peloponnese, Greece. (B) Picture of Marathousa quarry wall stratigraphy placed aside commercial drill core 89/60.

The Marathousa-1 archeological site is located at the northwestern edge of an opencast mining area (Marathousa Mine; Fig. 2) where the Marathousa Member lignites are being extracted for energy production by the Public Power Corporation S. A. Hellas since 1969 (Sakorafa and Michailidis, 1997). The archeological levels are well exposed in several laterally continuous but relatively thin stratigraphic sections (Panagopoulou et al., 2015) while sediments below the archeological levels are largely covered by quarry rubble waste. Several commercial drill cores were taken in 1958–1960 to assess the lateral and vertical extension of lignites. We could access the stratigraphic logs of 5 of these drill cores (Fig. 2; 75/60, 76/60, 25/58, 24/58, 89/60, this latter also displayed in Fig. 1B aside modern quarry stratigraphy) that we used in conjunction with our own field observations to reconstruct the general evolution of the Megalopolis Basin around the Marathousa-1 archeological site. We logged and sampled for paleomagnetism two stratigraphic sections named 1/2014, located ~1 km to the east of the Marathousa-1 archeological site, and 2/2014, located a few km to the south of it (Fig. 2).

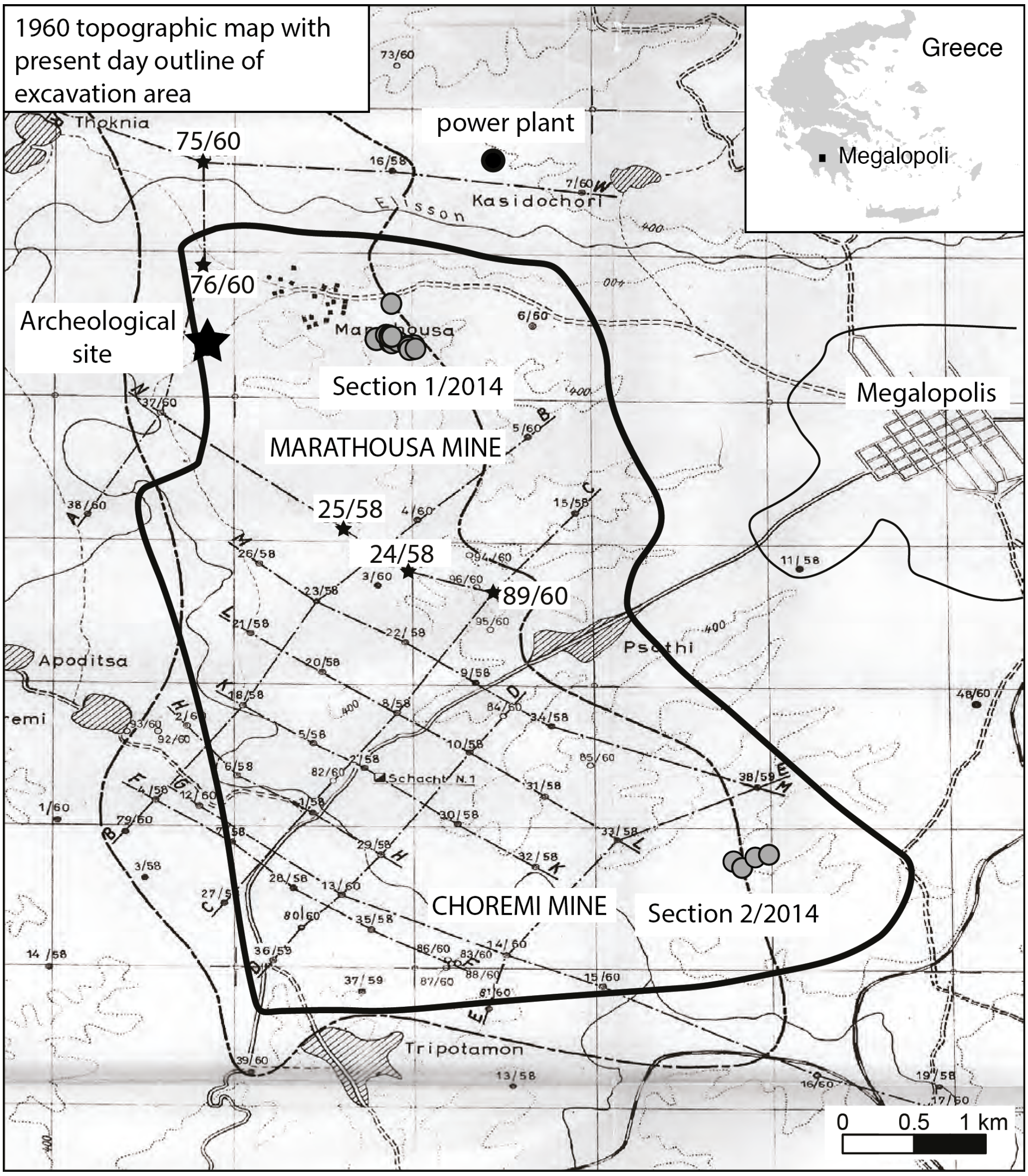

Figure 2 1960 topographic map of the study area with locations of sections and cores discussed in the text.

2. Stratigraphy

Section 1/2014 consists of a ~100 m-thick alternation of black lignites (L), organic matter rich silty clays (OMSC), gray silty clays (GSC), fining upward cycles of light gray sand and silt (LGSS), and fining upward cycles of light gray gravel, sand and silt (LGGSS) (Fig. 3, left panel). The lower part of section 1/2014 was studied for magnetostratigraphy (Fig. 3; see below). The 26 m-thick ancillary section 2/2014, also studied for litho-magnetostratigraphy (Fig. 4), is located at the adjacent Choremi Mine (Fig. 2) and it is considered correlative with the lower portion of section 1/2014.

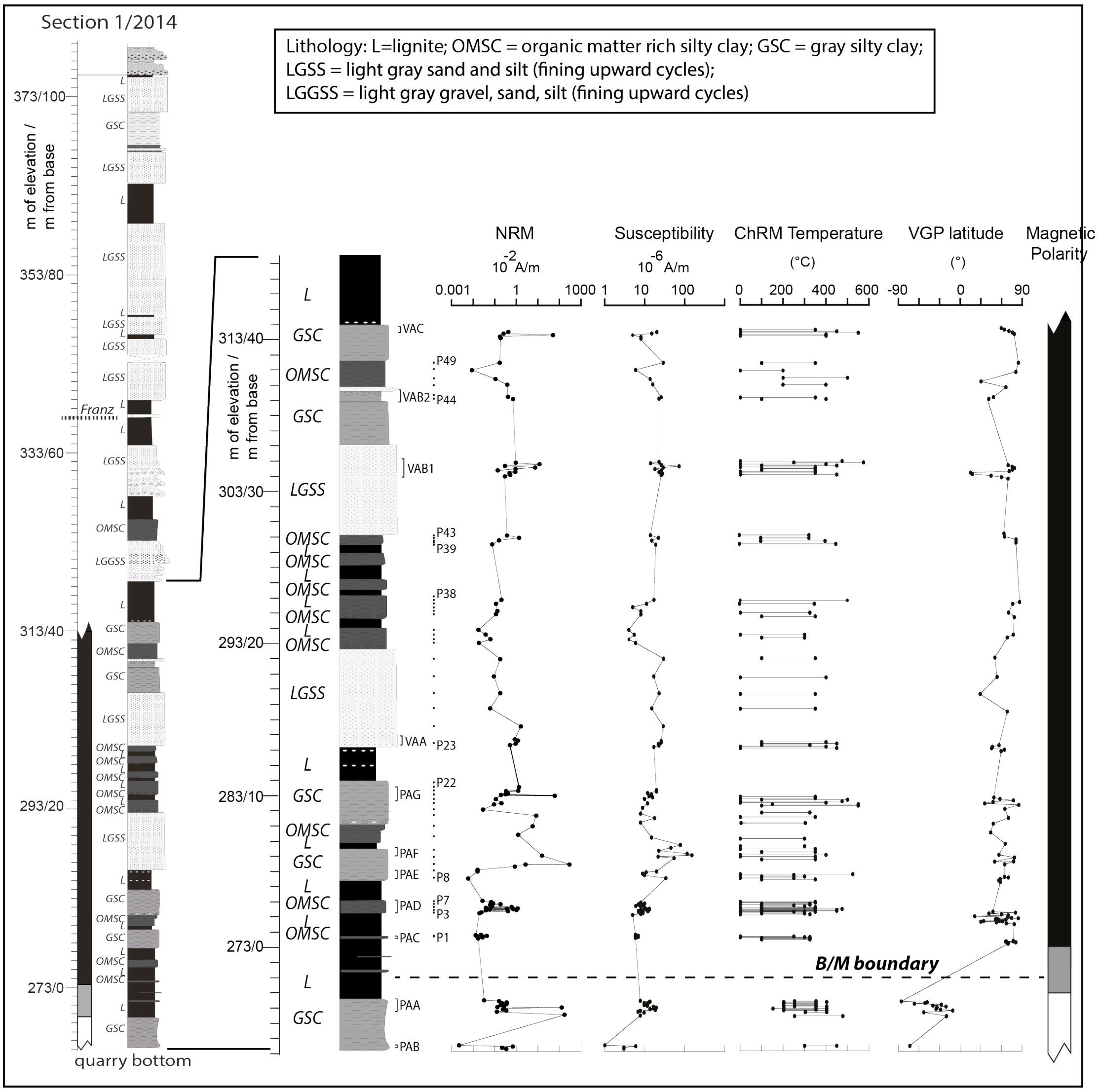

Figure 3 Section 1/2014 (this study) across the Pleistocene Megalopolis Basin sequence at the Marathousa mine. (L) is lignite, (OMSC) is organic matter rich silty clays, (GSC) is gray silty clays, (LGSS) is fining upward cycles of light gray sand and silt, and (LGGSS) is fining upward cycles of light gray gravel, sand and silt. Paleomagnetic data from the lower ~45 m of the section are as follows, from left to the right: natural remanent magnetization (NRM) intensity, magnetic susceptibility, the unblocking temperature spectra of the characteristic remanent magnetization (ChRM), virtual geomagnetic pole (VGP) latitudes and magnetic polarity where black is normal polarity and white is reverse polarity. See text for discussion.

A similar complex alternation of black lignites and grey sand-silt-clay intervals was observed and sampled for magnetostratigraphy by van Vugt et al. (2000) in two correlative sections located at the Marathousa and Choremi Mines, respectively, i.e. the same mines that we sampled. These authors found evidence in the lower part of both sections for a lower reverse-upper normal magnetic polarity reversal interpreted as a record of the Brunhes/Matuyama boundary (0.78 Ma). In addition, Okuda et al. (2002) studied the pollen record of a third section straddling the Marathousa Member, and correlated lignite seams bearing temperate oak forest taxa with warm Marine Isotope Stages (MISs) 15, 13, 11, and 9, whereas the intervening detrital beds with semi-arid steppe taxa (mainly Artemisia) were correlated with cold MISs 14, 12, and 10. Unfortunately, neither the van Vugt et al. (2000) magnetostratigraphic sections nor the Okuda et al. (2002) pollen record could be correlated with a high degree of confidence to the Marathousa-1 archeological levels or the correlative drill core levels used to erect our stratigraphic scheme (see below). Moreover, van Vugt et al. (2000) reported complex magnetic overprints apparently affecting the sediments straddling the Brunhes/Matuyama boundary, which deserve further scrutiny.

The Marathousa-1 archeological site, discovered in 2013 and still under investigation, yielded fossil bones and lithic artifacts from Layer 4 at excavation area B (Fig. 5; see Fig. 2 for location) as well as at nearby excavation area A (Panagopoulou et al., 2015). Layer 4 is a 0.6–1.8m-thick deposit of dark brown, organic matter-rich silty sand interbedded with lenses of fine sands, and is sandwiched (together with underlying clayey-sand Layer 5 and sandy Layer 6, and overlying mollusk-rich Layer 3) between a lower and an upper lignite seam represented by Layers 8 and 1, respectively (Fig. 5; see also Panagopoulou et al., 2015 for additional details). Layer 4 is interpreted as deposited in a generally low-energy environment such as a shallow-water swamp close to the paleolake shores (Panagopoulou et al., 2015), punctuated by higher-energy events such as mud-flows. We studied the anisotropy of magnetic susceptibility (AMS) to shed light on the depositional characteristics of excavation area B sediments (see below).

The lower part of layer 4 yielded remains of a virtually complete skeleton of *Elephas (Palaeoloxodon) antiquus* (Fig. 5) in association with remains of cervids and bovids, as well as micromammals such as turtles and birds, while the lithic assemblage is composed of well-preserved flakes and flake fragments, core fragments and chunks (Panagopoulou et al., 2015). The close association of artifacts and fossils (notably, elephant bones) may suggest the involvement of hominins in the exploitation of these animal carcasses (Panagopoulou et al., 2015).

3. Paleomagnetic properties and magnetostratigraphy

Paleomagnetic sampling was performed in the more cohesive silty clays intervals; lignite intervals crumbled upon handling and could not be sampled.

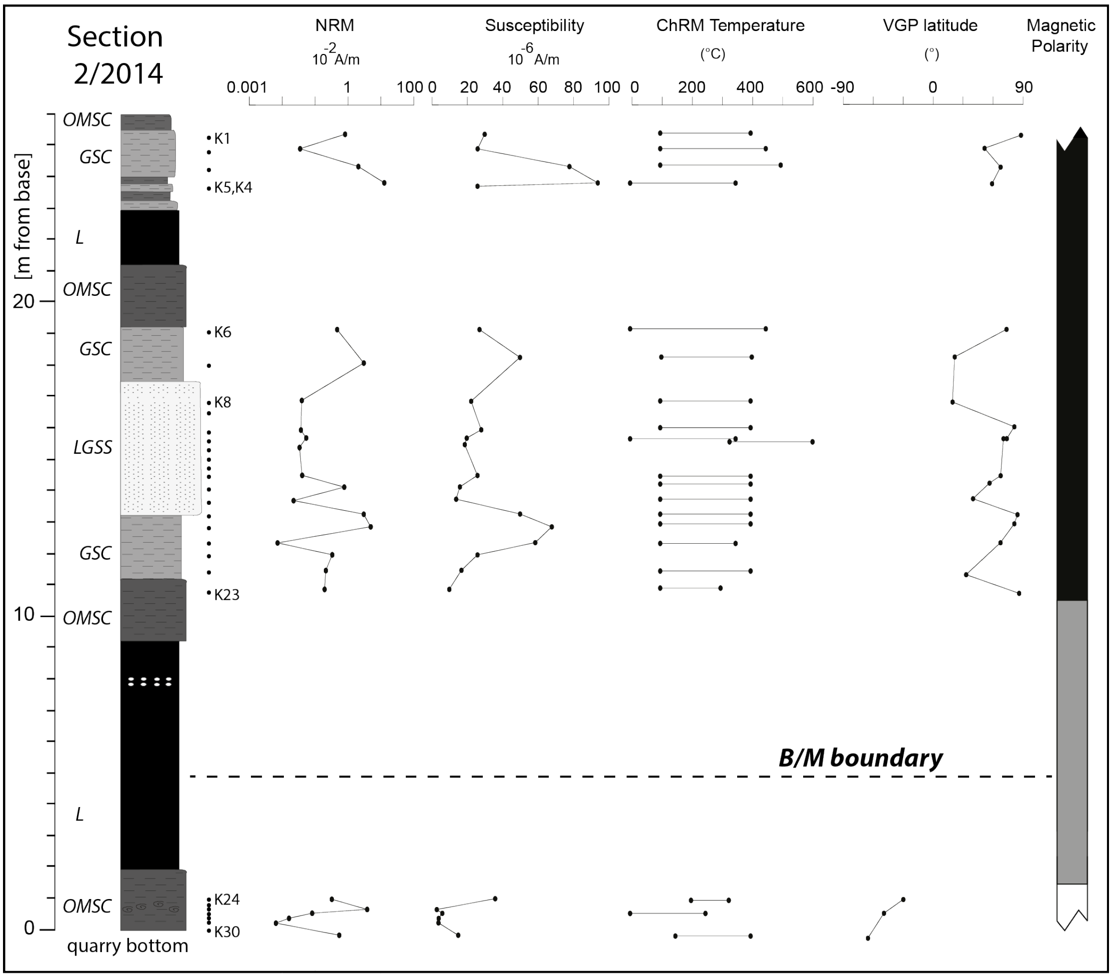

Figure 4 Section 2/2014 (this study) across the Pleistocene Megalopolis Basin sequence at the Choremi mine. (L) is lignite, (OMSC) is organic matter rich silty clays, (GSC) is gray silty clays, (LGSS) is fining upward cycles of light gray sand and silt, and (LGGSS) is fining upward cycles of light gray gravel, sand and silt. Paleomagnetic data are as follows, from left to the right: natural remanent magnetization (NRM) intensity, magnetic susceptibility, the unblocking temperature spectra of the characteristic remanent magnetization (ChRM), virtual geomagnetic pole (VGP) latitudes and magnetic polarity where black is normal polarity and white is reverse polarity. See text for discussion.

