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Evolution of multilevel caves in the Sierra de Atapuerca (Burgos, Spain) and its relation to human occupation

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ABSTRACT

The evolution of the Torcas cave system (Sierra de Atapuerca) is analysed in order to shed light on the formation of the Atapuerca archaeological sites and human occupation in the area, critical for identifying the paths of the first human dispersal into Europe. The geomorphological analysis of the endokarst system and the regional base levels has revealed a multilevel cave system, with drainage directions from south to north, where old karst springs fed the Pico River. Using morphological and topographic evidence we have correlated the fluvial terraces situated at relative heights of +84–80 m and +78–70 m above the Arlanzón River (main course), with the first and second cave levels, respectively, both of Early Pleistocene age. The fluvial levels T4 (+60–67 m) and T5 (+50–54 m) are linked with the third level (Early–Middle Pleistocene), which contains fluvial deposits probably related to terrace T6 (+44–46 m). Progressive fluvial incision allowed humans to gain access to the cave system through several entrances from ~1.22 Myr until the end of the Middle Pleistocene, when these cave entrances became filled, forming the most interesting hominid-bearing deposits in Europe.

1. Introduction

The present study is focused on the speleogenetic analysis of the sub-horizontal multilevel cave system of the Sierra de Atapuerca, which was occupied by hominids from the Early Pleistocene, and its relation with the geomorphological evolution of the area (Arsuaga et al., 1993; Bermúdez de Castro et al., 1997; Carbonell et al., 2001, 2008; Bermúdez de Castro et al., 2011). The formation of horizontal cave levels is thought to be the result of the circulation of groundwater during a relatively long period of stability of the phreatic level (water table) (Ford and Ewers, 1978; Bögli, 1980; Palmer, 1987; White, 1988). A series of horizontal caves at different elevations generally provides evidence for episodic downcutting of local base levels (Ford and Williams, 1989; Gillieson, 1998; Bakalowicz, 2005; Audra et al., 2006). Palaeo-water tables can be identified by cave features indicating the transition from phreatic to vadose conditions. The vadose entrenchments are normally formed after the drop in base level, as a result of river downcutting and/or the uplift of the limestone massif. It is widely accepted that the height of the passages in multilevel systems can be used to study the long-term evolution of caves and to infer the evolution of the landscape in limestone areas (Ford et al., 1981; Palmer, 1987, 1991; Granger et al., 1997, 2001; Anthony and Granger, 2004; Despain and Stock, 2005; Stock et al., 2005, 2006; Audra et al., 2006; Mocochain et al., 2006; Strasser et al., 2009; Kafri and Yechieli, 2010; Westaway et al., 2010; Frumkin et al., 2011; Yang et al., 2011). Consequently, caves are good markers to link past hydrogeological conditions with landscape evolution, since their development is often closely tied to the position of the local base level.

In the Sierra de Atapuerca, previous works reported on the relationships between regional landforms and speleogenetic processes. Benito-Calvo and Pérez-González (2007) described karst corrosion processes associated with the development of Miocene and Pliocene planation surfaces. These surfaces are related to base levels in the endorheic Duero Cenozoic Basin, before its capture by the external drainage network and change to exorheic conditions. This study reveals that the main phases of cave development took place in the Pleistocene, with the establishment of the drainage network in the Duero River Basin. The development of the new exorheic drainage network involved new flow directions and produced significant changes in the landscape like the formation of the Arlanzón River valley (Pineda, 1997; Benito-Calvo and Pérez-González, 2007). This paper

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analyses the relationships between the multilevel horizontal caves of the Sierra de Atapuerca and the evolution of the Arlanzón River along its middle reach (Benito, 2004; Benito-Calvo et al., 2008; Ortega, 2009). It thus sheds light on the development of the landscape occupied by hominids during their migratory routes across the interior of the Iberian Peninsula in the Lower and Middle Pleistocene.

2. Regional setting and geomorphological evolution

The Sierra de Atapuerca is located in the northeast sector of the Cenozoic Duero Basin, north-central Iberian Peninsula, which connects in its eastern sector with the Ebro Basin through the Bureba Corridor (Fig. 1A). The northeastern sector of the Duero Basin is bounded by the Cantabrian Mountains and Iberian Chain to the north and south, respectively (Fig. 1). The Sierra de Atapuerca constitutes an inlier of Mesozoic formations within the Duero Cenozoic Basin. This ridge is controlled by a NNW–SSE trending and NE-verging overturned anticline faulted on its northern end (Pineda, 1997; Benito, 2004). In the south of the Sierra de Atapuerca, Late Cretaceous marine limestones and dolostones crop out, in which the analysed endokarst system has been developed (Martín et al., 1981; Ortega, 2009). The Upper Cretaceous carbonates are unconformably overlain by continental Cenozoic sediments deposited in the Duero Basin under endorheic conditions (Fig. 1B) and associated with the development of planation surfaces in the Sierra de Atapuerca (Benito-Calvo and Pérez-González, 2007). The Cenozoic deposits include syntectonic conglomerates and clays (Oligocene to Lower Miocene), and a post-orogenic Neogene sequence (Armenteros et al., 2002). In the study area, the latter comprises alluvial and lacustrine sediments, Lower Miocene (Orleanian) to the Upper Miocene (Vallesian) in age, in which three units separated by discontinuities can be distinguished (Benito-Calvo and Pérez-González, 2007). At the end of the Neogene (Upper Miocene to Pliocene), once the Duero Basin was opened to the Atlantic Ocean, a new exorheic fluvial network started to develop and dissect the basin fill. In the study area this drainage network is represented by the Arlanzón River and its main tributaries, the Vena and Pico rivers (Fig. 1B). The Quaternary evolution of these valleys is characterised by alternating incision and aggradation stages recorded by a sequence of 14 fluvial terraces and the current floodplain (Benito, 2004).

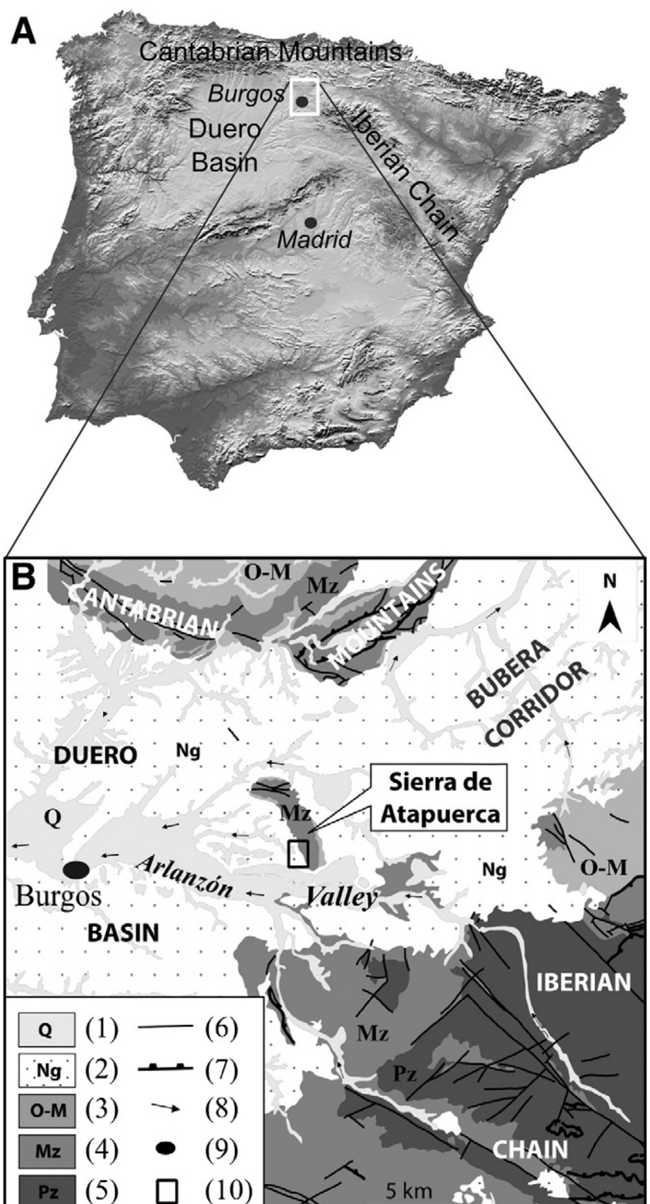

Fig. 1. A) General location of the study area in the Iberian Peninsula. B) Geological map of the NE sector of the Duero Basin. Legend: (1) Quaternary; (2) Neogene; (3) Oligocene–Lower Miocene; (4) Mesozoic; (5) Palaeozoic; (6) fault; (7) thrust; (8) drainage direction; (9) city; (10) study area (after Benito-Calvo et al., 2008).

The geomorphic evolution of the region is characterised by the development of planation surfaces related to erosion–sedimentation/uplift cycles during the Neogene, and by the predominance of fluvial incision of the valleys in Pleistocene and Holocene times (Benito, 2004; Benito-Calvo et al., 2008) (Fig. 2B). The oldest planation surface (SE1), situated at 1084–1060 m a.s.l. in the Sierra de Atapuerca, developed in Oligocene–Lower Miocene times, during the accumulation of synorogenic sediments in the basin (Zazo et al., 1983; Benito-Calvo and Pérez-González, 2007) (Fig. 2A, B). The second planation surface (SE2, 1065–1050 m a.s.l.) has been correlated with the alluvial deposits and the overlying limestone unit (Astaracian, Middle Miocene) that crop out in the NE sector of the Duero Basin. In the areas adjacent to the Sierra de Atapuerca these sedimentary units are tilted 2–7° (Figs. 2A and 3) and unconformably overlain by Upper Miocene horizontal deposits (Fig. 2A), indicating tectonic uplift of Middle Miocene age. A third planation surface (SE3, 1030–1035 m a.s.l.) lies at an elevation similar to that of Upper Miocene deposits designated as the Upper Páramo units (Benito-Calvo and Pérez-González, 2007). In nearby mountains, a fourth planation surface (SE4) can be distinguished at 950–1000 and 1025 m a.s.l., correlatable with Plio-Pleistocene alluvial fan gravels (Fig. 2A, B). Within the basin, this planation surface is developed mainly on Middle Miocene limestones (Lower Páramo limestones, Benito-Calvo and Pérez-González, 2007).