All paleomagnetic samples were cored in the field with an electric drill and oriented with a magnetic compass to obtain a total of 157 standard (10 cm^3) cylindrical specimens for section 1/2014 (Fig. 3) and 30 samples for section 2/2014 (Fig. 4). Seven cylindrical core samples were subjected to rock magnetic analyses by means of acquisition curves of an isothermal remanent magnetization (IRM) and thermal demagnetization of a three-component IRM imparted in fields of 2.5 T, 0.4 T, and 0.12 T (Lowrie, 1990). A total of 169 cylindrical core specimens were subjected to thermal demagnetization in steps of 50 °C or 25 °C using a ASC TD48 furnace, and the natural remanent magnetization (NRM) was measured after each demagnetization step with a 2G Enterprises DC-SQUID cryogenic magnetometer located in a shielded room. Standard least-square analysis (Kirschvink, 1980) was used to calculate magnetic component directions from vector end-point demagnetization diagrams, and standard Fisher statistics was used to analyze the mean component directions. Magnetic measurements were carried out at the Alpine Laboratory of Paleomagnetism (ALP) of Peveragno (Cuneo, Italy).

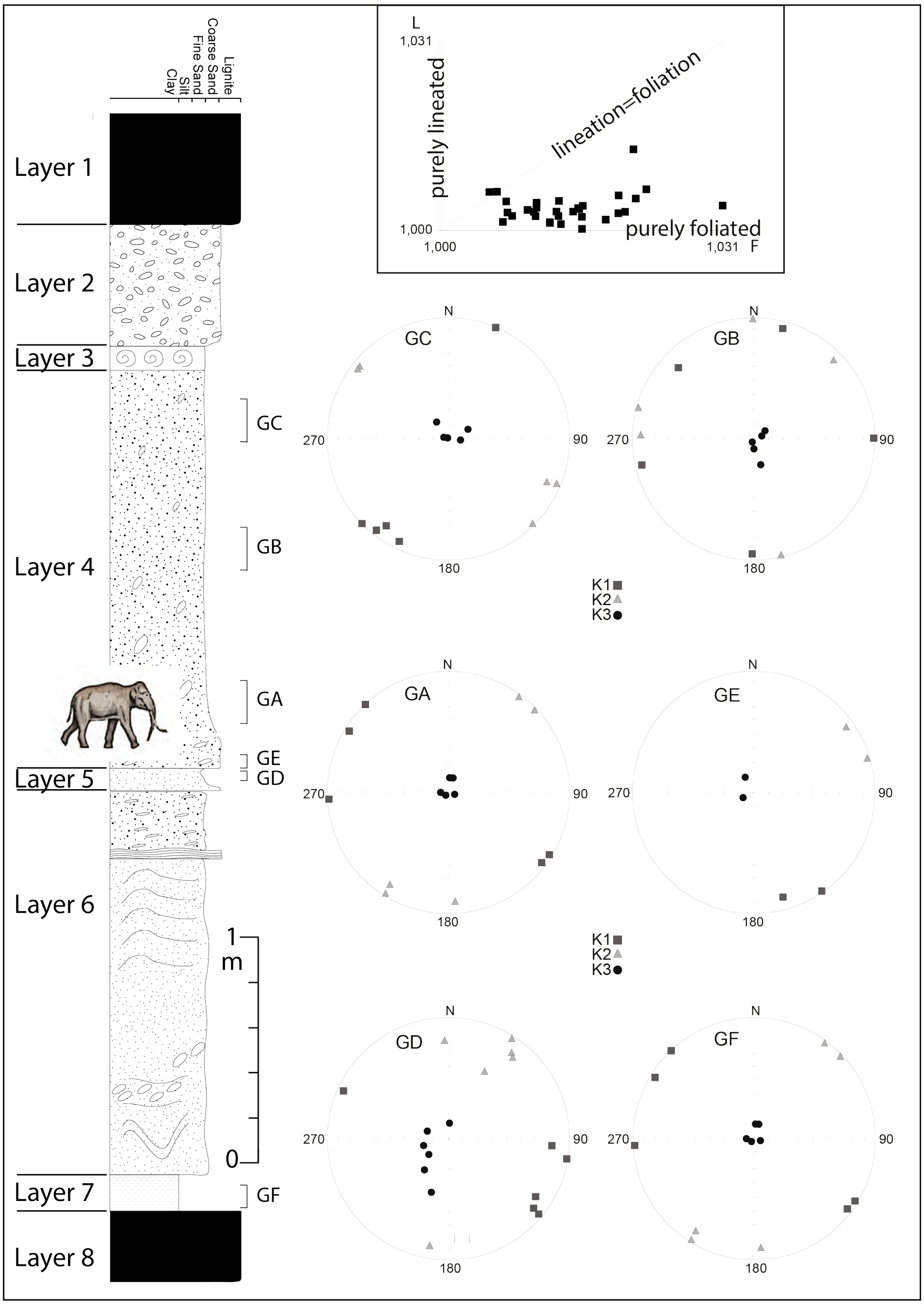

Figure 5 Stratigraphy of the Marathousa-1 archeological excavation area B with anisotropy of magnetic susceptibility (AMS) data. See text for discussion.

The intensity of the NRM varies by orders of magnitude across the various sampled lithologies from less than $0.01*10^{-2}$ A/m to more than $100*10^{-2}$ A/m (Figs. 4,5). The initial magnetic susceptibility co-varies with the NRM and attains values of generally less than $100*10^{-6}$ SI (Figs. 4,5). The IRM acquisition curves show the presence of a magnetic mineral assemblage that invariably saturates well below 500 mT (Fig. 6; samples P39, P07, K05). The thermal demagnetization of a three-component IRM is more diagnostic and reveals two main behaviors:

1. The low (0.12 T) coercivity curve shows maximum unblocking temperatures up to ~570 °C, interpreted as signaling the presence of magnetite (Fig. 6, samples P39, P07).
2. The intermediate (0.4 T) as well as the low (0.12 T) coercivity curves show a drop in intensity at around 300 °C interpreted as due to the presence of iron sulphides (Fig. 6, sample K05).

Vector end-point demagnetization diagrams show the presence of characteristic component (ChRM) directions trending to the origin of the demagnetization axes and oriented to the north and down (positive inclinations) or south and up (negative inclinations) (Fig. 7A,B). These ChRM component directions were unblocked from ~100°C to ~400°C or up to a maximum of ~570°C (see 'ChRM Temperature' unblocking window in Figs. 4,5; see also Fig. 7A,B). These bipolar ChRM component directions, obtained from a total of 95 and 21 specimens at sections 1/2014 and 2/2014, respectively, are grouped in *in situ* (geographic) coordinates around a mean of Dec. = 3.3°E, Inc. = 53.8° (k = 3, α95 = 10.3°) at section 1/2014 (Fig. 7C), and of Dec. = 358.9°E, Inc. = 58.0° (k = 7, α95 = 14.7°) at section 2/2014 (Fig. 7D). The declination and inclination values of these ChRM component directions were used to calculate virtual geomagnetic pole (VGP) latitudes and magnetic polarity stratigraphy, with VGP latitudes approaching +90° interpreted as normal polarity and VGP latitudes approaching -90° as reverse polarity (Figs. 4,5). A clear upper normal-lower reverse polarity reversal is evident at both sections and interpreted as a record of the Brunhes/Matuyama boundary (0.78 Ma), in broad agreement with previous data (van Vugt et al., 2000; Okuda et al., 2002).

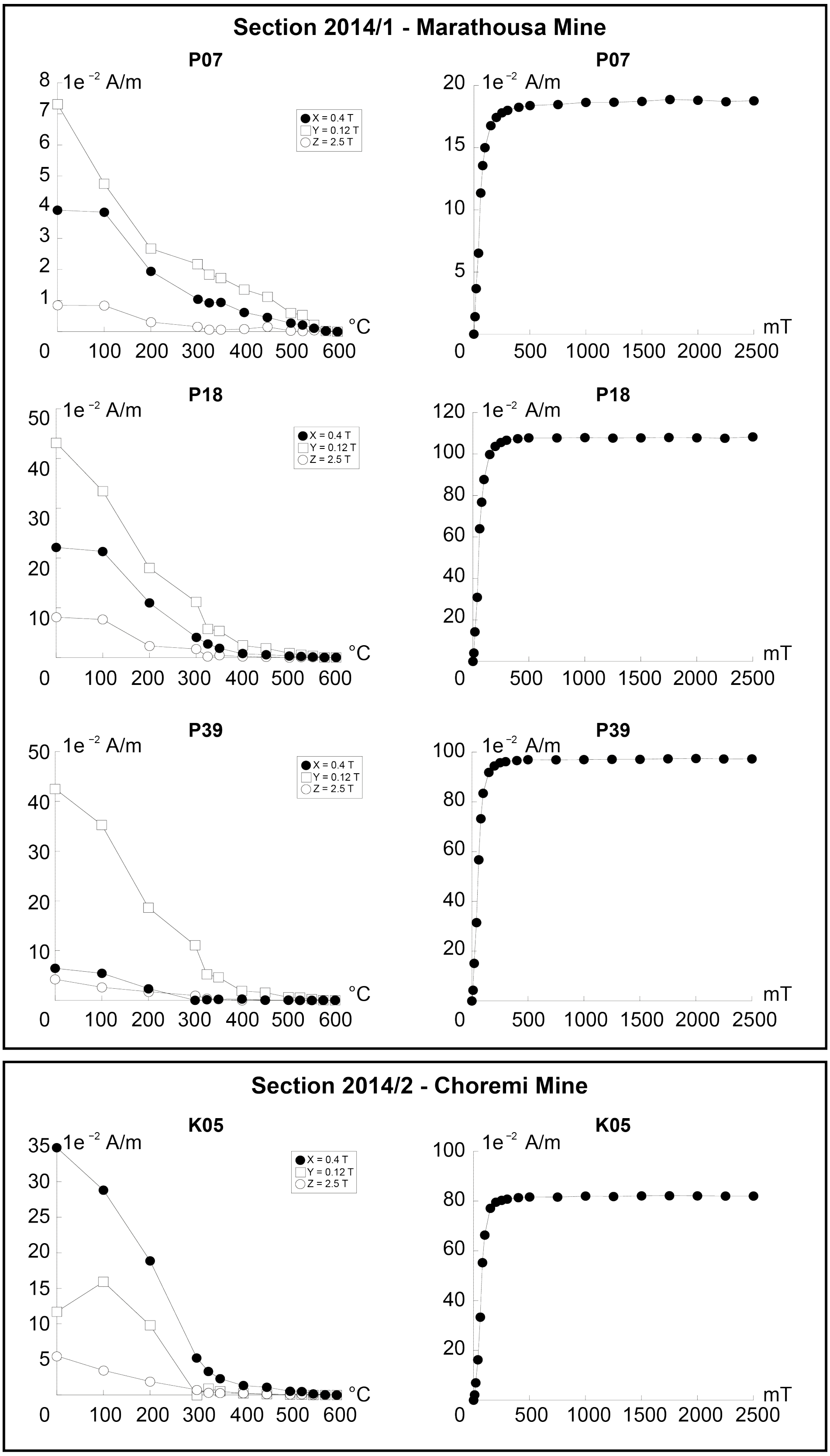

Figure 6 Isothermal remanent magnetization (IRM) acquisition curves and thermal demagnetization curves of a 3-component IRM representative samples from sections 2014/1 and 2014/2.

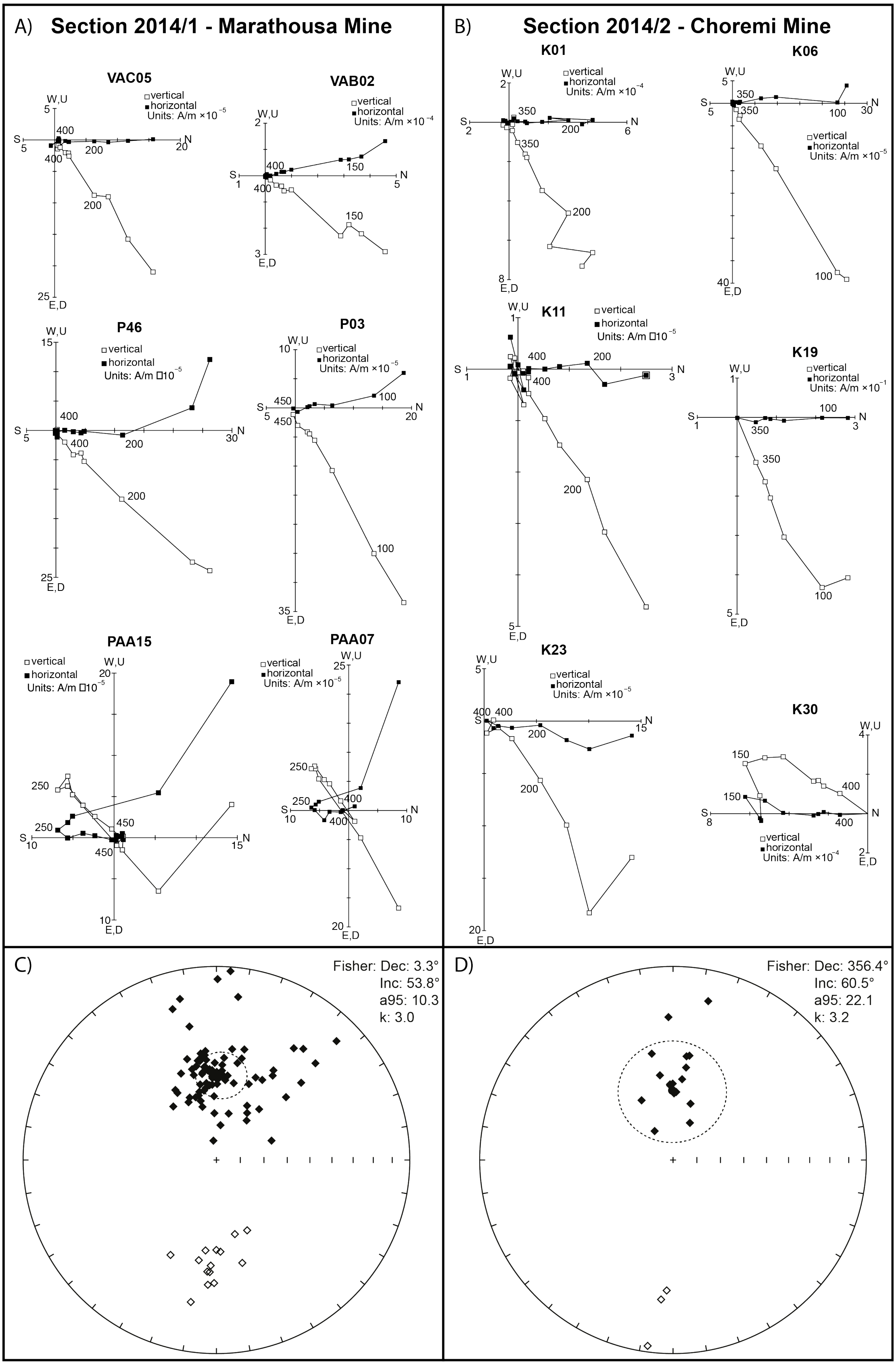

Figure 7 Vector end-point demagnetization diagrams of representative samples from sections 2014/1 (A) and 2014/2 (B). Full symbols are projections on the horizontal plane and open symbols in the vertical plane. Demagnetization temperatures are expressed in °C. In panels (C) and (D) equal area projection of the characteristic (ChRM) component vectors in *in situ* coordinates from sections 2014/1 and 2014/2, respectively. Full symbols represent down-pointing vectors (normal polarity), open symbols represent up-pointing vectors (reverse polarity).

Van Vugt et al. (2000) observed a complex magnetization pattern with overprints affecting the Brunhes/Matuyama boundary at their Choremi section. In a few thermal demagnetization diagrams they observed high-temperature magnetic component directions of normal polarity that were not trending straight to the origin of the demagnetization axes, and were therefore interpreted to signal the presence of a hidden component of reverse polarity. This interpretation led them locate the Brunhes/Matuyama boundary in levels above the lowermost lignite interval and within a sequence of detrital sediments. However, most researchers agree that the detrital intervals likely correspond to cold (glacial) stages, while the lignite seams represent warm (interglacial) periods (Nickel et al. 1996; van Vugt et al. 2000; Okuda et al. 2002); therefore, as the broadly accepted position for the Brunhes/Matuyama boundary is within the warm stage of MIS 19 (e.g. Tauxe et al., 1996; Scardia and Muttoni, 2009), this reversal should correlate with a lignite deposit.