During the Quaternary, the fluvial network dissected the Neogene surfaces and generated a stepped sequence of terraces (Benito, 2004; Benito-Calvo et al., 2008). In the Arlanzón Valley 14 terrace levels and the present floodplain have been mapped (Fig. 2A, B). This sequence has also been identified in other valleys of the region like the Arlanza Valley, which includes two older terrace levels located at +107–114 m and +121–130 m above the river channel. So far, dating conducted on terrace deposits (Benito-Calvo et al., 2008) allows ascribing T14 (+2–3 m) to the Holocene (4827 ± 338 TL yr BP) and T11 (+12–13 m) to the Middle–Upper Pleistocene transition (Fig. 2B), since the equivalent terrace in the Arlanza Valley has yielded a TL age of 115.052 ± 11.934 yr BP, whereas preliminary magnetostratigraphic data for the Arlanzón terraces reveal normal and reverse polarity for T5 (+50–54 m) and T4 (+60–67 m), respectively, suggesting that the Matuyama–Brunhes reversal could be located between both terraces (Benito-Calvo et al., 2008).

The evolution of the base levels in the area during the Neogene and Pleistocene has controlled the onset and development of the Torcas cave system in the Sierra de Atapuerca (Ortega, 2009). These caves levels were hydrologically abandoned during the Lower Pleistocene (Parés and Pérez-González, 1995; Pérez-González et al., 2001; Parés et

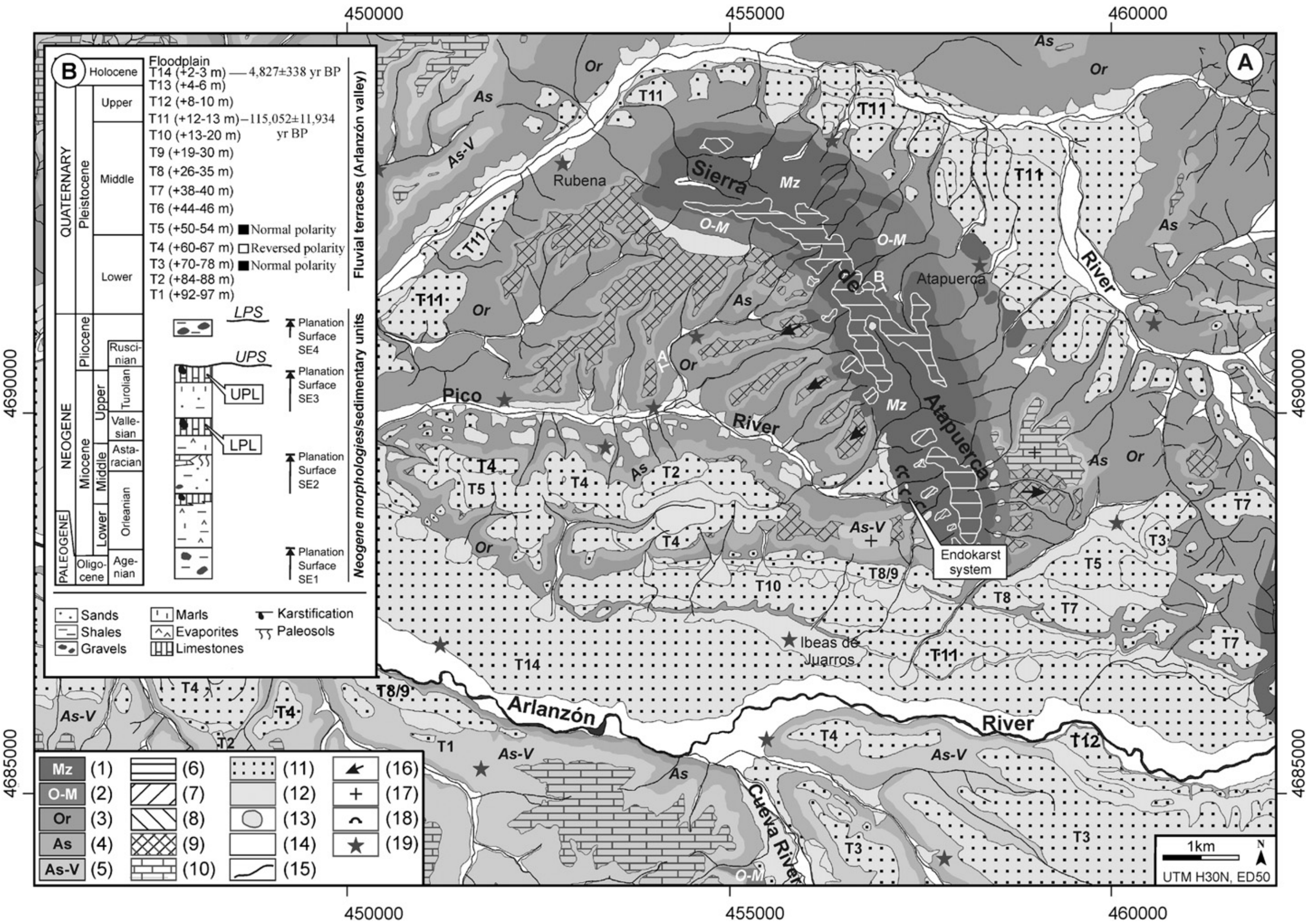

Fig. 2. A) Geomorphological map of the Sierra de Atapuerca and the middle reach of the Arlanzón Valley. Legend: (1) Mesozoic; (2) Oligocene–Lower Miocene; (3) Lower Miocene (Orleanian); (4) Middle Miocene (Astaracian); (5) Middle–Upper Miocene (Astaracian–Vallesian); (6) planation surface SE1; (7) planation surface SE2; (8) planation surface SE3; (9) top of sediments correlative to SE2 (Astaracian); (10) lower *Páramo* planation surface; (11) Quaternary fluvial terraces (T1–T14); (12) alluvial and colluvial sediments; (13) dolines; (14) modern floodplains and valley floors; (15) drainage network; (16) tilting; (17) horizontal sediments; (18) archaeo-palaeontological sites; (19) towns. B) Geomorphological evolution stages in the NE sector of the Duero Basin, UPL: Upper Páramo Limestones; LPL: Lower Páramo Limestones; LPS: Lower Páramo planation surface; UPS: Upper Páramo planation surface. Chronostratigraphy of Neogene sequences derived from mammal sites in the Duero Basin (derived from Calvo et al., 2008 and Armenteros et al., 2002).

al., 2006; Benito-Calvo et al., 2008). The latter process led to the accumulation of the allochthonous detrital deposits that host the outstanding archaeo-palaeontological sites of Atapuerca (Cuenca-Bescós and García, 2007; Carbonell et al., 2008).

3. Methodology

The present study is focused on the multilevel cave system in the Sierra de Atapuerca, within the Arlanzón River watershed. The investigation is based on previous detailed explorations and surveys of the caves (Martín et al., 1981; Martín, 2000) and data related to the spatial distribution of speleological, archaeological and geomorphic elements (Ortega et al., 2005; Ortega, 2009).

By georeferencing all the data to the same coordinate system, it was possible to prepare precise topographic maps and combine geological, geomorphic and speleological information using GIS and CAD packages (Benito, 2004; Ortega, 2009; Pérez-Martínez, 2011). These data, combined with the reconstruction of regional base levels (Benito-Calvo et al., 2008), provided a set of field observations and spatial data useful to determine the relationships between the cave levels and the evolution of the fluvial systems.

Field observations, such as the identification of resurgence or discharge sectors were used to establish the position of the palaeo base levels that controlled the development of horizontal passages (Palmer, 1991). The differentiation of sub-horizontal caves levels allowed inferring a sequence of cave formation phases at water table surfaces. Finally, a simplified model for the evolution of the Torcas multilevel system from the Plio-Pleistocene to the present-day is proposed.

An approximate age for the formation of the different cave levels is proposed using preliminary ages of surface landforms (Benito, 2004; Benito-Calvo and Pérez-González, 2007; Benito-Calvo et al., 2008), as well as the chrono-stratigraphic records of the Sierra de Atapuerca archaeo-anthropological sites (Dolina, Elefante, Galería and Sima de los Huesos; Parés and Pérez-González, 1995; Parés et al., 2000; Falguères et al., 2001; Bischoff et al., 2006; Parés et al., 2006; Berger et al., 2008; Carbonell et al., 2008). Additionally, the bio-stratigraphic data of the fossiliferous karst fills provided valuable chronological and palaeoenvironmental information (Carbonell et al., 1995; Arsuaga et al., 1997; Bermúdez de Castro et al., 1997; García and Arsuaga, 2001; Pérez-González et al., 2001; Cuenca-Bescós and García, 2007; Cuenca-Bescós et al., 2010, 2011; Rodríguez et al., 2011).

4. Description of the caves

The caves in the Sierra de Atapuerca have mainly developed in a 40–70 m thick sequence of Upper Cretaceous limestones and dolomites (Pineda, 1997). The Sierra de Atapuerca can be divided into

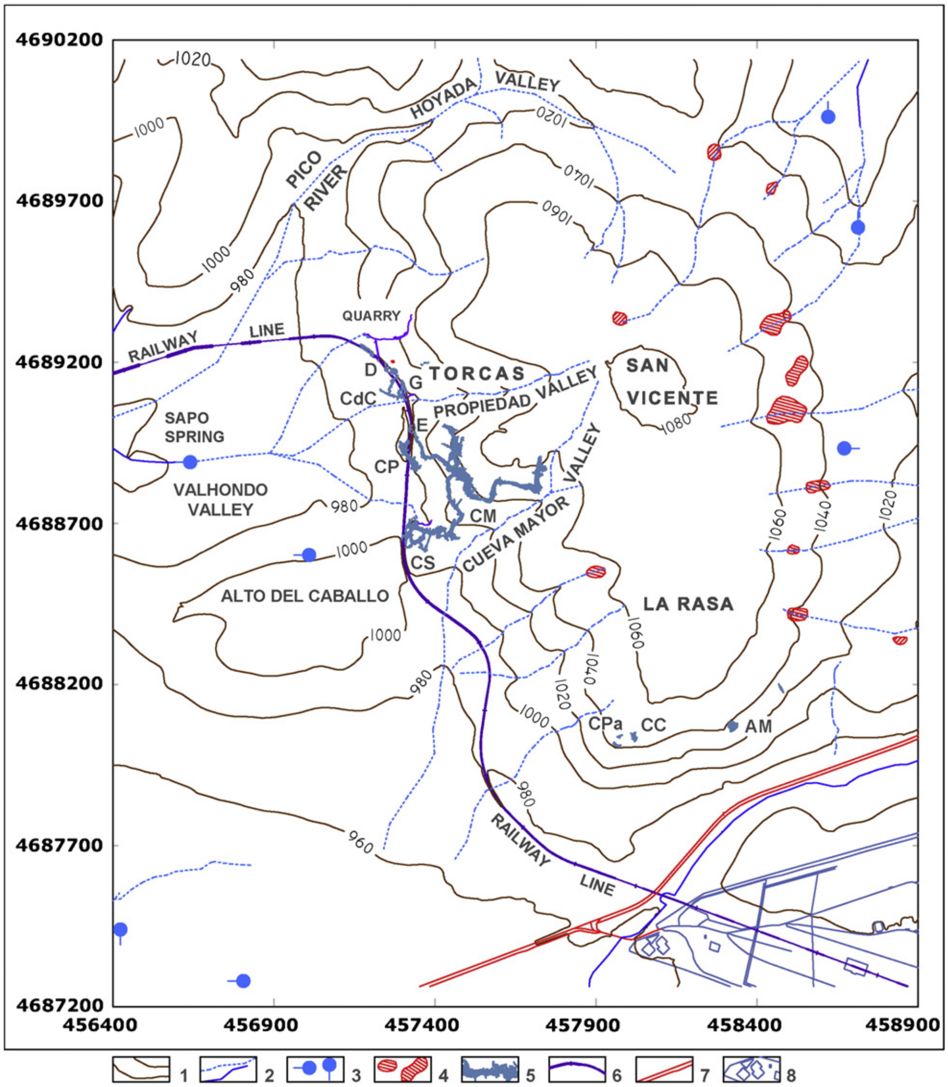

Fig. 3. Location of the caves in the Sierra de Atapuerca. Legend: (1) contour lines; (2) surface drainages; (3) springs; (4) dolines; (5) caves; (6) railway line; (7) road; (8) buildings; AM: Mirador Rock-Shelter; CC: Cueva Ciega; CdC: Cueva del Compresor; CM: Cueva Mayor; CS: Cueva del Silo; CP: Cueva Peluda; CPa: Cueva La Paredeja; D: Dolina site; E: Elefante site; G: Galería site.

two topographic units separated by the Hoyada Valley; Matagrande (1077 m a.s.l.) in the north, and San Vicente (1081 m a.s.l.) to the south. The known caves are located in the San Vicente unit, in contrast with the scarce development of surface karst landforms (Fig. 3). The endokarst morphologies consists of a sequence of subhorizontal inactive passages perched above the modern courses of the Arlanzón and Pico rivers.

4.1. Cueva Ciega–Cueva Paredeja

The caves are grouped in two sectors of the San Vicente ridge (Figs. 3 to 6). The southernmost caves are located just under the edge of a Middle Miocene planation surface (SE2, Benito-Calvo and Pérez-González, 2007). They consist of small caves (Cueva Ciega, Cueva Paredeja, and CR6, Fig. 5), which correspond to the same subhorizontal conduit. These caves, with an explored length of 110 m, are situated at 1055 m a.s.l, and +115 m above the modern course of the Arlanzón River. They represent the highest (and oldest) known cave level in the Sierra de Atapuerca.

4.2. Torcas multilevel system

The northwestern sector of San Vicente (Torcas area) is the main area of cave development in the Sierra de Atapuerca and one of the most significant in the Duero Depression (Martín et al., 1981). It hosts an inactive multilevel cave system with about 4.7 km of explored passages, 3.7 km of which belong to Cueva Mayor–Cueva del Silo, and about fifty cavities completely filled by sediments (Figs. 4, 9 and 10). The cave system is distributed in three main levels with an orientation parallel to the slope, and a fourth secondary level (Ortega, 2009; Ortega et al., 2011). The cave levels correspond to passages controlled by past phreatic levels during periods of base level stability (water table caves following Ford's, 1977, 2000 terminology). These cave levels are at altitudes of +88 m, +70 m and +58 m above the Arlanzón River, and are composed of sub-horizontal passages showing a zig–zag horizontal pattern due to structural control, which changes towards the NW into a linear pattern parallel to the axis of the anticline, guided by the bedding planes. Significant vadose incision can be observed in their terminal sectors connecting with the lower cave levels. The passages decrease in volume with depth and are progressively displaced towards the west, due to the downcutting and lateral migration of the Arlanzón and Pico valleys (Benito and Pérez-González, 2005).

The conduits begin on the northern side of Cueva Mayor Valley and head towards the north as far as the confluence of the Propiedad and Valhondo valleys (Fig. 4). In this area, the Propiedad Valley is a U-shaped gorge about 25 m deep, partially filled with alluvium. This

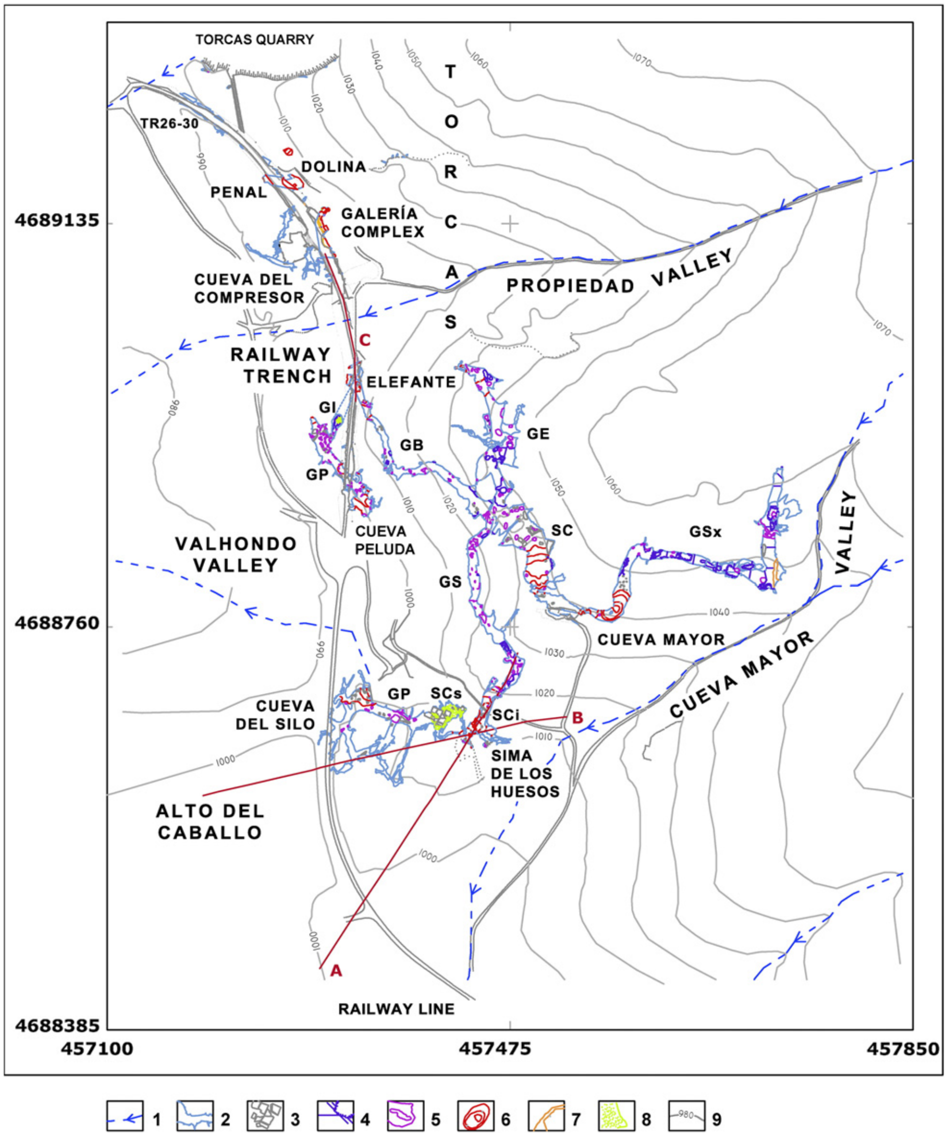

Fig. 4. Detailed map of the Torcas cave system in the Sierra de Atapuerca, located in the northwest sector of San Vicente Mount (see location in Fig. 3). Legend: (1) drainage network; (2) caves; (3) blocks; (4) eroded speleothem; (5) speleothem; (6) allochthonous facies; (7) autochthonous facies; (8) fluvial gravels; (9) marls; GSx: Galería del Sílex; SC: Salón del Coro; GE: Galería de las Estatuas; SCi: Sala de los Cíclopes, GS: Galería del Silo; GB: Galería Baja; SCs: Sala del Caos; GP: Galería Principal; GI: Galería Inferior. A, B and C: Geophysical profiles (see Fig. 8).
(Surveying by the Edelweiss Speleological Group).

drainage intersects the intermediate and lower levels of Atapuerca multilevel cave system restricting the original continuation of the passages (Martín et al., 1981) (Figs. 4, 6 and 12) and separating Cueva Mayor, Cueva del Silo and Cueva Peluda to the south, from Trinchera caves and Cueva del Compresor to the north.

The Torcas multilevel system includes the following levels:

- *Upper level*: *Sílex–Estatuas passage* (*Cueva Mayor*)
  The upper level of the system consists of a long sub-horizontal passage about 615 m long situated at +88 m above the Arlanzón River. Its average size is over 10 m in width and 15 m in height, although in places it reaches 25 m in height. This level consists of Galería del Sílex, El Portalón, Salón del Coro and Galería de las Estatuas (Fig. 4). The first section shows an irregular path (zig–zag pattern), clearly controlled by fractures with N–S and E–W directions (Galería del Sílex and Portalón), analogous to that of the Cueva Mayor Valley. Downstream, in the Hombrera de Cueva Mayor, the passage turns abruptly to a NNW orientation (Salón del Coro and Sala de las Estatuas) controlled by bedding planes. It follows a sinuous route towards the Propiedad Valley, the discharge zone, where the passage is blocked by a clastic fill derived from the surface (Ortega, 2009; Ortega et al., 2011).
  The cross-sections of this passage exhibit variable geometries, with phreatic geometries and arched roofs at 1015–1022 m in altitude, while some dissolution chimneys in the cave roof can reach altitudes of 1025–1030 m a.s.l. Vadose entrenchment in the terminal sector has produced vertical conduits and mixed keyhole sections, which drop until the intermediate level (Figs. 5 and 6). The Salón del Coro is the largest chamber in the system (about 30–40 m wide and 18–30 m high) comprising the three cave levels. Besides, this chamber was enlarged by collapse processes controlled by the bedding planes and fractures (Fig. 9A). The lowest point in this chamber is situated beneath a large collapsed block at 985 m a.s.l., which can be ascribed to the lower level in the system.
  This upper level is profusely decorated with speleothems (Figs. 6A and 9B). Throughout the whole passage, thick strongly eroded flowstones developed at an altitude of 1014–1010 m, mark the position of a former floor in this level. Magnetostratigraphic data from this