We did not observe the complex magnetization pattern with overprints described by van Vugt et al. (2000) and hence we used our ChRM component directions trending to the origin of the demagnetization axes to place the Brunhes/Matuyama boundary within – or at the base of – the lowermost lignite interval L1 (Figs. 3,4; see also below).

4. Age models of sedimentation

We placed the more expanded and complete section 1/2014 together with the available drill core logs (75/60, 76/60, 25/58, 24/58, 89/60) as well as the Marathousa-1 archeological site (excavation area B of Panagopoulou et al., 2015) in a common meter elevation framework (Fig. 8). We attempted to place in this correlation framework also the van Vugt et al. (2000) litho-magnetostratigraphic profile from the Marathousa mine and the Okuda et al. (2002) pollen profiles from the Choremi mine although we remind that neither their locations nor their elevations relative to the other sections and cores are known (Fig. 8).

According to this stratigraphic scheme, the main lignite intervals, represented by black bars on the drill core logs and stratigraphic sections, fall at slightly different elevations but appear laterally continuous and have been therefore used to erect 5 chronostratigraphic surfaces, from base to top: Lignite 1a base (L1a), Lignite 1b base (L1b), Lignite 2a base (L2a), Lignite 2b base (L2b), Lignite 2b top (L2bT), Lignite 3 base (L3) (Fig. 8; for the original identification and description of the Megalopolis three main lignite seams see Löhnert and Nowack 1965 and Vinken 1965).

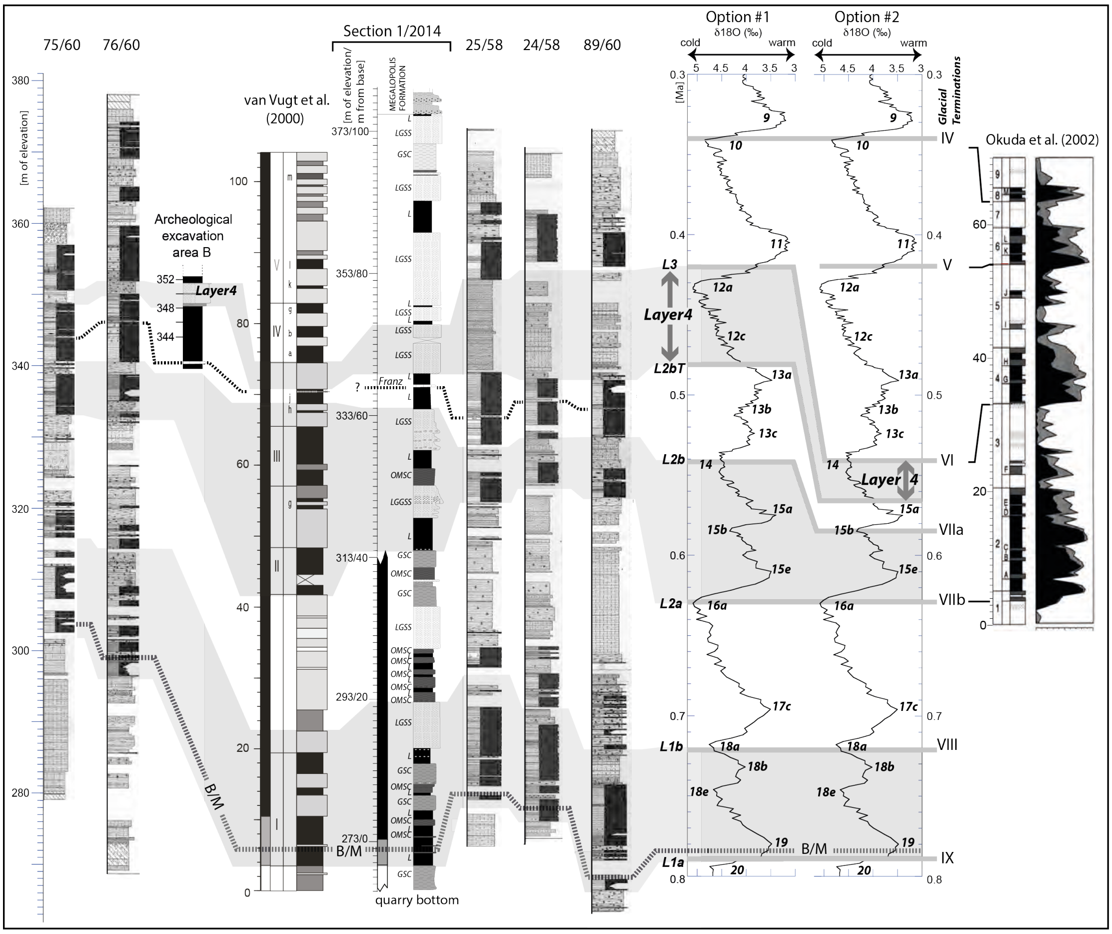

Figure 8 Correlation scheme of a selection of commercial drill core stratigraphies and section 1/2014 of this study with the with the Pleistocene climatic variability represented by the d[18]O curve of Lisiecki and Raymo (2005). Two correlation options (#1 and #2) are proposed and discussed in the text, with option #1 considered the preferred option. See text for discussion.

We created two age models of sedimentation (Fig. 8) based on two different correlations of the studied litho-magnetostratigraphies with the standard $\delta^{18}O$ benthic isotope record of Lisiecki and Raymo (2005).

4.1 Age model option #1

In this option, we consider a position for the Brunhes/Matuyama boundary (0.78 Ma) just above L1a and correlate this boundary with MIS 19; thus, L1a is assumed to represent Glacial Termination (GT) IX dated to ~0.79 Ma (Fig. 8). By applying the equivalence between main lignite beds and interglacials, and between main detrital intervals and glacials, we correlate L1b, L2a, and L2b with, respectively, GT VIII (at the end of MIS 18a) dated to ~0.72 Ma, GT VII (at the end of MIS 16a) dated to ~0.63 Ma, and GT VI (at the end of MIS 14) dated to ~0.54 Ma (Fig. 8). L2bT could be less confidently resolved within the cooling trend from MIS 13 to MIS 12, and was assigned a nominal age of ~0.48 Ma, while L3 was correlated with GT V dated to ~0.42 Ma (Fig. 8). According to this age model, the archeological Layer 4 between chronostratigraphic levels L2bT and L3 should have an age broadly comprised between ~0.48 Ma and ~0.42 Ma (Fig. 8). This chronological bracketing agrees well with recent radiometric assays: ESR dating of a mollusk sample from a unit overlying the find-bearing layers provided a minimum age for this unit at 414± 42 ka, while five subsamples of a cervid tooth excavated from the find horizon gave an age of 484 ± 13 ka (Blackwell et al. submitted). For this reason, option #1 is at present considered the preferred option.

4.2 Age model option #2

This alternative option is equivalent to preferred option #1 from L1a (=GT IX at ~0.79 Ma) across the Brunhes/Matuyama boundary (0.78 Ma) up to L2a (= GT VII at the end of MIS 16a at ~0.63 Ma) (Fig. 8). It then departs from option #1 by assuming that L2b corresponds to the (minor) glacial termination at the end of MIS15b with an age of ~0.585 Ma, L2bT to a level within the cooling trend from MIS 15a to MIS 14 with a nominal age of ~0.565 Ma, and L3 to GT VI at the end of MIS 14 dated to ~0.54 Ma (Fig. 8). According to this age model, the archeological Layer 4 between chronostratigraphic levels L2bT and L3 should have an age comprised between ~0.565 Ma and ~0.54 Ma (Fig. 8).

4.3 Sedimentation rates

According to the age constraints of preferred option #1, the long-term sediment accumulation rate curve calculated for section 1/2014 is of ~230 m/Ma from section base up to L2bT at 66 m, and of ~100 m/Ma from L2bT up to L3 across (projected) archeological Layer 4 (Fig. 9). Instead, according to the age constraints of alternative option #2, the long-term sediment accumulation rate curve of section 1/2014 is more linearly centered around a median value of ~260 m/Ma (Fig. 9).

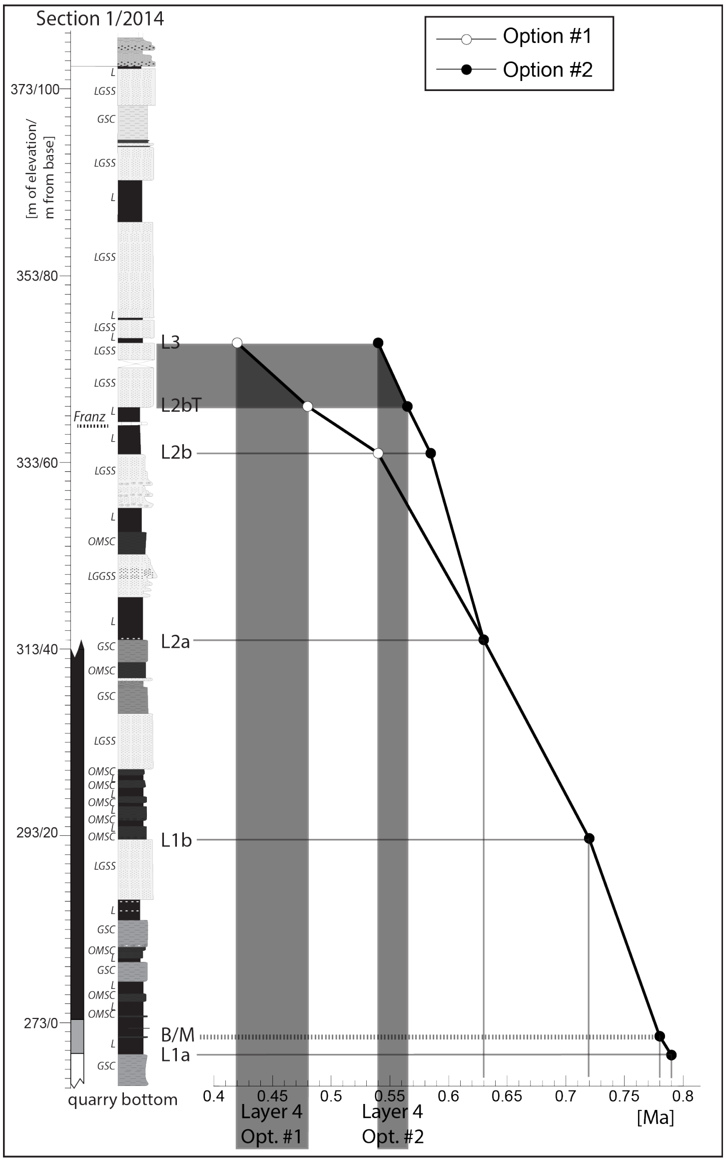

Figure 9 Age model of sedimentation of the Pleistocene Megalopolis Basin sequence according to preferred correlation option #1 and alternative correlation option #2. See text for discussion.

In both options, drill cores 75/60 and 76/60 as well as excavation area B bearing archeological Layer 4 display lower long-term sediment accumulation rates relative to section 1/2014 and correlative cores 89/60, 24/58 and 25/58, consistent with the general geometry of the basin whereby cores/sections with higher sedimentation rates are located more to the E-SE toward the basin depocenter while cores/sections with lower rates are located more to the W closer to the paleolake shores (see also Vinken 1965). Overall, our values agree well with those estimated by both van Vugt et al. (2000) and Okuda et al. (2002).

5. The anisotropy of magnetic susceptibility of archeological Layer 4 (DRAFT)

The anisotropy of magnetic susceptibility (AMS) is a useful tool to assess depositional dynamics and characteristics, and was applied to excavation area B sediments. The AMS ellipsoid reflects the bulk orientation of the minimum (k_{min}), intermediate (k_{int}), and maximum (k_{max}) susceptibility axes of paramagnetic grains contained in a given sediment volume (usually ~10cc). For example, phyllosilicates tend to decant in still water with their short shape axis perpendicular to the bedding plane, and as a result, an oblate mineralogical fabric develops. The AMS should reveal this fabric because in phyllosilicates, the short shape axis broadly corresponds to the k_{min} axis, and therefore, a magnetic foliation (defined by the plane containing k_{max} and k_{int}) should develop parallel to the depositional surface; instead, when bottom currents are present, the long shape axis of elongated magnetic grains tend to line up parallel (or sometimes perpendicular) to the current direction, and the AMS should reveal this because in such grains the k_{max} axis usually lies broadly along the flow-aligned particle length (e.g., Tarling and Hrouda, 1993; Pares et al., 2007; Felletti et al., 2016).

We sampled archeological Layer 4 as well as underlying Layers 5 and 7 obtaining a total of 6 sites and 28 samples (Fig. 5) that were measured for AMS with a KLY-3 Kappabridge. The lineation coefficient (k_{max} /k_{int}) is usually close to 1 while the magnetic anisotropy is essentially controlled by the foliation coefficient (k_{int} /k_{min}) that implies the AMS ellipsoids are essentially oblate (Fig. 5, upper inset). The k_{min} axis of all samples lies invariably perpendicular to the bedding plane; samples from sites GA, GE, GD and GF show a tendency to have the k_{max} axes broadly aligned in a NW–SE direction, while the k_{max} axes of site GC appear oriented NE–SW; only at site GB seem the k_{max} and k_{min} axes dispersed in a girdle parallel to the bedding plane (Fig. 5). These data seem to suggest that sedimentation occurred either in the presence of an aligning current (e.g., GA, GE, GD, GF) or as the result of simple gravitational settling of particles (GB). These data substantiate the interpretation of Panagopoulou et al. (2015) that Layer 4 deposited in a generally low-energy environment, which we suggest was also characterized by the occurrence of grain-aligning, higher-energy events, possibly debris-flows. This overall interpretation is also consistent with the general stratigraphy of the area whereby the thin stratigraphic interval of clastic sediments with debris-flows straddling archeological Layer 4 opens up to the SE into a much thicker clastic interval dominated by fining-upward sequences of turbiditic origin in what is interpreted as the deeper part of the basin (Fig. 8). Hence, we conclude that archeological Layer 4 deposited close to the western paleolake margin and was subject to debris-flow events coming to the NW and propagating as turbidites toward the east into the paleolake depocenter (Figs 2,8).

5. Conclusions

In this study we reached the following achievements:

1. We correlated several commercial drill core logs and two outcrop sections straddling the Marathousa Member of the Choremi Formation in the Megalopolis Basin of Greece.
2. We placed the recently discovered Marathousa-1 archeological site (excavation area B) within this general correlation scheme.
3. By using litho-magnetostratigraphy and correlation with a standard $\delta^{18}O$ record from the literature, we generated two age models of sedimentation (options #1 and #2) for the Marathousa Member based on 7 independent chronostratigraphic surfaces.

Based on these achievements, we conclude that:

1. according to preferred option #1, the archeological Layer 4 of the Marathousa-1 site should have an age broadly comprised between ~0.48 Ma and ~0.42 Ma, in broad agreement with preliminary ESR dates (Blackwell et al., submitted), while according to alternative option #2, the archeological Layer 4 could have an age comprised between ~0.565 Ma and ~0.54 Ma.
2. Archeological Layer 4 deposited close to the paleolake shores, in a proximal low-energy environment punctuated by higher-energy, debris-flow events that evolved toward the paleolake depocenter into fining-upward turbiditic sequences.

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Public Power Corporation S. A. Hellas.

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MAGNETOSTRATIGRAPHIC STUDY OF THE PRINCE'S CAVE STRATIGRAPHIC SEQUENCE (BALZI ROSSI COMPLEX, VENTIMIGLIA, NORTHERN ITALY)

My personal contribution in this work started with a single day of fieldwork in October 2015, my personal duty consisted in the measuring, description and sampling of the stratigraphic sequence. The following step consisted in the analysis of all the collected samples in the Alpine Laboratory of Paleomagnetism of Peveragno (Cuneo), and thus in the interpretation of the data. Afterward I provided the interpretation of the dataset, contributed in the creation of the figures and in the writing of the paper, as well as to check the completeness and the correctness of the references.

MAGNETOSTRATIGRAPHIC STUDY OF THE PRINCE'S CAVE STRATIGRAPHIC SEQUENCE (BALZI ROSSI COMPLEX, VENTIMIGLIA, NORTHERN ITALY)

Abstract

The Prince's cave is the largest one of the Balzi Rossi complex located between Menton and Ventimiglia close to the Italian-French border (Northern Italy). Evidences of human occupation since the middle Pleistocene in this area were known since the end of the nineteenth century. A human iliac bone attributed to an adult female of *Homo heidelbergensis* was found in 1968 in the Br2 unit of the Prince's cave and was dated back to MIS 7 by the means biostratigraphy and an absolute dating based on the Gamma Ray Spectrometry system. Since no magnetostratigraphic study was ever done in this sequence we chose to go and investigate this site because an eventual reverse magnetic polarity found in the Br2 unit would prove the occupation of the area by early modern humans before the Brunhes – Matuyama boundary (0.78 Ma) therefore corroborating the hypothesis of a human colonization of the european continent starting with the EPR, not before MIS 22. Unfortunately only normal magnetic polarity was found throughout the entire stratigraphic sequence then confirming the chronology already suggested by the literature. Knowing that the entire alpine and Po Plain area are subjected by uplift since the beginning of the middle Pleistocene and considering the actual position of the entrance of the Prince's cave we elaborated a possible uplift rate model that if compared to the actual known uplift rate of the nearby areas would suggest the impossibility of a human frequentation of the cave previous the MIS 7 since the area was probably submerged before that moment. This solution wouldn't come into conflict with the hypothesis suggesting a human income into the European continent starting from MIS 22 because it would just mean that the specific investigated area wasn't available for occupation at that time thus not denying the possibility of human frequentation of other available areas in the North of Ligurian Alpine chain.