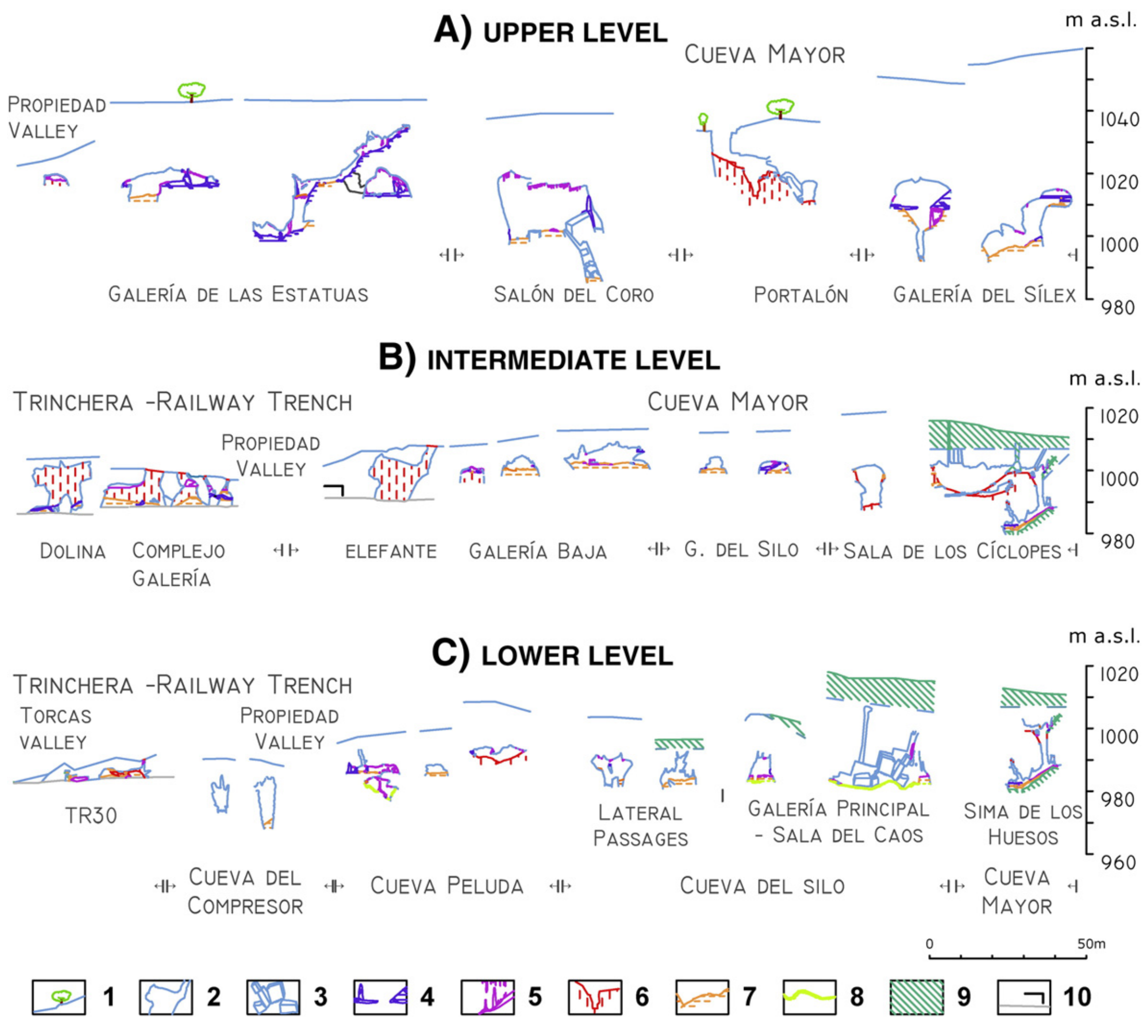

Fig. 5. Transverse sections of the multilevel karst system of the Sierra de Atapuerca. A) Upper level. B) Intermediate level. C) Lower level. Legend: (1) land surface; (2) caves; (3) blocks; (4) eroded speleothem; (5) speleothem; (6) allochthonous facies; (7) autochthonous facies; (8) fluvial gravels; (9) marls; (10) base of railway trench.

speleothem at the end of Galería de las Estatuas, as well as from the fine-grained sediment underlying the flowstone in Galería del Sílex indicate reverse polarity Parés et al. (unpublished data).

- *Intermediate level*: *Cíclopes–Elefante passage* (*Cueva Mayor*) *and Dolina Group–Galería Complex* (*Trinchera*)

  This intermediate level consists of Sala de los Cíclopes, Galería del Silo, Galería Baja and Elefante deposit in Cueva Mayor (Fig. 4), in addition to the lower passages in the Sílex–Estatuas described above. Dolina Group and Galería Complex, exposed in the abandoned railway trench, also belong to this level (Fig. 12). All together, this level forms a conduit at about 1000–1003 m in altitude; i.e. +68 m above the modern Arlanzón River (Figs. 4 to 6).

1. Cíclopes–Elefante passage (Cueva Mayor)

   This level in Cueva Mayor with a sinuous plan-view is about 500 m long, 2–4 m high and 6–12 m wide, noticeably smaller than the upper level. Vadose morphologies occur in the distal sectors of the level. Sala de los Cíclopes is a conduit with a wide “keyhole” cross-section, 60 m long, 11–20 m wide and up to 14 m high. The resurgence at Elefante also exhibits a wide mixed cross-section, with a visible height of about 16 m and widths of 11 m and 18 m in the base and the upper parts, respectively.

   The initial point of this level is in Sala de los Cíclopes. Geophysical surveys (Ortega et al., 2010) have revealed the existence of faults, which mark an abrupt contact between the Cretaceous carbonates and the Miocene marls (Fig. 8A, B). Along these fractures, rising flow chimneys developed, which reveal inputs of upward-flowing groundwater for this zone (Fig. 9E) (Audra et al., 2006; Klimchouk, 2009; Palmer, 2011). These chimneys reached the top of the highly fractured Cretaceous carbonates in contact with the Miocene sediments. This contact represents the limit of the karstification that causes favouring the development of major collapses, which allowed the entry of the overlying Miocene mudstones and the opening of new entrances to the cave system. The roofs of the chimneys are found at an elevation of 1003–1008 m, at the same altitude as the roof of the Sala de los Cíclopes. This conduit turns towards the NNW (Silo and Baja Passages), parallel to the hillside, until the confluence between the Propiedad and Valhondo valleys, in the sediment-filled Elefante site (Fig. 7A, B).

   The shallow depth of the intermediate level has facilitated the proliferation of speleothems, often eroded by karst reactivation. Such an erosion process is attested by the removal of sediment on which the speleothems formed and by the vadose entrenchment in the Cíclopes and Elefante sectors, which connects with the third level in the cave system (Fig. 6). Sala de los Cíclopes exhibits a major erosional phase, which left the sedimentary sequence perched in the phreatic part of the mixed cross-section (Figs. 7C and 9C). At its base, the sequence consists of a unit of silt and clay, on top of which allochthonous deposits are deposited, consisting of two accumulations of angular limestone clasts embedded in reddish clay, separated by a layer of silt (Bischoff et al., 1997). A palaeomagnetic study of the fine-grained sediments reveals reverse polarity in the sediments, indicating that they were deposited in the Matuyama Chron (Parés et al., 2010). The

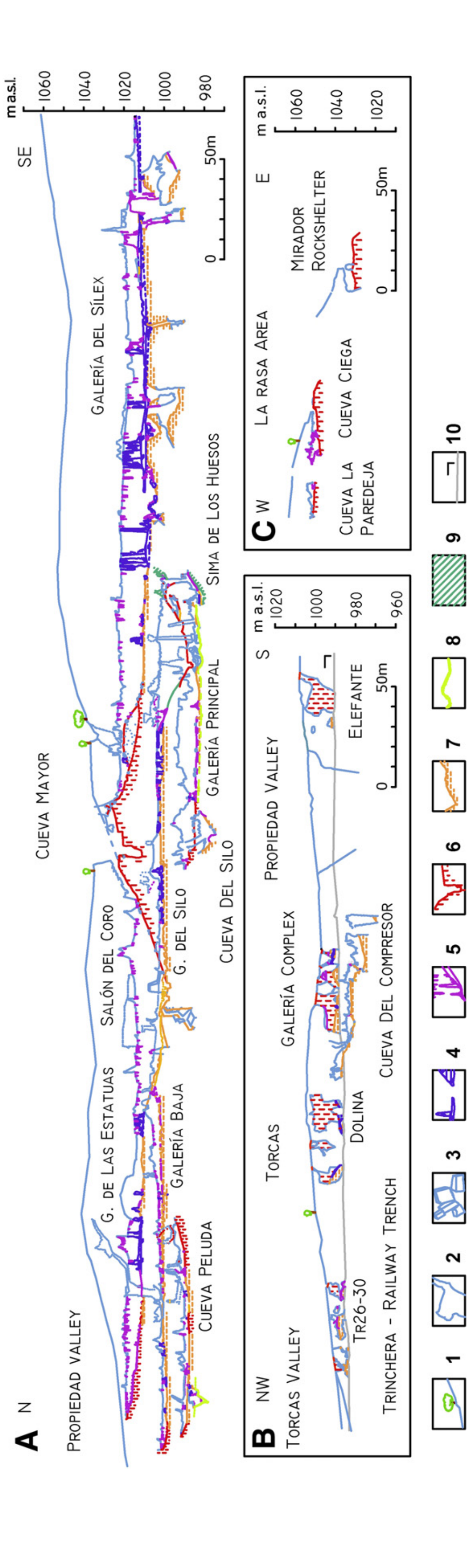

Fig. 6. Longitudinal profiles of the caves of the Sierra de Atapuerca. A) Cueva Mayor. B) Torcas and Propiedad Valley. C) La Rasa area (southern sector of San Vicente Mount) (see legend in Fig. 5).

location of the sediments, attached to the cave walls, suggests that the original conduit was nearly filled (Fig. 7C).

With the lowering of the water table, phreatic waters abandoned the conduit and alluvial and colluvial sediments entered from the immediate surroundings. The entrances also allowed hominids and animals to gain access to the system from about 1.22 Myr onwards (Pérez-González et al., 2001; Berger et al., 2008; Carbonell et al., 2008). The Elefante section exhibits a vadose-type shape with a phreatic roof at 1003.5 m a.s.l and an incision 10 m in width (Fig. 10B). The archaeological excavation has revealed a sequence about 16 m thick recording two sedimentary phases (Rosas et al., 2001, 2006). This sequence begins with stratigraphic Units TE7–14 (Phase I), characterised by gravitational accumulation of clay and clasts from the immediate surroundings and with clay and laminated sandy silts at the top of the sedimentary package (TE10–14). The presence of archaeological remains provides evidence of a Mode 1 lithic assemblage together with typical fauna of the Middle–Late Villafranchian or Epi-Villafranchian, which suggest a warm humid period in the Lower Pleistocene (Carbonell et al., 2008). Similarly, the micro-fauna record has been related to with the Waalian in northern Europe (Cuenca-Bescós and García, 2007). The oldest human fossils in these deposits come from layer TE9, dated at 1.22 ± 0.16 Myr by cosmogenic nuclides (Carbonell et al., 2008). Both the faunal record and the sedimentological characteristics indicate the presence of ponded water (Huguet, 2007). Phase II corresponds with a massive entry of sediments from the immediate surroundings. The lower units (TE15–17) correspond mainly to water-flow facies and water laid deposits, related with the sediments deposited in the nearby Propiedad Valley (Benito, 2004; Rosas et al., 2006). These stratigraphic units are lacking in archaeo-palaeontological remains. The change in magnetic polarity from reverse (Matuyama) to normal (Brunhes) has been documented between units TE16 and 17 (Parés et al., 2006). Unit TE18 consists of layers of stratified detrital sediment and erosional channels indicating the presence of significant water currents. Acheulian lithic pieces have been found in this unit. The top of the sequence (TE19) consists of detrital deposits and laminated silt, with a faunal and lithic record attesting to human occupation of the area in the central phases of the Middle Pleistocene (Rosas et al., 2006; Huguet, 2007).