1. Introduction

Balzi Rossi is a complex of caves located in the Grimaldi locality in the western Ligurian coastline between the French city of Menton and the Italian city of Ventimiglia (Figure1). Evidences of human occupation of these caves are known since the half of the Nineteenth century. The Balzi Rossi caves opens in a Jurassic dolomitic limestone cliff less than 1km East of the Italian-French border. A total of twelve archeological sites were discovered in this area of less than 2 km^2 extension, seven of which are located inside the caves, three are shelters, while the other two are open air sites on the beach in front of the cliff. The contents of the archeological sites attributed to the Paleolithic period vary from animal fossil remains, lithic tools, Venuses, and human remains sometimes associated with burials (Rivière, 1887; Mortillet de, 1898; Villeneuve et al., 1906; 1912; Breuil, 1930; Mussi, 1986; 1991; 1995; 1997; 2004; 2008; Formicola, 1988; 1997; Delporte, 1993; Frayer, 1995; Bolduc et al., 1996; Malerba et al.; 1997; Onoratini et al., 1997a,b; 2012; White et al., 1991; Henry et al., 2001; 2008; de Lumeley et al., 2011).

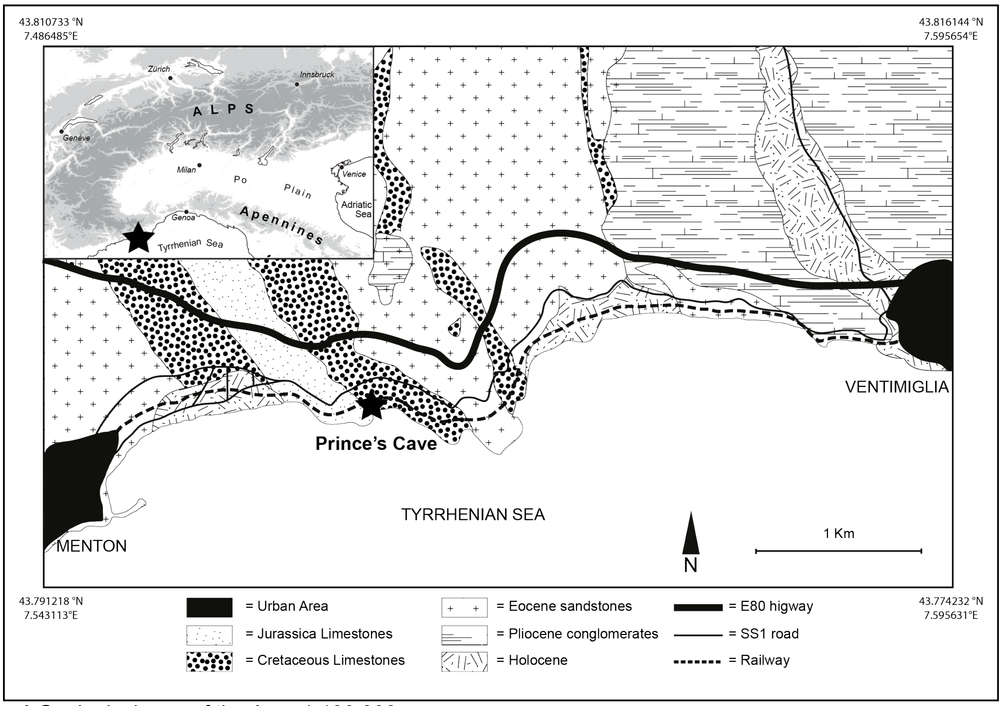

Figure 1 Geological map of the Area 1:100.000

The Prince's cave is the biggest in the Balzi Rossi's complex being 34 m deep, 9 m wide and 16 in height at the entrance (Villeneuve e al., 1906; 1912). The original name was Barma del Ponte, but it was changed into the actual one after it was bought by Prince Albert I of Monaco in 1895 with the intent to initiate some archeological surveys in the internal deposit. Since the beginning of the excavation, evidences of multiple occupation of the cave from MIS 5 were found through the recovery of lithic tools belonging to Mousterian industries (Rossoni et al., 2011; 2016a,b), in later years also Acheulean layers were discovered (Barral et al., 1965; 1967; 1968; 1971; 1976; 1985; 1985; Simone, 1970; 1997; Rossoni et al., 2016c,d). In 1968 an incomplete human iliac bone was found in a breccia layer inside the cave deposit, it was dated using Gamma Ray spectrometry by Yokoyama (1989) obtaining an age of 220 ± 120/50 ka (Barral et al., 1987). The human fossil was determined as belonging to a female adult of a preneanderthalian species, a.k.a. *Homo heidelbergensis* (Barral et al., 1967; 1968; Lumley de, 1972a,b).

The incoming of this species in this region is supposed to have happened in a time interval corresponding to the latter part of the Matuyama reversal geomagnetic polarity chron included between the end of the Jaramillo normal polarity subchron (0.99 Ma) and the base of the Brunhes normal polarity chron (0.78 Ma) (Muttoni et al., 2010; 2011; 2014; 2015a,b). More precisely, the human colonization of Europe is supposed to have occurred not before MIS 22 (0.87 Ma) when the late Early Pleistocene climate Revolution (EPR) occurred bringing the onset of the major Pleistocene galciations in the Northern hemisphere. As a consequence of the glacio-eustatic lowstand brought by the EPR, the erosion on the Alpine-Dinaride mountain belt increased exponentially causing the accumulation of detritus in the surrounding plains with as an effect the formation of large lowstands in the Pannonian basin, the Dacian plain, modifying also the drainage basins giving the modern fluvial systems, especially the Danube in Eastern Europe. The same effects were recorded in Northern Italy where starting from this period the infilling with sediments of the previous Padan Marine gulf brought to a progradation eastwards of the coast line bringing to the formation of the modern Po plain and the Po river drainage system (Kent et al., 2002; Muttoni et al., 2010; Scardia et al., 2006; 2010; Monesi et al., 2016). As a consequence of this profound climate change, even the habitats changed from closed forests to open space grasslands with minimal arboreal vegetation especially at glacial/interglacial transitions, creating for the first time in the Pleistocene the savanna-like environments at these latitudes suitable for African and Asian large herbivores to migrate into (Muttoni et al., 2010; 2014; 2015a). The incoming of the species in the European continent seems therefore to have occurred not before that specific moment in the geological history; they presumably entered Mediterranean Europe coming from the Balkans through these open environments to which they were already well adapted as migration corridors, essentially the Danube and the Po fluvial systems (Muttoni et al., 2010; 2011; 2014; 2015b). Being the large herbivores and other species a main source of proteins for the hominin populations, it is reasonable to support the idea, synthetized in the so-called "Follow the herd hypothesis" that early humans first colonized Europe following the herds of the animals they fed on (Muttoni et al., 2010; 2011; 2014; 2015b).

Since no magnetostratigraphic analysis were ever performed on the sediments constituting the Prince's cave deposit, we chose to investigate this site using this method that nowadays is considered essential for a reliable chronological attribution of continental stratigraphic sequences. The eventual identification of reverse magnetic polarity in the unit where the *H. heidelbergensis* iliac bone was found would imply that the Balzi Rossi area was among the first localities in Europe to be colonized by the early hominins.

2. Stratigraphy

The cave opens 8.3 m above sea level (asl from now on) within the reddened step cliff that gave its name to the complex. The basis of the sequence is constituted with a thin layer of dark green Cenomanian marls.

A 1 m wide cross-section extends from 13 m asl to 25 m asl through the Quaternary deposit. The oldest Quaternary units, attributed to the Upper Sicilian period (Bonifay, 1975, Rossoni-Notter et al., 2016c), are two marine units called respectively M1 and M2. M1 is exposed from ~17 m asl up to ~19 m asl (Figure 2), and in another small windows about 0.2 m thick around 23 m asl (Figure 2); this unit was dated back to MIS 11 (Bonifay, 1975; Simone, 2008). M2 is about 0.5 m thick and debuts around 13.5 m asl (Figure 2); this marine unit was dated to MIS 9 (Bonifay, 1975; Simone, 2008).

A breccia unit called Br2 that goes from 14 to 16.2 m asl (Figure 2) (Barral et al., 1967) gave evidence of Acheulean occupation of the cave (Simone, 1970). This unit is composed by cryoclatic gravel with small nodules included in a brown limestone hard breccia (Barral et al., 1967; 1976; Simone, 1970). Two fissures known as f3, located at the basis of the unit (14.2 m asl) (Figure 2), and f2, in the first lower quarter (14.9 m asl) (Figure 2), retain traces of littoral facies attributed to the Tyrrhenian sea in the posterior part, while in the anterior part exposes remains of Mousterian red clays (Barral et al., 1967); the human ilium was recovered between f2 and f3 (Barral et al., 1967; 1970a,b; 1976; Simone, 1970). The paleontological remains recovered in Br2 counts *Capra ibex*, *Cervus elaphus*, *Ursus* sp., *Canis lupus* and *Hippopotamus* sp. as regards the macrofauna (Barral et al., 1976; Simone, 2008) the micromammals species recovered are *Apodemus sylvaticus*, *Muscardinus avellanarius*, *Glis glis*, *Eliomys quercinus*, *Microtus agrestis*, *Microtus arvalis*, *Oryctolagus cuniculus* and *Arvicola terrestris* (a.k.a. *Arvicola amphibious*) (Viriot et al., 1991), thus implying a temperate environment at the moment of the deposition of this unit that is therefore associated with MIS7 (Simone, 2008). On top of the Br2 units a fissure f1 separates it from another continental breccia unit called Br1 goes until 17.5 m asl (Figure 2) (Barral et al., 1967), and then again in a small window around 23 m asl (Figure 2). Like Br2 this unit is constituted with cryoclatic gravels but includes larger modules and light brown sediment of calcite (Barral et al., 1967; Simone, 1970). This last unit was attributed through the use of biostratigraphy to a still temperate period even if colder compared to the Br2 unit deposition environment (Barral et al., 1976), thus was ascribed to MIS6 (Simone, 2008), the mammal species that were found in this unit are *Cervus elaphus*, *Cervus capreolus*, *Reginifer tarandus*, *Capra ibex*, *Canis lupus* and *Hyaena* sp. (Barral et al., 1967; 1976; Simone, 2008).

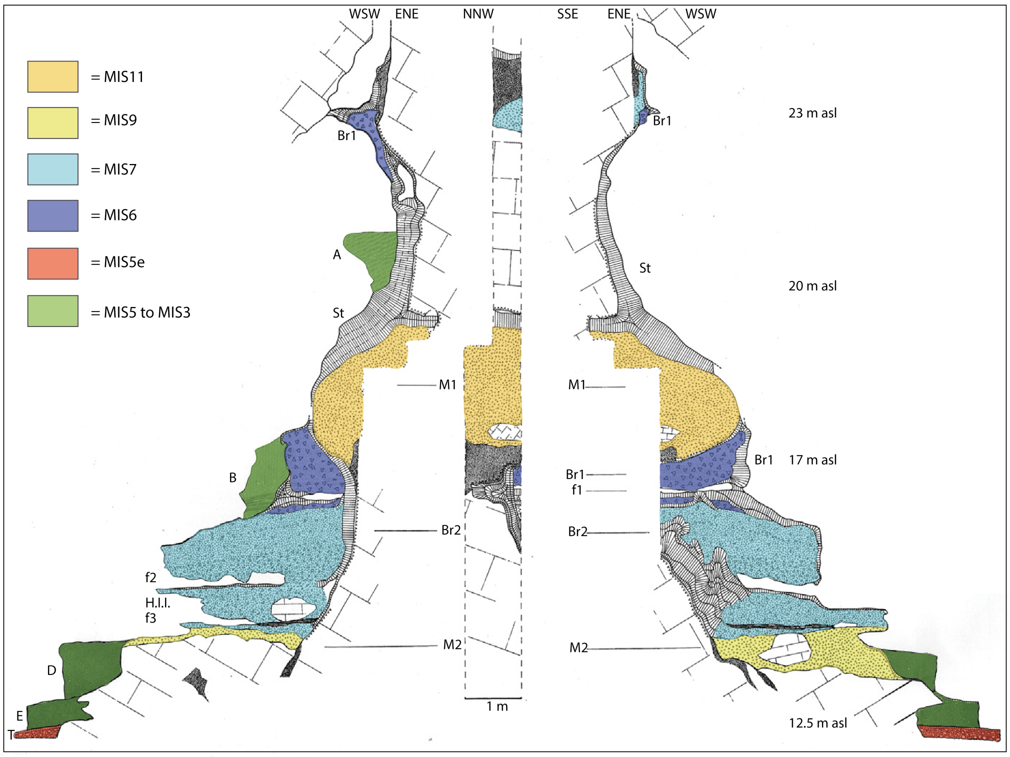

Figure 2 Sections of of Prince's cave deposits (Ventimiglia, Italy) (after Simone, 2008). At the center: face of the trench (longitudinal cut); laterally: sides of the trench (transversal cuts). M1, M2: marine formation, MIS11, MIS9;, Br2, Br1: continental breccia with anthropogenic remains, MIS7, MIS6; H.I.I.: human remain, f3, f2, f1: fissures; T: Tyrrhenian marine deposit, MIS5e; v: marine spot-level; St: stalagmitic floors and flows; E, D, B, A: Mousterian deposits, MIS5-MIS3 (from Rossoni-Notter et al., 2016c, modified).

At 12 m asl lies the top of a 1.5 m unit made of conglomerates described as pertinent to the Tyrrhenian in age (MIS6/5 boundary to MIS 2/1 boundary; Cita et al., 2005) and more precisely attributed to MIS 5e (Villeneuve et al., 1906; 1912; Blanc, 1955; Simone, 970) (Figure 2). During the Tyrrhenian the cave is considered to have been the locus of marine deposition (Blanc, 1955) because of the presence of marine facies and a *Strombus bubonic* association on the top of this unit that is considered to be evidence of a 10 m below sea level deposition environment (Barral et al., 1967; 1976; Blanc, 1955; Simone, 1970; Villeneuve et al., 1906; 1912;).

The younger units pertinent to this sequence are five Middle Paleolithic units associated with Mousterian lithic industries (Figure 2) that represent an interval comprised between MIS 5 and MIS 3 based on biostratigraphic (Villeneuve et al., 1906; 1912; Chaix et al., 1982; 1983; 1991; Arellano-Moulle, 1997-1998; Moussus, 2014) and techno-typological studies (Villeneuve et al., 1906; 1912; Iaworsky, 1961; 1962; Lumley et al.; 1969; Vicino et al.; 1976; Yamada, 1993; Rossoni et al.; 2011; 2016a,b,c). The five Mousterian units were named from top to bottom with letters going from A to E (Boule, 1906; Villeneuve at al., 1906; 1912), the older units (E and D) are characterized by small rounded pebbles (conglomerates) in a reddish clayey sand matrix and were associated with temperate periods (Villeneuve, 1906), the Mousterian E unit is almost 1m thick and is exposed from 12m asl (Figure 2), the Mousterian D unit lies on top the Mousterian E unit up to ~13.5 m asl (Figure 2). The most recent units (A and B) are made of yellowish sand and concretions and were attributed to a cold climate period (Villeneuve, 1906), the Mousterian B unit debuts ~16 m asl up to ~17.5 m asl (Figure 2); the Mousterian A unit is exposed ~20 m asl and is around 1 m thick (Figure 2). The middle Mousterian unit (C) is usually considered deposited during a transitional period between the cold and the warm climate and doesn't outcrops in the described section (Villeneuve et al., 1906).

3. Paleomagnetic methods

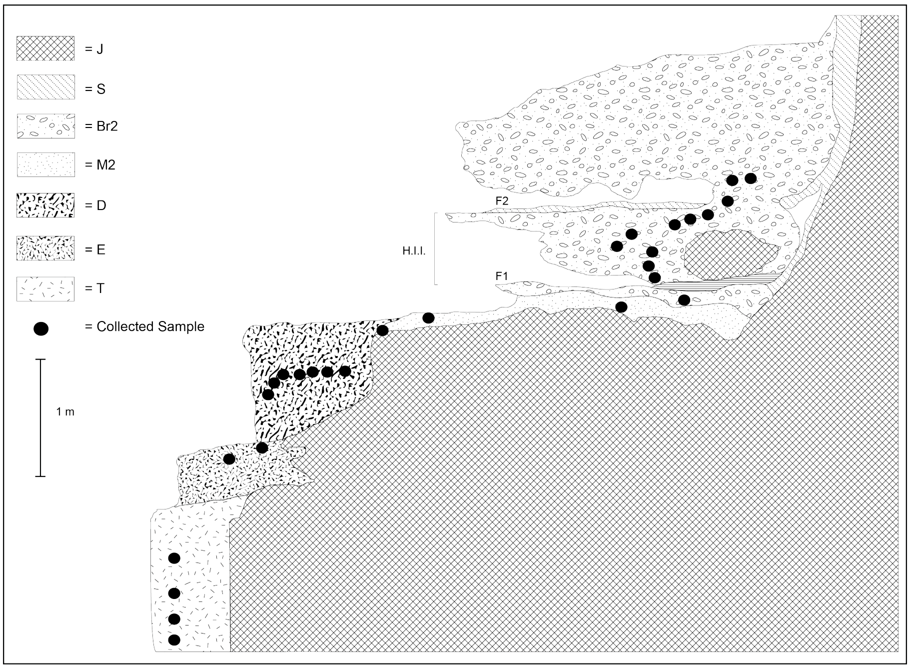

Figure 3 Stratigraphic position of the sampled cores (ater Simone, 2008, modified). J= Jurassic limestone; S=Stalagmitic floors and flows; Br2= Breccia level 2; M2= Marine level 2; D= Mousterian D unit; E= Mousterian E unit; T=Tyrrhenian unit; F1= fissure 1; F2= Fissure 2; H.I.I.= Human Ilium Interval

Since our interest for the Br2 unit, as it is considered the oldest one in the stratigraphic sequence, and also the unit bearing the *H. heidelbergensis* remain, and considered some local difficulties to reach the Br1 unit, during our preliminary sampling campaign we only sampled top to bottom the Br2, M2, Mousterian unit D, Mousterian unit E, and the Tyrrhenian unit. We took the height of the fissure f2 as a reference for the stratigraphic depth of the samples since it was very difficult to tell the limits between the single units on the field, thus the stratigraphic position of every sample was expressed as f2 + depth in cm for the samples collected above the fissure f2, and f2 – depth in cm for the samples collected below the fissure f2.

Paleomagnetic samples were cored using an electric drill and oriented with a magnetic compass to obtain a total of 29 cores from which 34 standard (10 cm^3) cylindrical specimens for Paleomagnetic analyses, 12 coming from the Br2 unit, 3 from the M2 unit, 8 from the Mousterian D unit, 2 from the Mousterian E unit and 4 from the Tyrrhenian unit (Figure 3). The initial magnetic susceptibility was measured on all samples at room temperature with a KLY 3 Agico Kappabridge. A set 5 samples, 3 coming from the Mousterian D unit, 1 from the Mousterian E unit, and 1 from the Mousterian unit, were used for magnetic mineralogy analyses first by means of isothermal remanent magnetization (IRM) backfield acquisition test, and then by the means of the Lowrie test getting imparted in fields of 2.5T, 0.4T, 0.12T (Lowrie, 1990). No samples coming from the Br2 and the M2 units were used for magnetic mineralogy analyses since these units were the more interesting ones for the magnetostratigraphic study, thus we chose not to risk to lose any polarity data available from those units. The other 29 samples were subjected to thermal demagnetization in steps of 50 or 25°C from room temperature up to the Curie point of the magnetic minerals therein using a ASC TD48 furnace. The natural remanent magnetization (NRM) was measured after each step with a 2G Enterprises DC-SQUID cryogenic magnetometer located in a shielded room. Standard leas square analysis was used to calculate magnetic component directions from vector to end-point demagnetization diagrams and standard Fisher statistical analysis was used to analyze the mean component direction. All the magnetic measurements were carried out in the Alpine Laboratory of Paleomagnetism – Roberto Lanza of Peveragno (CN), Northern Italy.

4. Paleomagnetic results

The magnetic susceptibility is characterized by values of ~$2*10^{-6}$ SI with two peaks of ~$30*10^{-6}$ SI, the first one just below the f2 fissure, and the second one in the contact point between the Mousterian D and E units, while a negative peak of ~ $-30*10^{-6}$ SI is yelded in the contact part between the Mousterian E units and the Tyrrhenian unit (Figure4B).

Samples coming from the Mousterian levels are characterized by IRM acquisition curves that reach saturation ~300 mT (Figure 5A, B); this behavior is interpreted as due to presence of low coercivity magnetite as proved also by the Lowrie test where the curves show unblocking temperatures between 575 and 600 °C (Figure 5A, B). The sample coming from the Thyrrenian unit is characterized by IRM acquisition curve that never reaches saturation (Figure 5C); this was interpreted as due to the presence of high coercivity hematite, as proven by the Lowrie test where the unblocking temperature exceeds 625 °C (Figure 5C).

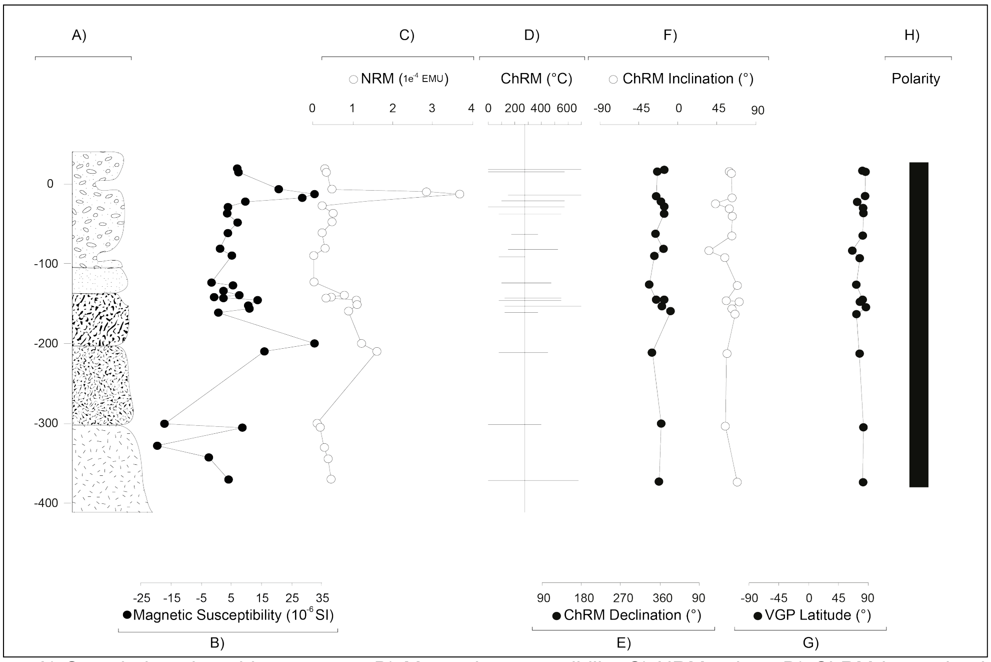

Figure 4 A) Sampled statigraphic sequence B) Magnetic susceptibility C) NRM values D) ChRM interval values E) ChRM declination F) ChRM inclination G) VGP Latitude H) Magnetic Polarity

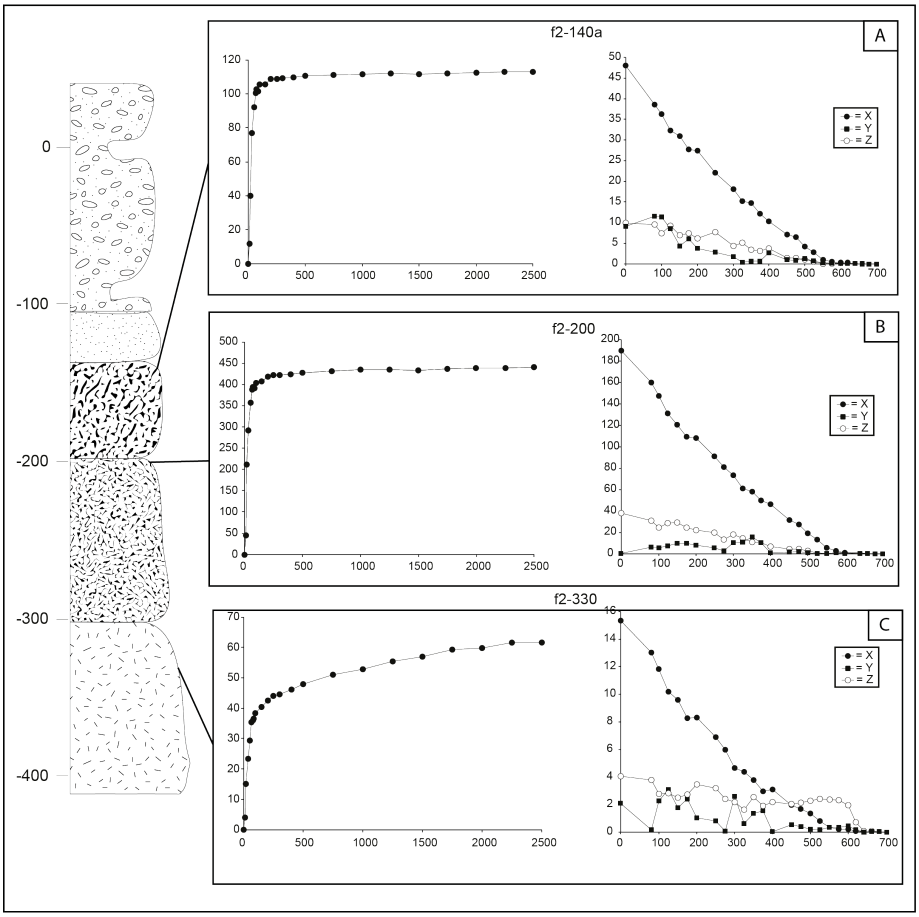

Figure 5 Magnetic mineralogy anaylises from three samples coming from three different units, A) Mousterian D unit B) Mousterian E unit C) Tyrrhenian unit. IRM on the left and Lowrie test on the right.

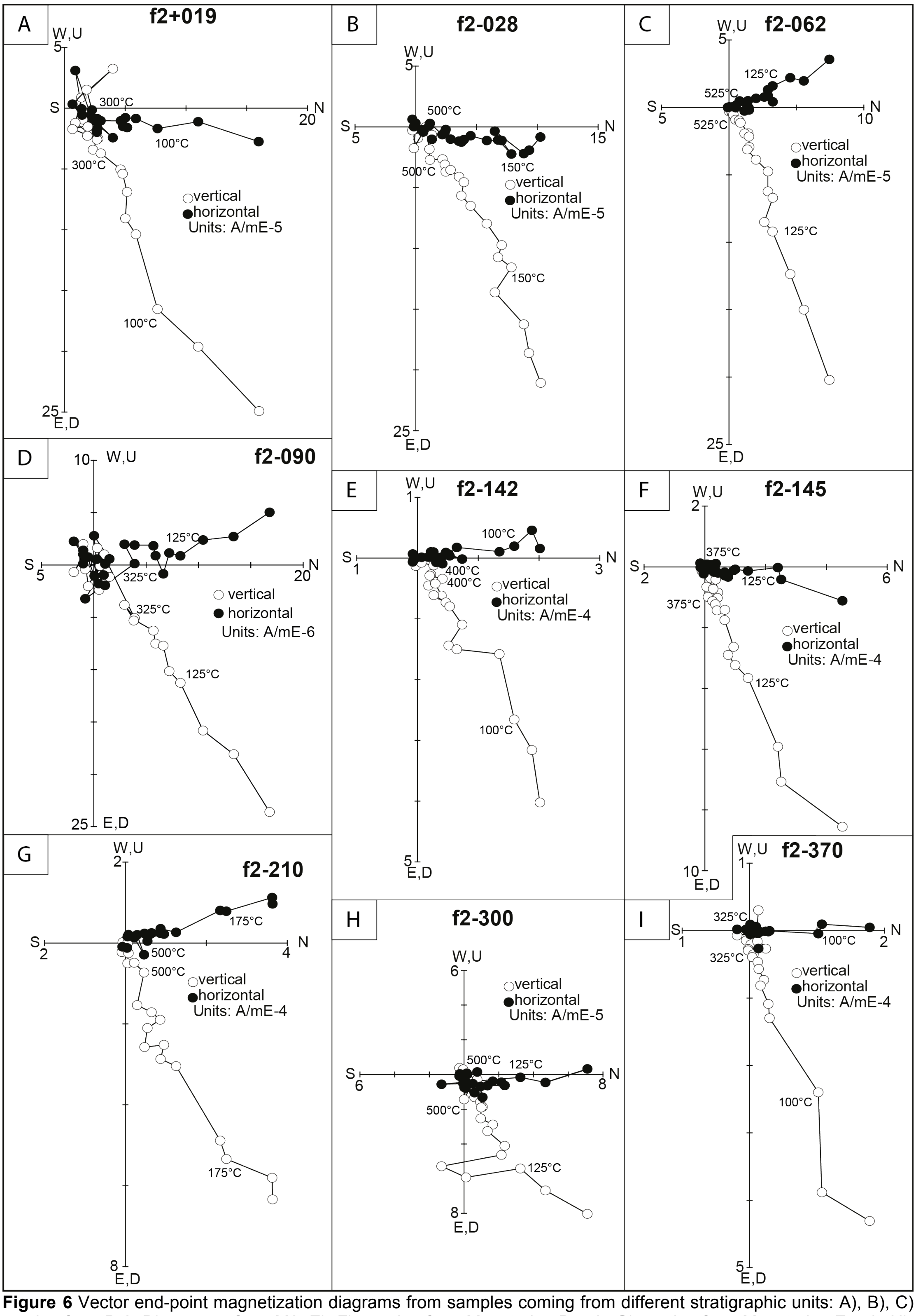

Figure 6 Vector end-point magnetization diagrams from samples coming from different stratigraphic units: A), B), C) coming from Br2; D) comung from M2; E), F), coming from Mousterian D unit; G) coming from Mousterian E unit; H), I) coming from Tyrrhenian unit

Vector end-point magnetization diagrams show the presence of characteristic remanent magnetization (ChRM) component directions oriented to the north and down (Figure 6A-I) that were isolated from ~100 °C up to ~500 °C in a total of 17 samples (Figure 4 D). These component direction with a mean angular deviation (MAD) that never exceeds 15° are grouped a mean of declination of = 359.9 °E, inclination = 59,0 °. The declination and inclination values of the ChRM component direction plotted versus stratigraphic depth were used to calculate the virtual geomagnetic pole (VGP) latitude. All VGP latitudes approached +90° (Figure 4 G) and thus were interpreted as normal polarity (Figure 4 H).

5. Discussion and conclusions

The normal polarity observed throughout the entire sampled sequence was interpreted as all pertinent to the Brunhes normal polarity chron (younger than 0.78 Ma) (Figure 7B) thus we can only just confirm the Middle Pleistocene age of this site as it was suggested by the Gamma Ray date obtained on the *H. heidelbergensis* bone recovered from and by the faunal association characterizing the Br2 unit (Yokoyama, 1989).