Several erosional processes have been documented in the sediments of the intermediate level, both in Elefante, and passages of Baja and Silo, including evidence for re-sedimentation of fluvial deposits, such as sandy-silts, marls and mud balls, and isolated remains of fossils and Lower Palaeolithic stone tools, indicating that the Elefante sector temporarily acted as a input area for the underground karst system (Ortega et al., 2005; Ortega, 2009). Palaeomagnetic data (Parés et al., unpublished data) obtained from the sediments of the silos carved in prehistoric times in the Baja–Silo passage, reveal reverse polarity for the lower clays, and normal polarity for the upper layers of sandy–silty clays and the flowstone capping the sequence. This flowstone contains *Ursus deningeri* remains (Ortega, 2009), a typical Middle Pleistocene bear species. These data suggest a Chron Brunhes age for the top of the sedimentary sequence in this passage.

2. Dolina Group–Galería Complex (Trinchera)

The largest and most representative sections of Trinchera are found in the intermediate level, such as Dolina–Penal and Galería Complex (Figs. 4, 5, 10, 12 and 13) (Ortega et al., 2005). The Dolina–Penal group is in fact a single WNW conduit interrupted by the railway trench (Figs. 4, 10A, D, and 12). Its walls show signs of flow indicating palaeo-directions towards the west. In the Penal section, the inferred slightly ascending SE–NW palaeocurrent suggests it was one of the main resurgences for the karst (Eraso et al., 1998). The passage is now totally filled with sediments including, two sections to the north (TR20 and 21) (Ortega, 2009). The Dolina section (Fig. 10A) is characterised by a mixed morphology with a visible sedimentary fill about 16 m thick. The roof displays a phreatic geometry at about 1000–1001 m and solution domes at 1003 m a.s.l, while its section

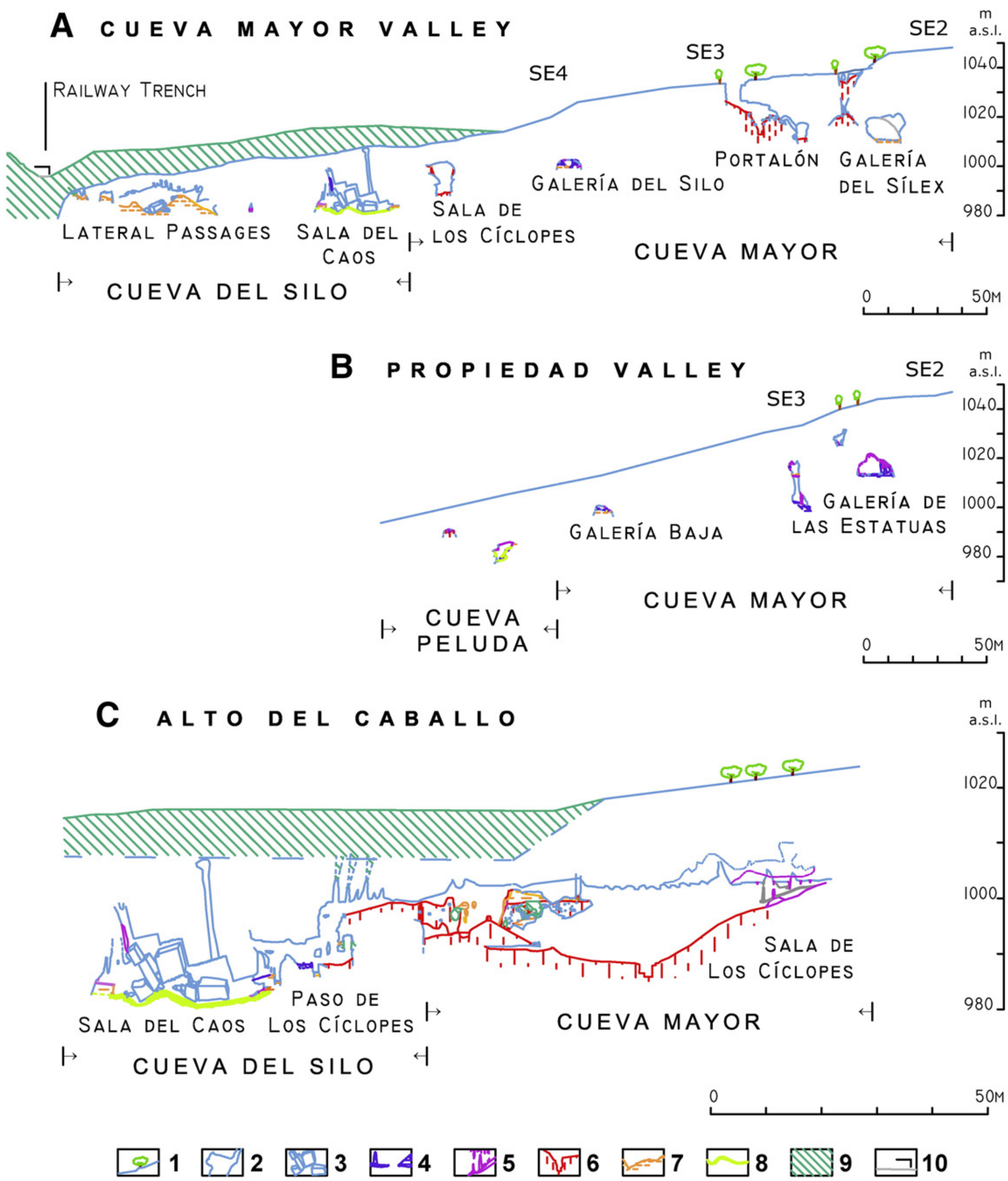

Fig. 7. Representative sections of the Cueva Mayor–Cueva del Silo and Cueva Peluda systems, along Cueva Mayor Valley (A) and Propiedad Valley (B). C) Detail of the connection area between the intermediate and lower passage levels in Cueva Mayor–Cueva del Silo System (Cíclopes sector) (see legend in Fig. 5).

cuts down from 995 m, associated with passages left at +68–70 m above the Arlanzón. The sedimentary sequence begins with the TD1–2 level, composed by autochthonous facies typical of a closed cave overlain by flowstone. From level TD3–4, the sequence is dominated by allochthonous facies, with evidence of human occupation, recording sedimentation from 900 ka until the end of the Middle Pleistocene in level TD11. A change in magnetic polarity was detected at the top of unit TD7 (Parés and Pérez-González, 1995), considered as the Matuyama–Brunhes Boundary at 780 ka. Further dating, including OSL and U-ESR, has supported this interpretation (Falguères et al., 2001; Berger et al., 2008).

Galería Complex is part of a series of filled sections exposed on the eastern wall of the railway trench. It corresponds to a large and elongated chamber which includes Zarpazos, Galería and Tres Simas, as well as section TR17 (Figs. 4 to 6, 10C–D and 12) (Ortega, 2009). They display phreatic morphology with semicircular roofs and domes just above 995 m a.s.l., at the same elevation as the entrenchment observed in the mixed cross-section of Dolina. The stratigraphic sequence begins with a thick basal package of fine-grained sediment forming unit TGI in the Galería section. This unit contains two major sub-units bounded by an erosional surface located in its upper third, which marks the Matuyama–Brunhes polarity reversal (Pérez-González et al., 1999). A second sedimentary unit (TGII–VI) records the entry of allochthonous deposits into the passage. Units TGII and TGIII are characterised by clastic deposits with clay matrix, as well as evidence of human and carnivore activity in the central phases of the Middle Pleistocene (Carbonell et al., 1999a; Falguères et al., 2001; Cuenca-Bescós and García, 2007; Berger et al., 2008).

- *Lower level*: *Sima de los Huesos* (*Cueva Mayor*), *Cueva del Silo*, *Cueva Peluda and Cueva del Compresor*

The conduits of the lower level are the smallest of the Atapuerca caves. They have phreatic morphology and show a westward displacement in

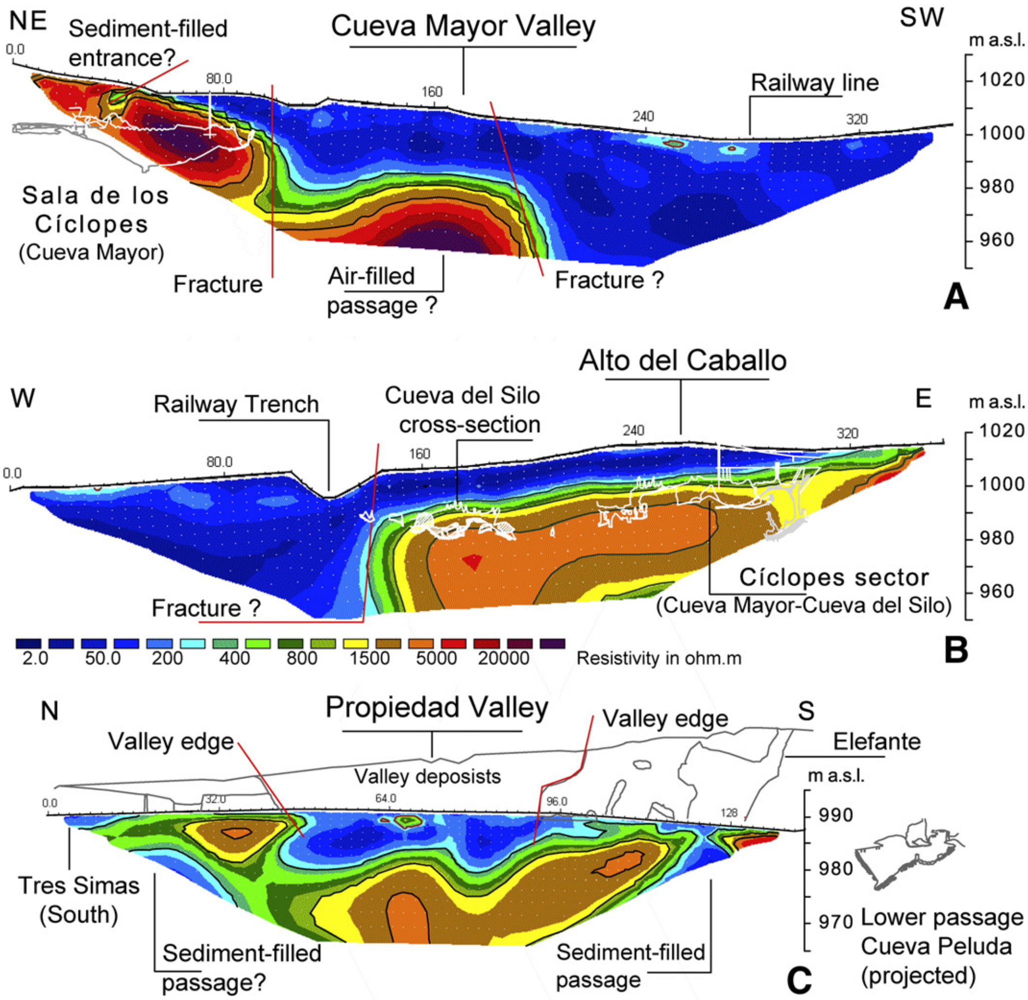

Fig. 8. Electrical resistivity tomography profiles acquired across the Cueva Mayor–Cueva del Silo systems (from Ortega et al., 2010). A–B) Profiles obtained across Cueva Mayor Valley. C) Profile obtained along the base of the railway trench and Propiedad Valley (for location of profiles see Fig. 4).

relation to the upper conduits. Cueva del Silo and Cueva del Compresor are characterised by maze networks, whereas Cueva Peluda is a linear passage (Figs. 4 and 12).

Cueva del Silo is a maze of sub-horizontal conduits at 51 to 58 m above the Arlanzón River, at 985–990 m a.s.l. (Figs. 4 to 6, and 12). It has a main axis (simple passage) with an ESE–WNW direction, to which a network of smaller conduits with SSW–NNE and SW–NE bearings converges. Sima de los Huesos is the eastern end of the main passage. Cueva Peluda, with a SSE–NNW direction, is the northern continuation of the main conduit (Ortega et al., 2010). This passage has developed at the edge of the Sierra west of the Cíclopes sector, in Mesozoic limestones and close to the contact with the Miocene shales. Thirty chimneys have been documented with signs of rising flows, indicating that these conduits were formed by ascending groundwater (Figs. 6, 7C, and 9E, D). Several of these ascending conduits are located in the modern entrance area and they represent the last known palaeo-resurgence of the karst according to Eraso et al. (1998). The main conduit continues towards the confluence area of Propiedad and Valhondo valleys.

The Sima de los Huesos in Cueva Mayor displays horizontal widening to about 15 m in the base, at about 983–984 m a.s.l., and several ascending chimneys. It is renowned for its important deposit with remains of *Homo heidelbergensis* (Arsuaga et al., 1993, 1997). The stratigraphic sequence exhibits three sedimentary episodes, interrupted by at least one erosional phase. From bottom to top it consists of re-sedimented shales, followed by sterile sand and clay with negative polarity, which are overlain discordantly by the fossiliferous breccia with clay matrix and positive polarity. This sequence was partially sealed by a flowstone layer (Bischoff et al., 1997; Parés et al., 2000; Bischoff et al., 2006).

Cueva del Silo is the continuation of Sala de los Cíclopes on a lower level, and is reached through Paso de los Cíclopes, Sala del Caos and the Main Gallery, which is the main and axial passage of the cave. A maze of small conduits guided by a system of joints converges on the Main Gallery (Fig. 4). Phreatic morphologies characterise sections of the cave, while the main gallery has suffered large roof collapses along planes of weaknesses. These have increased the size of the passage considerably, and the Sala del Caos is a good example of this (Fig. 7C). In contrast, the secondary passages exhibit vadose entrenchment in the areas of connection with the main axis, with some clear examples of mixed or keyhole cross-sections (e.g. Galería Frontal, Fig. 5) (Ortega et al., 2011).

Cueva del Silo has a thick fluvial fill consisting of gravels with clasts of metamorphic rocks in the main gallery, and sand and silt facies in the side passages (Ortega et al., 2005; Ortega, 2009). Magnetostratigraphic data indicate normal polarity for the sands and silts. These deposits evidence flooding events probably from the Arlanzón, at or near the local base level (Palmer, 2001; Despain and Stock, 2005).

Cueva Peluda is located to the north of Cueva del Silo. This cave is a rectilinear sub-horizontal conduit about 110 m long, following a SSE–NNW bearing towards the Propiedad Valley, at +56 m above the Arlanzón River (Figs. 4 to 6A). It contains a large number of pending tree roots and speleothems. In its final section it leads to a lower conduit which represents a sub-level with passage roofs at about 985 m a.s.l. This conduit is filled with fluvial sediments like those present in the main gallery in Cueva del Silo, located to the south, and further north in the lower passage of Elefante archaeological excavation (Rosas et al., 2006). All these fluvial sediments, with a visible thickness between 2 and 6 m, are at 981–985 m a.s.l., 49–53 m above the Arlanzón River, and record the entry of the Arlanzón River water in the cave system.

Geophysical studies (Electrical Resistivity Tomography) conducted in the Campa del Silo (Ortega, 2009; Ortega et al., 2010) have revealed the existence of filled conduits at approximately the same elevation as the Silo and Peluda caves. Similarly, in the base of the railway trench, near Elefante site, a lower conduit associated with the continuation of the lower sub-level in Cueva Peluda can be interpreted (Fig. 8C).

Cueva del Compresor, located near the Propiedad Valley, is a maze of small sub-horizontal conduits sloping towards the south-west. The conduits are characterised by phreatic morphologies with conspicuous vertical development including a large number of dissolution chimneys (Klimchouk, 2009; Ortega, 2009) (Figs. 5 and 9D), which reach the base of the Miocene deposits. It has a surveyed length of 475 m and is developed along two main bearings; WNW–ESE and NNE–SSW. Its conduits are at +45–51 m above

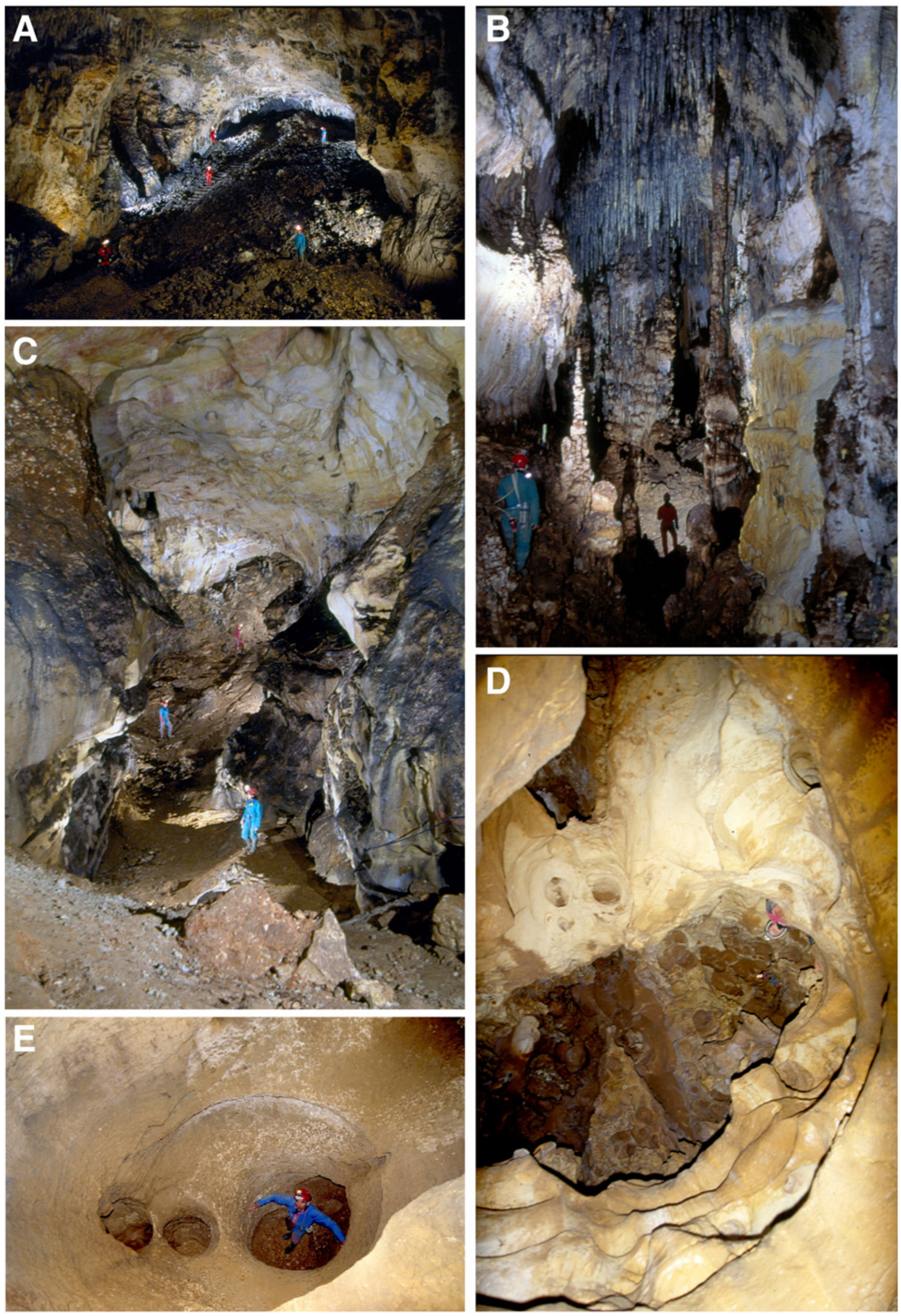

Fig. 9. Examples of morphologies and sediments of the Atapuerca caves. A) The Salón del Coro is the largest chamber, with significant breakdown deposits derived from the roof and walls. B) The Gallería del Sílex is characterised by high ceilings and abundant speleothems. C) The Sala de los Cíclopes (intermediate level) shows a typical keyhole section with significant erosion. D–E) The hypogenic chimneys are abundant in the lower level, with scallops indicating upward flow. D) Hypogenic chimney of the Cueva del Compresor. E) Hypogenic shaft at Paso de los Cíclopes connecting the intermediate and lower level.
(Photo courtesy of M. A. Martín, Edelweiss Speleological Group).

the modern Arlanzón River (Figs. 4 to 6C, 12 and 13). The northern conduit consists of a rectilinear NNE–SSW passage with roofs at 985–983 m a.s.l. and chimneys that reach 986–992 m a.s.l. The southern suite is characterised by a maze of passages forming an orthogonal grid with the presence of numerous shaft-chimneys and cupolas with signs of rising flows, and roofs at about 985 m a.s.l. (Fig. 10C). The base of these shaft-chimneys represents the lowermost point of the karst (at 969 m a.s.l.), which preserves wall marks of height of level water of modern flooding.