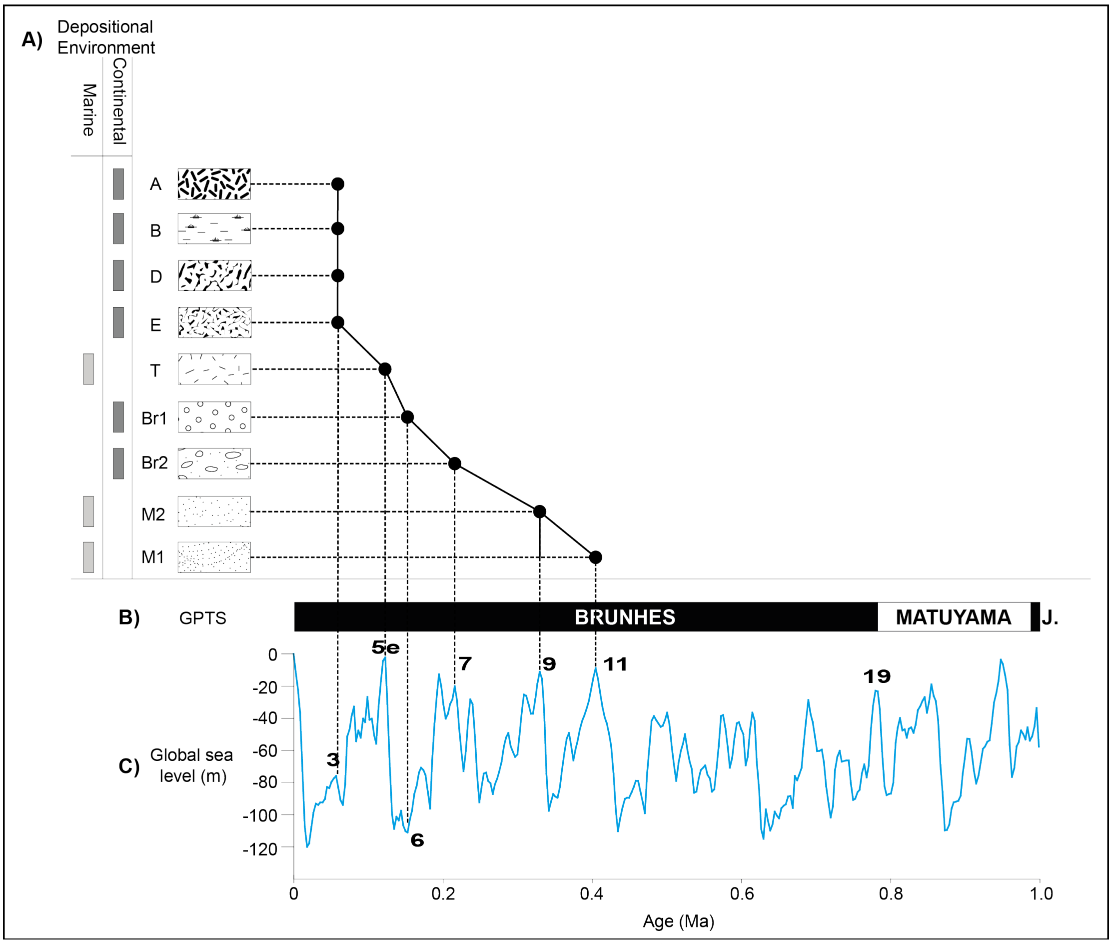

Figure 7 Age versus formation model of the stratigraphic sequence of the Prince's cave. A) Depositional environment B) Geomagnetic Polarity Time Scale C) Global sea level curve (Shackleton et al., 1995)

Considering the fact that the entire Alpine region is subjected to uplift since the beginning of the EPR (MIS 22) it is possible to shed light on the evolution of the Prince's cave and its deposits. We tried to estimate the uplift rate for the region starting from MIS 7 since we know that nowadays the opening of the Prince's cave is located 8.3 m asl and that the mean sea level at that time was ~10 m below the actual shore line, as seen from the global sea level curve of Shackleton et al. (1995) (Figure 7C). Supposing that the entrance of the Prince's cave was exactly at the same altitude of the shoreline during MIS 7, it would mean that the region would have raised 18.3 m during the last 243 ka implying a constant uplift rate of ~0.08 mm/yr. This value corresponds to a very low uplift rate if compared to the rates calculated for the Alpine (Barletta et al., 2006; Champagnac et al., 2007; 2009; Scardia et al., 2006; 2010; 2012) or the Appennine (Argnani et al., 2003; Schiattarella et al., 2016) chain that are on the order of ~0.16 mm/yr (Figure 8) (Champagnac et al., 2007). Since the minimal uplift rate required for the opening of the cave to be subaerial before MIS7 is the half of the actual uplift rate for the considered region we suggest that no continental units older than MIS 7 are present in the Prince's cave because it is very probable that the cave was submerged before that period, as suggested by the M1 and M2 Marine units, considered older than the Br2 unit (Figure 7A).

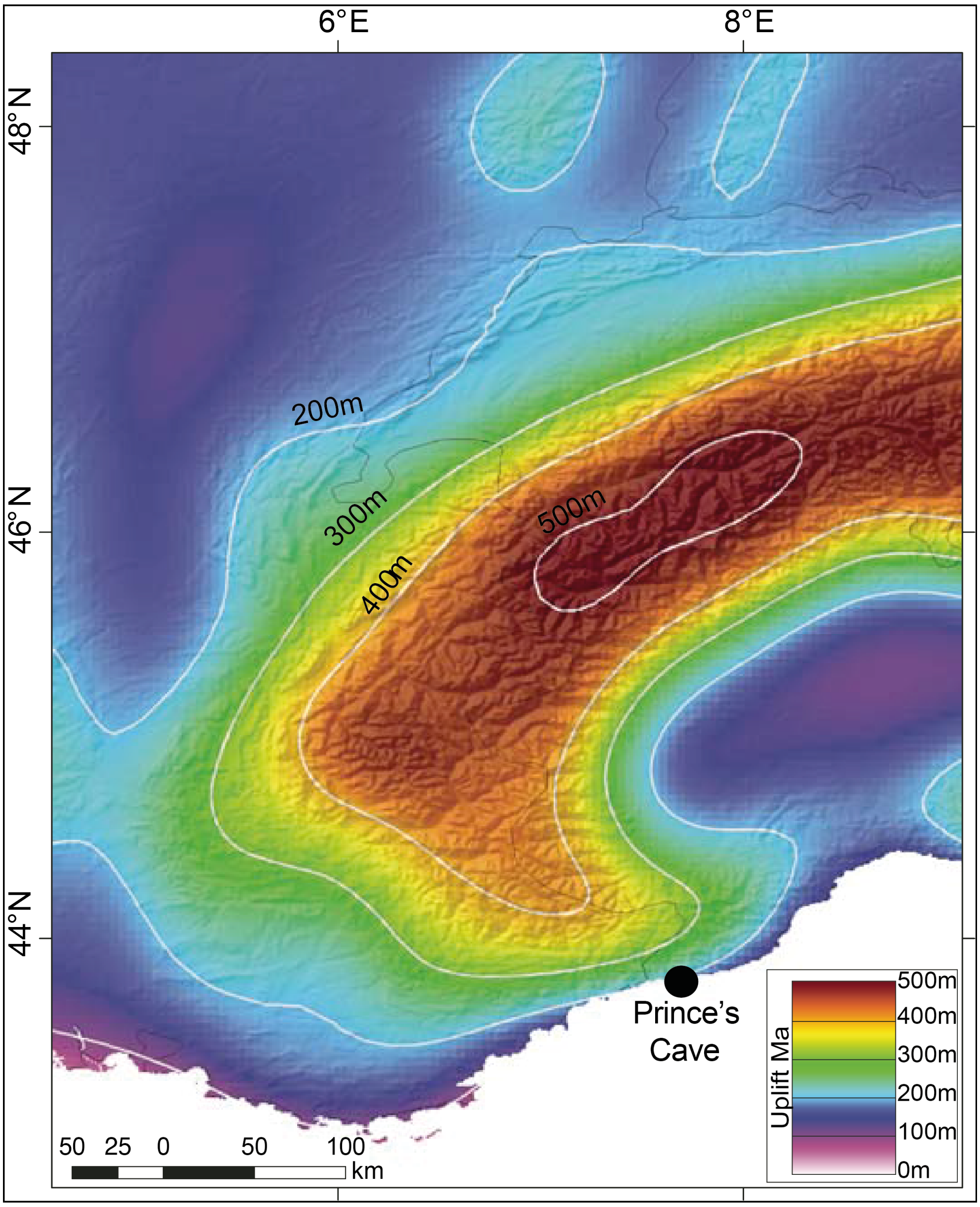

Figure 8 Map of isostatic rebound to erosion, calculated using a twodimensional elastic plate with point loads. (From Champagnac et al., 2007, modified)

This condition would make it impossible for early hominins transiting in northern Italy since MIS 22 to occupy this region. The evidence of human presence in the surrounding area in a time interval between MIS22 and MIS7 should be investigated on the Northern side of the Maritimes Alps since that region was suitable for the human transition starting from the beginning of the EPR. The results obtained from this study do not come anyhow in contrast with the "follow the heard" hypothesis since they only suggest a transitional path undertaken by the new come mammal faunas, and by the early modern hominins as a consequence, along a different route than the Ligurian coastline.

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8 - CONCLUSIONS

After a first discussion on the chronologies of the hominin sites known from the literature bearing a proper magnetostratigraphy we presented proper chronologies for the five investigated sites.

The Arda river site, even though it does not show evidence of a human occupation, yet provides a continuous series that includes the reverse polarity period that spans between the Brunhes chron and the Jaramillo subchron which represents the critic time interval suggested in these studies for the first stable peopling of the European continent (Figure 1). The presence of a mammal association showing a mixing between the Villafranchian and the earliest Galerian faunal assemblages (Figure 2 E) immediately preceding the EPR (Figure 1) suggests the possibility of the presence of levels (yet to be found) bearing human evidences in the stratigraphic meters just above the mammal layer.

The Serbian site of Kostolac, even thus not revealing any evidence of human occupation yet, strongly supports the “follow the herd” hypothesis since it yields the first occurrence of the *Mammuthus trogontherii* in the Pannonian region just before the Brunhes-Matuyama boundary (Figure 1). It’s presence in that precise moment suggests that the first income of this species in the investigated region occurred just after MIS 22 (Figure 2 B) supporting the idea that there is strong connection between these two events to the point that the income of the megafauna from the East (Figure 2 E), following the Danube drainage basin (Figure 3), is considered as a direct consequence of the EPR (Figure 2).

Among the presented sites, the Bulgarian site of Kozarnika offers the strongest evidence in support to the “follow the herd” hypothesis. It gives evidence of human occupation throughout the entire stratigraphic sequence as far down as the bottom of the loess deposit that is located exactly between the Jaramillo normal magnetic polarity subchron and the Brunhes normal polarity chron (Figure 1) (Figure 2 C). Even if there are still some discrepancies between the magnetostratigraphic and the biostratigraphic chronologies proposed for this site, our interpretation fits well with the “follow the herd” hypothesis thus strongly supporting the idea that the income of hominins in the investigated region started with MIS 22 along the Danube drainage system from the Black sea into Europe (Figure 3).

The Greek site of Megalopolis still does not show evidence of human occupation of the area during the critic time lapse for this study (Figure 1). However it is very clear the connection between the variation in the deposited facies and the glacial-interglacial cycles (Figure 2 D). The archeological site proves a continuous human occupation of the area during the middle Pleistocene and the presence of the *Elephas antiquus* with slaughtering evidences underlines the strong liaison that humans had with the megaherbivore species supporting the “follow the herd” hypothesis (Figure 2 E). The fact that the human phalanx recovered in the reworked material of the Marathousa formation does not have a specific collocation in the stratigraphic sequence does not exclude the possibility that it came from the bottom of the mine thus implying a possible pre-Brunhes age.

The Prince’s cave site, in the Balzi Rossi complex, near Ventimiglia, northern Italy, resulted to have developed in an unsuitable environment for early human occupation since it was probably submerged during MIS 22 time as suggested by the fact that the stratigraphic units present in the cave were deposited in marine environments dating back to no earlier than MIS 7. It was thus impossible for the *Homo heidelbergensis* populations that came into Northern Italy before MIS 7 (Figure 1) to have left trace of occupation in this area. This, however, does not preclude the possibility of human occupation of the northern side of the Ligurian Alps since MIS 22.

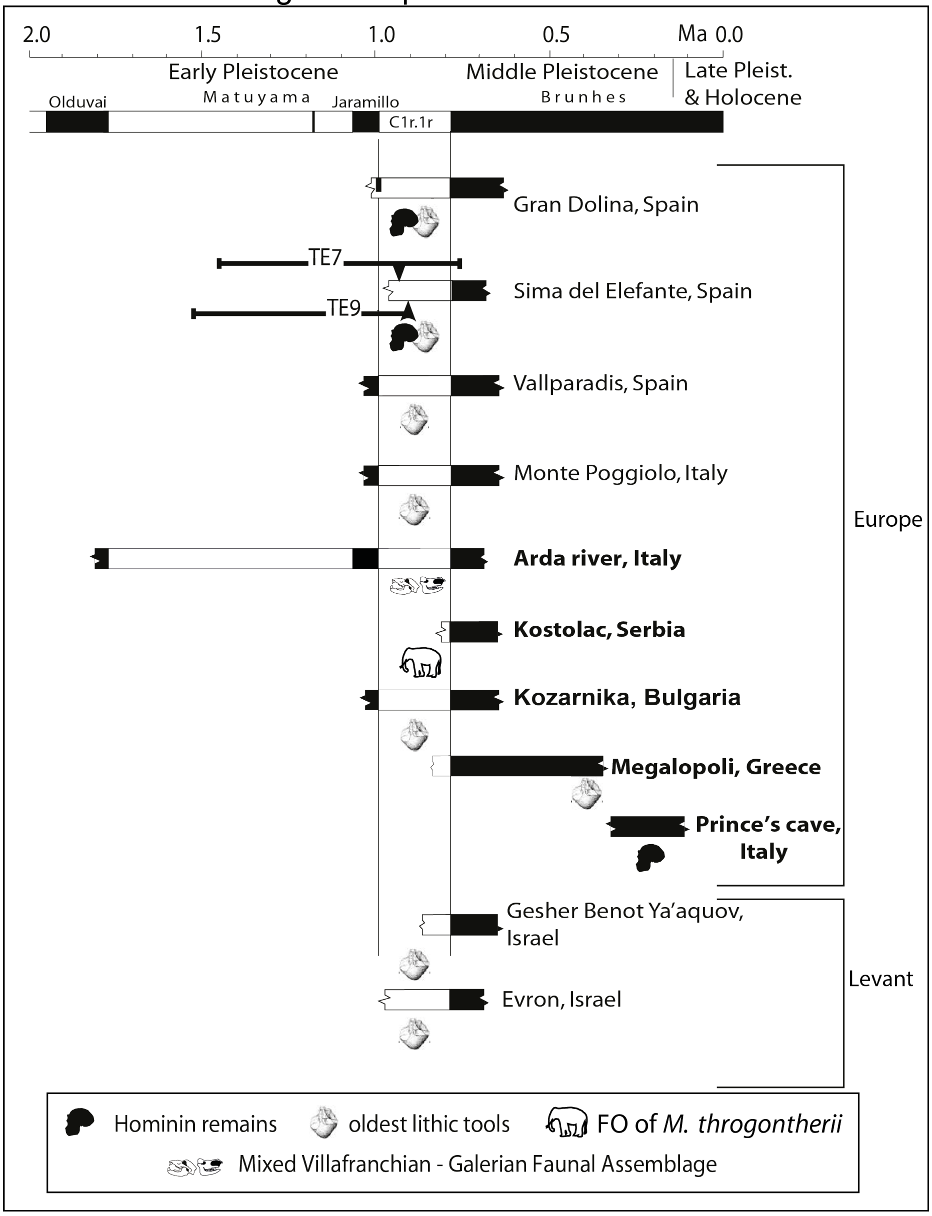

Figure 1 Evidence for the earliest human occupation of Europe and at the gates of Europe in the Levant with respect to the astrochronological geomagnetic polarity time scale (APTS) (Lourens et al., 2004). Oldest key hominin sites with reliable magnetostratigraphy tend to occur within the reverse polarity interval between the Jaramillo and the Brunhes (0.99 to 0.78 Ma). Europe: Gran Dolina (Pares and Perez-González, 1999; Pares et al., 2013), Sima del Elefante (Carbonell et al., 2008; with cosmogenic burial ages from levels TE7 and TE9 expressed at 2s level; Muttoni et al., 2013), Vallparadís (Martinez et al., 2010), Monte Poggiolo (Muttoni et al., 2011). Also shown are the different sites presented in this thesis: the Prince's cave in the Balzi Rossi complex, that yelded hominin remains but resulted being younger than the other presented sites; the Arda river in Italy, even though it does not show any human evidence it yields the first contact that occurred between the Villafranchian and the Galerian faunas at the beginning of the EPR; the site of Kostolac in Serbia that yielded remains of *M. trogontherii* (but no hominin remains) in pre-Brunhes levels (Muttoni et al., 2015); the Kozarnika site in Bulgaria that shows evidence of human frequentation since the beginning of the EPR; the Megalopolis site in northern Greece that shows evidence of human frequentation of the area in more recent periods than the EPR. Gates of Europe: Gesher Benot Ya'aqov (Goren-Inbar et al., 2000), Evron (Ron et al., 2003). (After Muttoni et al. 2014, modified)

We might say that the EPR-driven consequences (Figure 2) have been observed in all investigated sites except for the Prince's cave due to its too recent age. The onset of major Pleistocene glaciations (Figure 2 C) as a consequence of the variation from short period (40 ky) and low amplitude oscillation to long period (100 ky) and high amplitude oscillation in the glacio-eustatic regime (Figure 2 B) was evident in the cryoclatic elements recovered in the sediments coming from the Kozarnika cave. The starting of the deposition of thick loessic sequences during the glacial periods (Figure 2 C) after MIS 22 (~0.9 Ma) (Figure 2 A, B) was evident in the Serbian site of Kostolac and in the Bulgarian site of Kozarnika. The environmental change that brought new open space habitats characterized by low tree cover and abundant grassland vegetation during the interglacials (Figure 2 D) that triggered the income of new animals species both from Africa and Asia (Figure 2 E) was shown in the Arda river section with the mixed faunal association, in Kostolac with the finding of the first occurrence in Europe of the Asian species *Mammuthus trogontherii* (Figure 2 E), and in Megalopolis with the finding of the African species *Elephas antiquus* (Figure 2 E).