5. Discussion

The caves in Sierra de Atapuerca are arranged in a multilevel cave system located on the edge of the overturned western flank of anticline, on the San Vicente Hill. All the caves have developed in Upper Cretaceous limestones and dolomites next to the contact with Neogene sediments and record the episodic down-stepping of the passages and a displacement towards the west.

Structure-controlled maze-like conduit networks have developed in sectors located beneath the Neogene sediments, where the existence of chimneys generated by rising flows under confined conditions have been documented (Frumkin and Fischlendler, 2005). The San Vicente caves are composed of inactive sub-horizontal passages perched above the modern base level. The passages are grouped into three levels genetically associated with phase of water-table and base level stability.

The large size of subhorizontal conduits in the upper and intermediate levels may be related to allogenic recharge or relatively long sustained base level stability. The small area of the San Vicente cave system (2 km^2) and the absence of any large sinkhole or blind valleys suggest that allogenic or autogenic recharge cannot account for formation of the cave system. In addition, the palaeocurrents inferred from the scallops observed in the sub-horizontal passages in the three levels indicate a flow from the south toward the north. In the south, scallops and chimneys generated by rising flows have been documented associated with factures, especially in the lower and intermediate levels. These directions suggest inputs by rising groundwater in the south, near the Arlanzón Valley, which stabilised at the base level and flowed towards the north, giving rise to resurgences or springs at the head of the River Pico. Flow velocities estimated from scallops show the highest values in the input and output areas, whereas in the sub-horizontal passages they indicate slow flow velocities (Eraso et al., 1998). This information supports a hypogenetic input of water from a confined aquifer, controlled by the structure (Ortega et al., 2005; Ortega, 2009, Figs. 6A and 7C). The stability of the base level during landscape evolution would have favoured the formation of the multilevel cave system in Sierra de Atapuerca, where the position of the conduits may be linked with regional landforms.

There is some endokarst evidence associated with Miocene planation surfaces, particularly the altitudinal correlation between the Erosion Surface SE2, dated as Middle Miocene (Benito-Calvo and Pérez-González, 2007) and the small passage in Cueva Ciega–Cueva Paredeja, situated at 1050 m in elevation or +115 m above the Arlanzón River (Fig. 13). This conduit records to the oldest observed karstification phase developed before the incision of the Arlanzón River.

The Torcas multilevel system exhibits three interconnected sub-horizontal levels of passages (Figs. 11 to 14). The upper level (Sílex–Estatuas passage, Figs. 5, 6A, and 9A, B) is situated at 1015–1023 m a.s.l or +80–90 m above modern base level (Figs. 13 and 14). At this relative

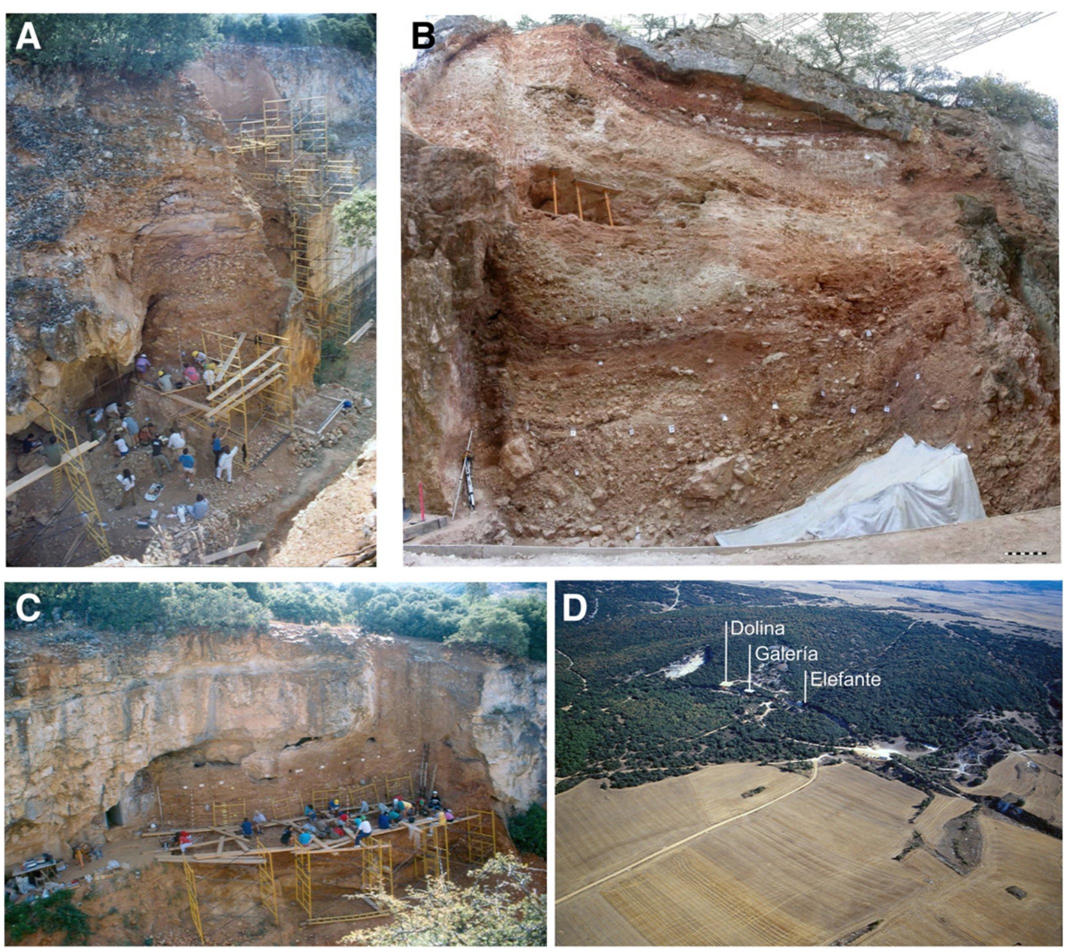

Fig. 10. Sediment-filled passages of the intermediate level exposed in the railway trench. A) Dolina site. B) Elefante site. C) Galería site. D) Aerial view of the railway trench. (Image courtesy of M.A. Martín, Edelweiss Speleological Group).

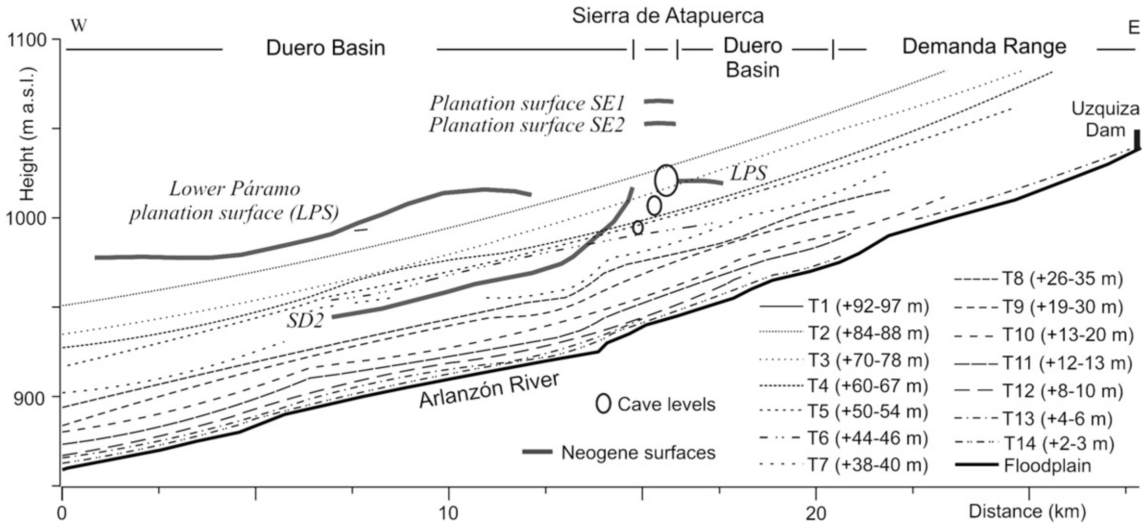

Fig. 11. Fluvial terrace profiles of the Arlanzón River and position of cave levels in the Sierra de Atapuerca. SE1: planation surface SE1; SE2: planation surface SE2; LPS: Lower Páramo planation surface; SD2: top of sediments correlative to SE2 (Astaracian).

height Benito (2004) has described several base-level indicators. The oldest corresponds to the Lower Páramo lithostratigraphic unit (Vallesian), which are lacustrine limestones located at 1020–1025 m a.s.l. A second base-level marker corresponds to planation surface SE4/SPPI (1025 m a.s.l.), whose development involved erosion of the above mentioned limestones under an exorheic regime in Pliocene–Pleistocene times. The third base-level marker is represented by the terrace T2 (+80–88 m) of the Arlanzón River with an Early Pleistocene age. Its projection perpendicular to the multilevel cave system lies at an elevation of 1020 m (Figs. 13 and 14, Benito-Calvo and Pérez-González, 2007; Benito-Calvo et al., 2008). This indicates relative stability of the water table over a long time span, favouring a significant enlargement