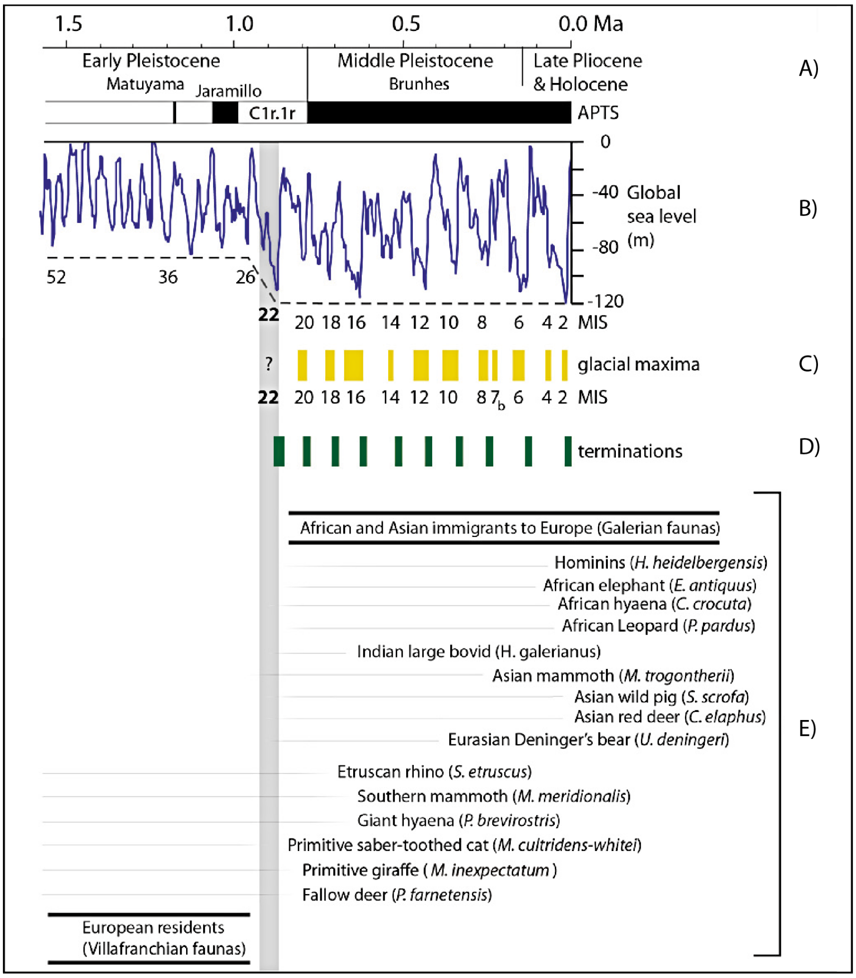

Figure 2 A) Astrochronological Polarity Time Scale (APTS) (Lorens et al., 2004) correlated to B) Pleistocene climate variability as revealed by benthic Oxygen isotope data (Shackleton, 1995) scaled to glacio-eustatic drop at the last glacial maximum time (Fairbanks, 1989); C) development of loess sequences with steppic vegetation associated with glacial maxima in Europe and the Black Sea area (Cremaschi, 1987; Sartori et al., 1999; Dodonov et al., 2006; Fitzsimmons et al., 2012; Ujvari et al., 2014; Jipa, 2014); D) main glacial /interglacial transition characterized by the occurrence of grassland-savanna environment (Leroy et al., 2011; Beaulieu de, et al., 2013) in the Danube-Po gateway; E) range chart of large mammals in Europe showing the most representative Galerian taxa that entered Europe from Africa and Asia during the EPR, that largely replaced the Villafranchian (European resident) taxa (Made Van de, 2011; Masini et al., 2007) (After Muttoni et al., 2014, modified)

This brings us to conclude that the data acquired in the investigated sites support the hypothesis stating that the colonization of Europe from early hominins have occurred starting from the MIS 22 through a migration path coming from the Levant (Figure 3).

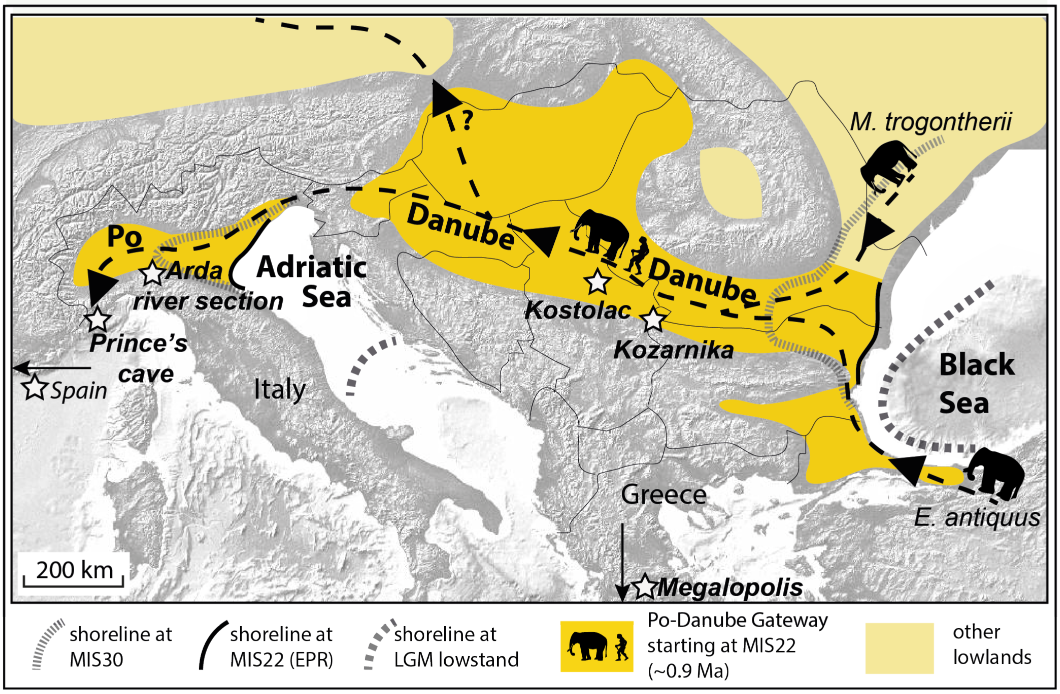

Figure 3 Paleogeographic scenario of the migrate-with-the-herd hypothesis of earliest expansion of hominins (and large mammals) from the Gates of Europe into Europe across the postulated Danube-Po Gateway during the EPR (dashed lines). Expansion occurred on stable lowlands developed as the Po and Danube deltas prograded over the Adriatic Sea and Black Sea, respectively, since MIS 22 (~0.9 Ma). Coastlines at pre-MIS 22 lowstands and at the last glacial maximum (LGM) are tentatively depicted illustrating the advancement of the Po and Danube deltas. (After Muttoni et al., 2014, modified)

The faunas modified their migration routes as a consequence of the formation in the Easter European regions of habitats to which they were already well adapted to, such as open space grasslands and savanna-like environments (Figure 3). This occurred for the first time as a consequence of the EPR (Figure 2) that brought the modification of the ecosystems in response to the onset of the first major Pleistocene glaciations that drove to the increase of the erosional rates and thus the modification of the previous fluvial regimes to the modern ones, mainly the Danube and the Po. The formation of the open space habitats created potential “highways” that worked as a connection between the european continent and the Levant, allowing the alloctonous mammal species to income for the first time in our regions with the hominins following their main protein sources along the newly created pathways (Figure 3) thus bringing to the first stable peopling of the European continent.

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10.CONFERENCE PAPERS

"Giornate della sostenibilità, Focus Ambiente" – Milano, 21/03/2014

Ecce *Homo* in Milan

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Quando e perchè?

Come ogni essere vivente anche l'uomo ha colonizzato gli habitat solo nel momento in cui questi presentavano le condizioni favorevoli alla sua sopravvivenza. La colonizzazione del continente europeo è avvenuta molto probabilmente da Est verso Ovest e l'ingresso in Italia
può essere avvenuto solo dal punto più comodo in cui si poteva superare la catena Alpina, ossia passando dai Balcani (Figura 2).

Dal record geologico si deduce il susseguirsi di periodi caldi a periodi freddi durante tutto il Pleistocene, tuttavia non ci sono evidenze di un passaggio ad un clima glaciale nel nostro paese prima del Pleistocene Superiore. Questo cambiamento ha come prima conseguenza l'espansione delle calotte glaciali legata all'intrappolamento dell'acqua degli oceani e il conseguente abbassamento del livello del mare che provoca il passaggio di molte zone precedentemente sommerse prima ad un ambiente litorale e infine emerso. Questo è quanto si è verificato in Pianura Padana.

Il cambiamento di ambiente ha provocato una variazione nel materiale che si stava depositando: prima si avevano limi e sabbie marine, poi ciottoli legati al trasporto fluviale e materiale fine legato alle esondazioni dei fiumi. La differenza nel materiale deposto è stata riconosciuta lungo tutta la Pianura Padana ed èstata nominata Discontinuità R.

La Discontinuità R è quindi legata a un cambiamento nel clima, e all'istaurarsi delle grandi glaciazioni nel continente europeo. Mediante lo studio di diverse carote prelevate in Pianura Padana è stato possibile creare un modello di età che ha permesso di associare la Discontinuità R al MIS22, datandola a circa 870.000 anni fa (Figura 1). Il MIS22 corrisponde inoltre alla fine della cosiddetta "Rivoluzione del Pleistocene Medio", un momento in cui si è assistito ad un cambiamento nella flora con la comparsa delle prime piante legate all'ambiente glaciale, ma anche ad un cambiamento nella fauna legato all'arrivo di specie come il mammuth (*Mammuthus meridionalis*), l'elefante antico (*Elephas antiquus*), e il rinoceronte lanoso (*Coelodonta antiquitatis*).

La nostra ipotesi è che l'arrivo dell'uomo in Europa e in Italia sia stato legato alla sua tendenza a seguire le onde migratorie degli animali che costituivano le sue principali prede (Figura 2), e che sia avvenuto in concomitanza con l'instaurarsi delle grandi glaciazioni Pleistocenica, ossia attorno all'età del MIS22 .

La magnetostratigrafia

Un metodo affidabile per la datazione di una sequenza sedimentaria è legato all'indagine magnetostratigrafica. Questo metodo è basato sulla duplice possibile configurazione del campo magnetico terrestre la quale può essere normale, ossia il polo Nord magnetico punta a Nord, oppure inversa, ossia il polo Nord magnetico punta a Sud. Quando del materiale si deposita i minerali magnetici tendono ad orientarsi secondo il campo magnetico presente in quel momento e questo segnale viene conservato nelle rocce. Le inversioni di polarità magnetica si sono verificate più volte nella storia del pianeta in maniera aperiodica ma sincrona in tutto il globo, conseguentemente il passaggio da un periodo a polarità normale ad uno a polarità inversa o viceversa è databile allo stesso istante geologico ovunque nel mondo.L'ultima inversione ha definito il passaggio dal periodo a polarità inversa Matuyama al periodo a polarità normale Brunhes ed è avvenuta 780.000 anni fa. Una volta riconosciuto nella successione sedimentaria il limite Brunhes-Matuyama è possibile determinare anche l'età dei reperti ritrovati nella sequenza.

Figura 1. Modello di età creato a partire dalla carota di Pianengo che mette in relazione la Discontinuità R con la scala dei tempi geologici, con la scala delle inversioni di polarità magnetica e il MIS22.

Figura 2. Possibili rotte migratorie intraprese dai grandi mammiferi e dagli ominidi che hanno portato all'occupazione del continente europeo

Figura 3. Cronologia dei siti a ominidi trattati messi in relazione con la scala delle inversioni di polarità magnetica

I siti a ominidi in Italia

Di seguito vengono brevemente descritti i principali siti a ominidi del nostro paese (Figura 3).

-Un cranio umano trovato nella località di Ceprano (FR) fu inizialmente considerato come uno degli ominidi più antichi d'Europa e venne datato come coevo al limite Brunhes-Matuyama, tuttavia una datazione basata sul metodo K-Ar attribuiva al reperto un'età di circa 450.000 anni. La magnetostratigrafia ha rivelato che il limite Brunhes-Matuyama era collocato circa 45 metri al di sotto del livello dalla quale proveniva il cranio in questione, andando a confermare l'età radiometrica del reperto.
-Dal sito di Monte Poggiolo (FC) provengono strumenti litici la cui datazione iniziale basata sul metodo RSE era di circa un milione di anni fa. L'elevato errore associato a questo tipo di analisi ha fatto sì che sia stata effettuata una successiva datazione magnetostratigrafica che ha evidenziato come il livello di provenienza degli strumenti si fosse deposto in un periodo a polarità inversa, ma in prossimità del passaggio ad un periodo a polarità normale. La datazione iniziale è stata quindi ringiovanita fino a 850.000 anni fa, subito dopo il MIS22.
-A Isernia sono stati trovati utensili nella località nota come La Pineta. Diverse datazioni sono state effettuate su questo sito utilizzando il metodo dell'K-Ar ottenendo un'età di circa 600.000 anni fa. Al momento non sono presenti datazioni magnetostratigrafiche attendibili, conseguentemente si accettano le datazioni radiometriche.
-Nella provincia di Potenza è presente il sito di Notarchirico da cui provengono diversi reperti sia litici che ossei di *Homo erectus*. I reperti litici sono stati datati sia attraverso il metodo della termoluminescenza che attraverso il metodo dell'Ar-Ar ed entrambi hanno dato un risultato di circa 650.000 anni fa. Un'ulteriore datazione condotta su un femore ha restituito un'età di circa 360.000 anni.
-Nel sito di Pirro Nord, in Puglia, all'interno di un inghiottitoio carsico sono stati trovati alcuni artefatti associati con delle faune di età stimata compresa fra 1.3 e 1.7 milioni di anni fa. Nessuna età radiometrica né analisi magnetostratigrafica è mai stata condotta sul sito. L'associazione faunistica di Pirro Nord tuttavia è comparabile con quella ritrovata in un altro sito in nord Italia a Leffe nella quale invece è stata condotta un'indagine magnetostratigrafica che ha datato la fauna a circa un milione di anni fa, una data quindi molto più giovane rispetto all'età attribuita al sito di pugliese, e prossima al MIS22.

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Abstract (Poster presentation)

Magnetostratigraphy of the Pleistocene Arda river section (Northern Italy).

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We investigated the magnetic properties of the Pleistocene sediments exposed in the Arda river section in southern Po plain, northern Italy. This site contains a complete record of the transition occurring in the greater Po basin between marine sedimentation typical of the Early Pleistocene and continental sedimentation typical of the Middle–Late Pleistocene. The study of the magnetic mineralogy shows a dominance of Magnetite as the main magnetic mineral in almost the whole sequence except for the top where it changes into Hematite and for two minor intervals at the base and the middle of the sequence where the signal is carried mainly by sulphides. Five magnetic polarity reversals were recognized and used to construct an age model of sedimentation for the whole sequence, which was found to span in substantial stratigraphic continuity between ~2.5 Ma in the Matuyama chron across the Olduvai subchron, the Jaramillo subchron to the Brunhes–Matuyama boundary at 0.78 Ma, the correct interpretation of these magnetostratigraphic data has been proven by biostratigraphic data collected at the same time as the paleomagnetic sampling. According to this age model, the age of continentalization occurred in this area between the top of the Jaramillo (0.99 Ma) and the Brunhes–Matuyama boundary (0.78 Ma) and during the late Early Pleistocene climate revolution (EPR). Using magneto-lithostratigraphic data from other sections from the literature outcropping nearby, we reconstructed the timing of continentalization of the greater Po basin area during the EPR. The comparison between data coming form different sections in the Po basin prove a slight diachrony in the marine-continental transtition occurring from the western to the eastern part of the plain due to the gradual infilling by continental sediments. This age for the continentalization of the northern italian area combines well with the age of the best-dated sites with evidence of the earliest peopling of Europe.

Magnetostratigraphy Of The Pleistocene Arda River Section (Northern Italy)

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Introduction

The Arda River section is located in northern Italy near the town of Castell'Arquato at the margin of the northern Appennines facing the Po plain. It starts at the bridge immediately to the East of the town of Castell'Arquato and extends northward along the banks of the Arda River for 300 stratigraphic meters exposing marine to continental deposits in which some faunistic remaing have been found.

Aside from a few paleoecological studies (Dominici, 2001; 2004), the Arda section has not been studied in detail, especially with regard to the chronostratigraphy. In this study, we generate an age model of sedimentation for the Arda section by integrating magnetostratigraphy with nannofossil data for comparison with other sections from the literature that document the marine-continental transition in the greater Po basin (Muttoni et al., 2003; 2011; Scardia et al., 2006; 2009; 2012; Gunderson et al., 2012; 2014; Pinti et al., 2001). This transition, which occurred during the late Early Pleistocene at the onset of enhanced glacial/interglacial activity, is thought to mark the time when Europe became stably populated by a renewed mammal fauna (Galerian) characterized by far-traveled immigrants, because, possibly for the first time in the Pleistocene, vast and exploitable new ecosystems were generated along a newly formed continental Po-Danube migration gateway, as recently described in Muttoni et al. (2014; 2015) (Figure 7).

Paleomagnetic data and interpretation

185 cylindrical 10 cm³ cores specimens were subjected to thermal demagnetization, magnetic properties (Fig 2) and the NRM was measured after each demagnetization step in a shielded room. Standard least-square analysis (Kirschvink, 1980) was used to calculate magnetic component directions from vector end-point demagnetization diagrams, and standard Fisher statistics was used to analyze the mean component directions

We interpret the magnetic polarity stratigraphy by means of correlation to the Pleistocene geomagnetic polarity time scale of Gradstein et al. (2012). Starting from the top, the uppermost normal polarity interval is interpreted as a partial record of the (early) Brunhes Chron with base set at 0.781 Ma, in agreement with previous studies from the Po Plain indicating continental sedimentation during the Brunhes Chron (e.g., Muttoni et al., 2003; Scardia et al., 2012). Proceeding downsection, the second normal polarity interval from about 240 m to 223 m is interpreted as the Jaramillo Subchron (0.99–1.07 Ma), the third normal polarity interval from about 113 m to 92 m has been interpreted as the Olduvai Chron (1.77–1.95 Ma), whereas the intervening reverse polarity intervals have been interpreted as the Matuyama Chron (Fig. 2I). A lowermost normal polarity interval recorded from 23 m to 12 m has been conservatively excluded from magnetostratigraphic interpretation because it straddles a stratigraphic interval with faults (Fig. 2A) associated with high susceptibility and NRM intensity values (Fig. 2C, D).

This magnetostratigraphic interpretation is augmented with nannofossil data from three samples collected in the uppermost transitional-marine level at 275 m (Fig. 2A). *Helicosphaera sellii*, small *Gerphyrocapsa* spp., and *Reticulofenestra asanoi* whose finding indicates sedimentation of the uppermost transitional-marine level at 275 m during a generic time interval comprised between 1.14 and 0.91 Ma (Raffi, 2002; Rio et al. 1990), in substantial agreement with the magnetostratigraphic interpretation.

Age Model

We created an age versus depth plot for the Arda River section by using magnetostratigraphy and correlation with the $\delta^{18}O$ record of Shackleton (1995), which is substantially consistent with the more recent record of Lisiecki and Raymo (2005) (Fig. 5). Five magnetochronologic tie points have been used: the Matuyama–Brunhes boundary, top and base Jaramillo, top and base Olduvai. The last occurrence of *R. asanoi* (0.91 Ma; Raffi, 2002) provides an upper age limit for the transitional-marine level at 275 m, which is considered to have deposited during the MIS 25 highstand (~0.95 Ma) (Fig. 5).

According to the above, the proposed age model implies that:

1) The long-term sediment accumulation rate between the base of the Olduvai and the base of the Jaramillo is of ~15 cm/ky (=150 m/Ma); this represents the average between faster turbidite and slower hemipelagic sedimentation typical of this part of the section. The base of the section should be older than 1.95 Ma (= base Olduvai) and younger than the top of the Gauss (2.58 Ma), which was not found in the studied section but recorded in the nearby and older Stirone section (Mary et al., 1993; Channell et al., 1994).

2) The FO of *Artica islandica* at 103 m within the Olduvai has an interpolated age of 1.85 Ma in agreement with a radiometric (He/Th) age of 1.81 ± 0.1 Ma on corals from a level immediately above the FO of A. islandica in the Santerno section (northern Apennines) as reported by Kukla et al. (1979) (Fig. 5).

3) The transition from marine to fully continental conditions, represented by the regressive sequence starting with littoral sands at 200 m and evolving into the first fluvial conglomerates at 237 m, may correspond to the MIS 30 regression and lowstand at ~1.04 Ma within the Jaramillo.

4) The mammal bed with remains of *Sus strozzii*, *Stephanorhinus hundsheimensis*, *Ursus rodei*, *Pseudodama* cf. *farnetensis*, *Bison* sp., *Hippopotamus* sp., and *Praemegaceros* sp. is approximately dated to the MISs 27–29 interval centered at ~0.99 Ma (Fig. 5).

5) The uppermost fluvial conglomerate at 275 m, immediately above the last transitional-marine ingression with R. asanoi attributed to MIS 25 (~0.95 Ma), presumably deposited during the profound glacioeustatic lowstand culminating with MIS 22 at ~0.9 Ma, which marks the first most prominent continental glaciation of the Pleistocene (Muttoni et al., 2003) (Fig. 5).

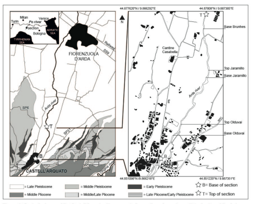

Figure 1: Geological map of the Castell'Arquato village area in the northern Apennines with indication of the Arda River section (left panel); detailed topographic map of the sampled section with location of the main magnetic polarity reversals (right panel).

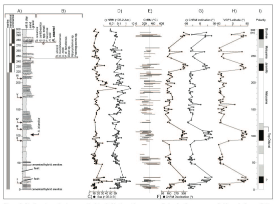

Figure 2: Stratigraphy and paleomagnetic data. A: Stratigraphic sequence; B: key fossil occurrences; C: Magnetic Susceptibility; D: NRM; E: Demagnetization temperature window of the characteristic magnetic component (ChRM); F: Declination of the ChRM; G: Inclination of the ChRM; H: Latitude of the Virtual Geomagnetic Pole of the ChRM; I: Magnetic Polarity (black is normal, white is reverse).

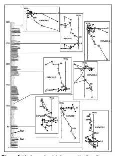

Figure 3: Vector end-point demagnetization diagrams of representative samples plotted aside the Arda stratigraphic sequence. Full symbols are projections on the horizontal plane and open symbols in the vertical plane. Demagnetization temperatures are expressed in °C.

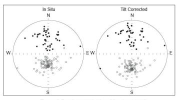

Figure 4: Equal area projection of the characteristic (ChRM) component vectors in in situ and tilt corrected coordinates. Full symbols represent down-pointing vectors (normal polarity), open symbols represent up-pointing vectors (reverse polarity).

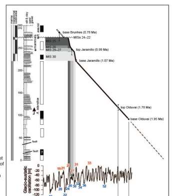

Figure 5: Age model of sedimentation of the Arda section correlated to the geomagnetic polarity time scale (GPTS) of Gradstein et al. (2012) placed aside the δ18O record of Shackleton (1995) scaled to the glacio-eustatic drop at the last glacial maximum time (Fairbanks, 1989).

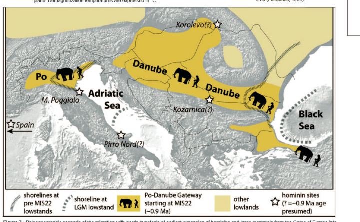

Figure 7 - Paleogeographic scenario of the migration-with-herds hypotesis of earliest expansion of hominins and large mammals from the Gates of Europe into Europe across the Danube-Po gateway during the EPR (Muttoni et al. 2014).

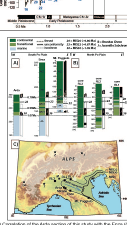

Figure 6: (A) Correlation of the Arda section of this study with the Enza (Gunderson et al., 2014) and Monte Poggiolo (Muttoni et al. (2011) sections from the northern Apennines margin (= south Po basin). IMO 1= Imola Sands 1; IMO 2= Imola sands 2; IMO 3= Imola sands 3; AEI= Lower Emilia Romagna Synthem. (B) Correlation of deep cores (RL1, RL2, and RL3) from the northern part of the Po basin (Scardia et al., 2006; 2012). (C) Paleogeography of the Po basin at the first major regression of the coastline in consequence of the MIS 22 lowstand during the late Early Pleistocene climate Revolution (EPR).

Conclusions

We used data from the Arda River section in conjunction with data from the nearby coeval Stirone (Gunderson et al., 2013; 2014) and Enza (Gunderson et al., 2012) rivers sections, as well as data from the Monte Poggiolo section (Muttoni et al., 2011), to reconstruct the timing of the marine-continental transition in this part of the greater Po basin (Fig. 6A). While the critical stratigraphic interval comprised between the Olduvai and the Jaramillo is substantially reduced in the Stirone river section (only 20 m thick) probably due to the syn-depositional growth of the Salsomaggiore thrust between 1.8 and 1.0 Ma (Gunderson et al., 2012; 2013), the correlations of the more complete Arda, Enza, and Monte Poggiolo sections allow to estimate that the marine-continental transition was in these sections slightly diachronic: while marine conditions persisted at Monte Poggiolo in the early part of the post-Jaramillo Matuyama, in the western part at Arda and Enza, littoral sediments started to deposit during MIS 30 in the Jaramillo (Fig. 6A). Persistent continental to transitional conditions were first established along the ~230 km-long studied transect between Arda and Monte Poggiolo only at the MIS 22 low-stand and the ensuing MIS 22/MIS 21 sea level rise and MIS 21 high stand at ~0.85 Ma (Fig. 6A).

A similar situation has been observed in several deep cores across the northern part of the Po basin (Scardia et al., 2006; 2012). While the western cores displayed continental sedimentation since the pre-Jaramillo Pleistocene (e.g., RL3 Fig. 6B), it is only since MISs 22–20 that continental sedimentation was established in the more eastern cores (e.g., RL2, RL1). It appears therefore that a first major jump eastward of the coastline was attained along the studied portion of the Po basin in consequence of the MIS 22 lowstand (Fig. 6C). MIS 22 represents the first major northern hemisphere continental glaciation of the Pleistocene (Shackleton et al., 1976; Berger et al., 1993; Shackleton, 1995; Head et al., 2005; Muttoni et al., 2003; Scardia et al., 2006; 2012) occurring during the so-called late Early Pleistocene climate Revolution (EPR), a term that substitutes for the often-used term Middle Pleistocene revolution (e.g., Berger et al., 1993) in deference to modern time-scales in which the base of the Middle Pleistocene is placed at the Brunhes–Matuyama boundary (Head et al., 2005). The EPR regression centered at MIS 22 had profound implication for the full opening of the Galerian migration pathway, as described hereafter.

The mammal association recovered at Arda in levels attributed to MIS 27–29 at ~0.99 Ma is characterized by mixed Villafranchian and Early Galerian taxa. The Villafranchian *Sus strozzi* is commonly regarded to have been present in the Italian peninsula up to the Early Pleistocene pre-Jaramillo (>1.07 Ma) Farneta faunal unit (Gliozzi et al., 1997; Masini et al., 2007), while our data indicates its presence up to ~0.99 Ma at the top of the Jaramillo. The occurrence of *Bison* sp. more evolved than previous *Eobison* and *Ursus rodei* represents the entrance in the Italian peninsula of new taxa. *U. rodei* may have immigrated from central Europe, where it was found at Untermassfeld (Germany) in levels attributed to MIS 31 at the base of the Jaramillo (Kahlke et al., 2011). It is however only when fully continental conditions were established in the Po basin during the EPR regression that the Galerian revolution could take place in its full extent with a total rejuvenation of the fauna. At that time we recorded the entrance in Europe of far-traveled guests: megaherbivores requiring large dietary grass supply such as the straight-tusked elephant (*Elephas antiquus*), the steppe mammoth (*Mammuthus trogontherii*), the red deer (*Cervus elaphus acoronatus*) are among the most representative species of the far-traveled Galerian elements that entered the Italian peninsula and Europe in general during the EPR since around 0.9 Ma (Muttoni et al., 2014; 2015 and references therein), and hence shortly after the Arda fauna with its mixed Villafranchian and Early Galerian elements.

Muttoni et al. (2014) speculated that large mammals, and possibly hominins with them, may have migrated to Europe starting at around 0.9 Ma because the EPR generated for the first time in the Pleistocene vast and exploitable ecosystems for African and Asian mammals especially along a conjunct Po-Danube Gateway connecting southern Europe with the Balkans (Figure 7). These new environments were characterized by stable continental lowlands with open grassland vegetation and reduced woody cover during the onset of glacial/interglacial transitions (starting with MIS 22/MIS 21). Our data from the Arda section confirms that the progressive infill of the Po basin driving the transition from marine to fully continental environments was established only during the EPR since MIS 22 in the same magnetochronologic window that is believed to include also some of the best-dated sites with evidence of the first entrance in Europe of far travelled megaherbivores and hominins (e.g., Muttoni et al., 2015). This is also the same magnetochronologic window of the earliest peopling of Europe (Muttoni et al., 2010; 2011; 2014), albeit we acknowledge that the debate concerning the age of the first stable peopling of Europe, whether before – and therefore detached from – the ecologic and climatic turnover of the EPR (e.g., Carbonell et al., 2008; Toro Moyano et al., 2013), or as its direct consequence (Muttoni et al., 2013; 2014; 2015) remains a matter of debate.

Bibliography

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Giornata Assereto. Dipartimento di Scienze della Terra Ardito Desio, Università degli Studi di Milano – 11/02/2014

Abstract (Oral presentation)

Magnetostratigrafia della serie Pleistocenica di Castell'Arquato (PC)

Monesi, E.[1], Muttoni, G.[1], Scardia, G.[2], Felletti, F.[1]

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We investigated the magnetic properties of the Pleistocene sediments exposed in the Arda river section in southern Po plain, northern Italy. This site contains a complete record of the transition occurring in the greater Po basin between marine sedimentation typical of the Early Pleistocene and continental sedimentation typical of the Middle–Late Pleistocene. The study of the magnetic mineralogy shows a dominance of Magnetite as the main magnetic mineral in almost the whole sequence except for the top where it changes into Hematite and for two minor intervals at the base and the middle of the sequence where the signal is carried mainly by sulphides. Five magnetic polarity reversals were recognized and used to construct an age model of sedimentation for the whole sequence, which was found to span in substantial stratigraphic continuity between ~2.5 Ma in the Matuyama chron across the Olduvai subchron, the Jaramillo subchron to the Brunhes–Matuyama boundary at 0.78 Ma, the correct interpretation of these magnetostratigraphic data has been proven by biostratigraphic data collected at the same time as the paleomagnetic sampling. According to this age model, the age of continentalization occurred in this area between the top of the Jaramillo (0.99 Ma) and the Brunhes–Matuyama boundary (0.78 Ma) and during the late Early Pleistocene climate revolution (EPR). Using magneto-lithostratigraphic data from other sections from the literature outcropping nearby, we reconstructed the timing of continentalization of the greater Po basin area during the EPR. The comparison between data coming form different sections in the Po basin prove a slight diachrony in the marine-continental transtition occurring from the western to the eastern part of the plain due to the gradual infilling by continental sediments. This age for the continentalization of the northern italian area combines well with the age of the best-dated sites with evidence of the earliest peopling of Europe.

Parchi del Ducato: Il monitoraggio ambientale nelle aree protette dell'Emilia Occidentale. Parco del Taro, Collecchio (PR) – 27/02/2014

Abstract (Oral presentation)

Magnetostratigrafia, un metodo per datare le sequenze sedimentarie: il caso di studio del torrente Arda.

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[1]= Università degli Studi di Milano

A small introduction on the magnetostratigraphic theory was given in order to explain to the audience how does a magnetic polarity reversal works. The fieldwork procedures were then introduced as well as few basic notions on the data interpretation. The case study of the Pleistocene stratigraphic sequence of the Arda river section (Northern Italy) was then exposed. The magnetic proprieties of the sediments exposed in this series were investigated as they present a complete record of the marine to continental transition that occurred in the Po-Plain at the end of the Early Pleistocene. Five magnetic polarity reversals were recognized and used to construct an age model of sedimentation for the whole sequence, which was found to span in substantial stratigraphic continuity between ~2.5 Ma in the Matuyama chron across the Olduvai subchron, the Jaramillo subchron to the Brunhes–Matuyama boundary at 0.78 Ma, the correct interpretation of these magnetostratigraphic data has been proven by biostratigraphic data collected at the same time as the paleomagnetic sampling. The study of the magnetic mineralogy shows a dominance of Magnetite as the main magnetic mineral in almost the whole sequence except for the top where it changes into Hematite and for two minor intervals at the base and the middle of the sequence where the signal is carried mainly by sulphides.

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- **Monesi, E.**, Muttoni, G., XXXX. Magnetostratigraphic study of the Prince's Cave stratigraphic sequence (Balzi Rossi complex, Ventimiglia, Northern Italy). *Yet to be submitted.*