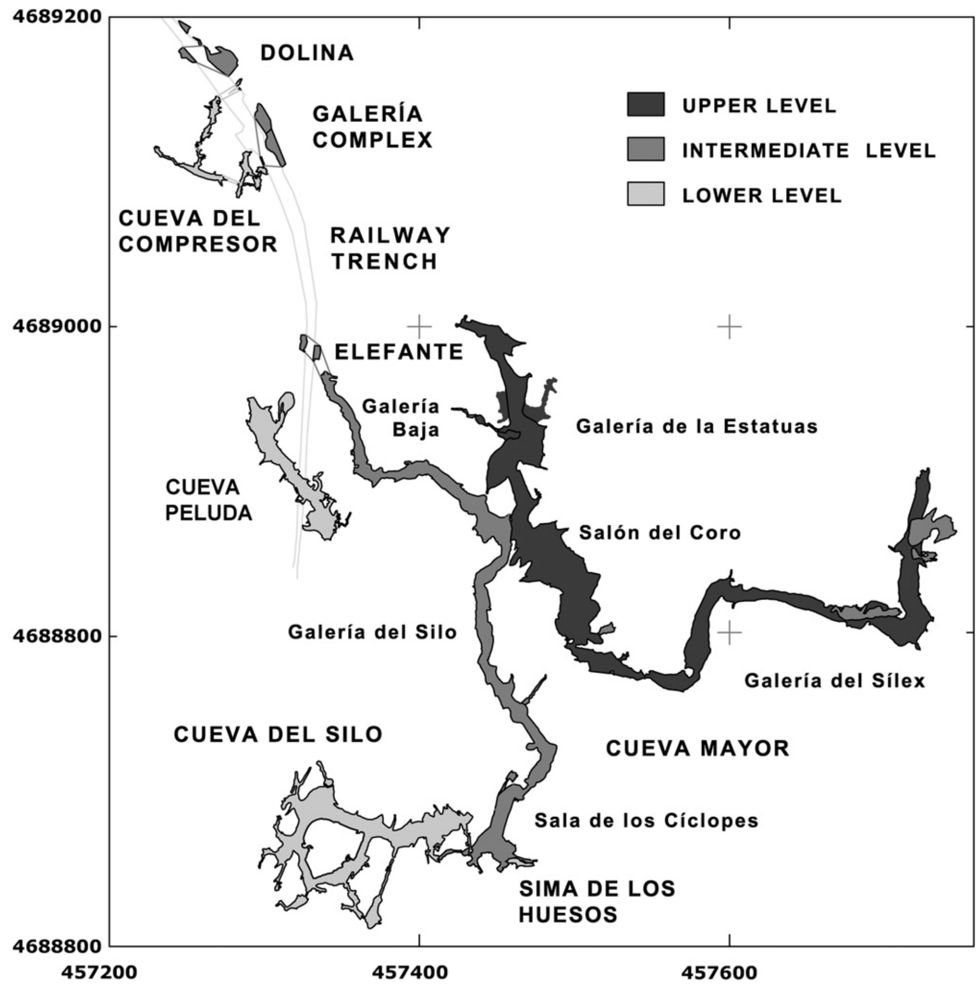

Fig. 12. Map of the Atapuerca multilevel cave system.

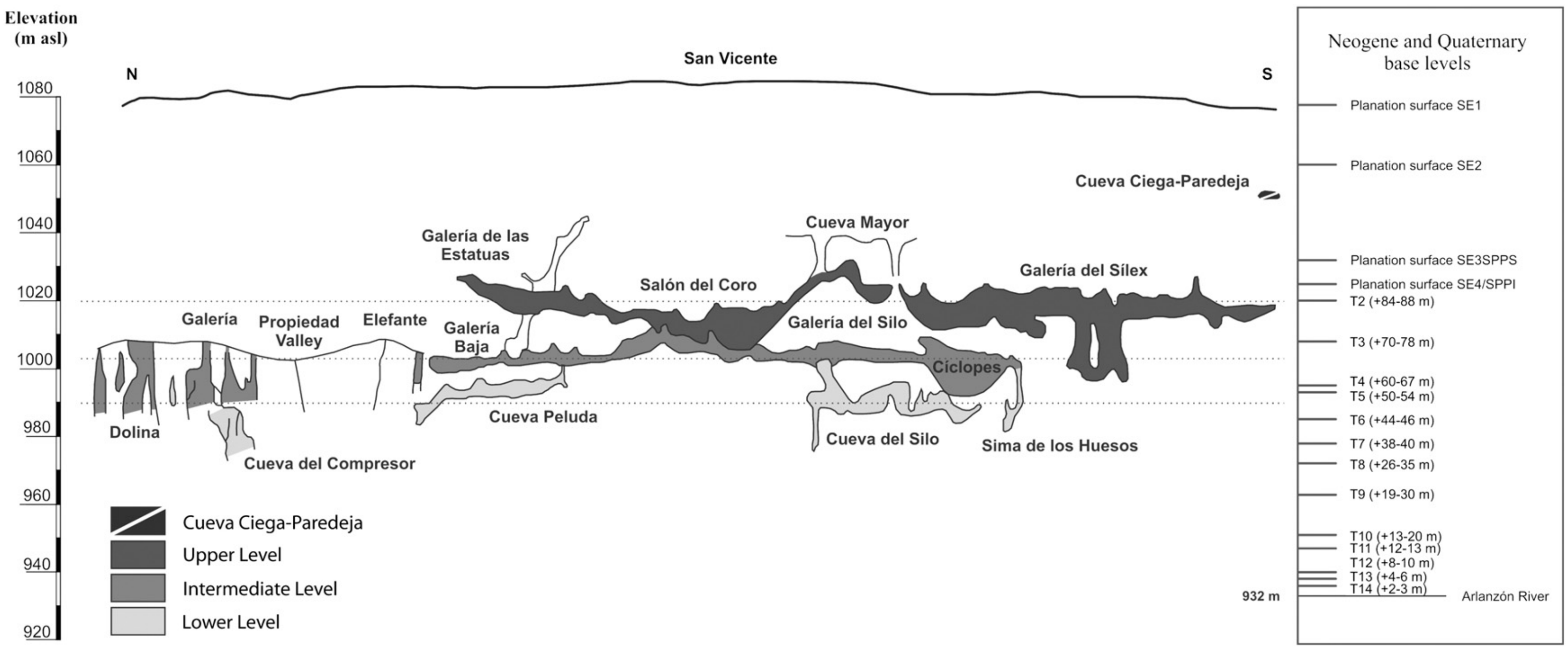

Fig. 13. Synthetic section of the Sierra de Atapuerca cave system in relation with the altitudinal distribution of Neogene planation surfaces and Quaternary terraces. Profile of the Sierra de Atapuerca, indicating the correlation with surface landforms.

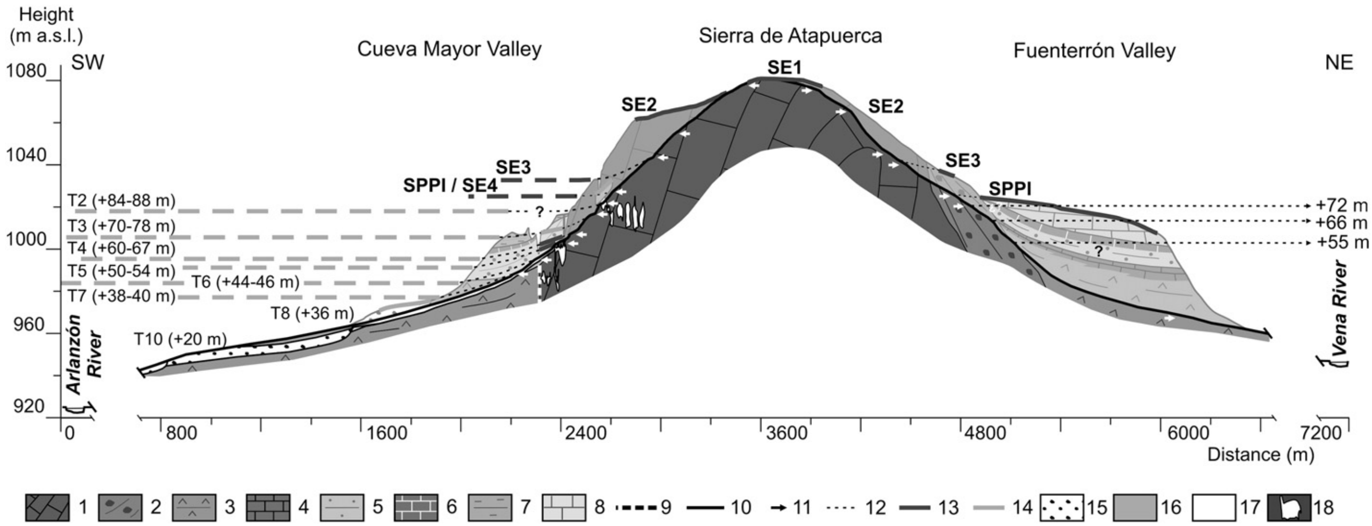

Fig. 14. Cross-section of the Sierra de Atapuerca along with Cueva Mayor and Fuenterrón valleys, indicating the relationships between the cave levels and the landforms developed during the Neogene and Quaternary. Legend: (1) limestones and dolostones (Mesozoic); (2) conglomerates (Oligocene–Lower Miocene); (3) shales (Lower Miocene); (4) limestones (Lower Miocene); (5) shales (Middle Miocene); (6) limestones with flint (Middle Miocene); (7) marls and limestones (Middle–Upper Miocene); (8) limestones (Upper Miocene); (9) probable fault; (10) longitudinal profile valleys; (11) knick points in the longitudinal profiles; (12) correlation lines; (13) erosional landforms; (14) depositional landforms; (15) fluvial terraces; (16) colluvial–alluvial deposits; (17) valley floors; (18) caves.

of conduits; these are the biggest passages of the multilevel system (Fig. 14).

As a consequence of the evolution of the water-table, an extensive flowstone formed on the floor of the passages of the first level, from Galería del Sílex to Galería de las Estatuas. The drop in local base level recorded by the development of the T3 terrace (+70–78 m) of the Arlanzón River led to the formation of sections with mixed or "keyhole" cross-sections at the distal sectors of the Sílex and Estatuas conduits, and favoured the enlargement of the main chamber, Salón del Coro, located at the connection with the structure-controlled intermediate level (Figs. 5, 6A, 9A and 13).

Palaeomagnetic data (Parés et al., unpublished data) indicate reverse polarity for the fine-grained sediments and flowstones located in Galería del Sílex and Estatuas. These data suggest vadose conditions during Matuyama Chron, before 1.22 Myr, which corresponds to the age of TE9 stratigraphic unit at Elefante site, situated in the end north of the intermediate cave level (Carbonell et al., 2008).

The intermediate level is associated with the period of stability represented by terrace T3 (+70–78 m) in the Arlanzón Valley, developed during the early Lower Pleistocene (Benito-Calvo et al., 2008) (Figs. 11 and 13). It is formed by the Cíclopes–Baja–Elefante ensemble in Cueva Mayor and the Dolina–Penal sections in the railway trench, located at about 1000–1003 m a.s.l. and +68–70 m above the modern Arlanzón River (Figs. 5, 6B, and 12 to 14). The abandoned water is marked by the river incision of the terrace T4 (+60–67 m) in the Arlanzón Valley. This drop in base level allowed the entry of surface sediments in the resurgence sectors and entrenchment in the conduits in their distal sectors (Cíclopes, Elefante and Dolina) forming vertical and wide keyhole-type cross-sections (Figs. 5, 9A and 10) (Ortega et al., 2005, 2011). Cíclopes room, corresponding to this phase, shows a sedimentary infill of breccias and fluvial sands and silts with reverse polarity attributed to the Matuyama Chron (Parés et al., 2010).

In addition, the lowest stratigraphic unit in the Elefante fill (TE9, TE7) yielded a Lower Pleistocene age (cosmogenic burial ages of 1.13 ± 0.18, 1.22 ± 0.16 Myr, and reverse polarity, Carbonell et al., 2008), and represents the entry of fossil and sediments from the surface near the palaeo-resurgence sector of Elefante (Parés et al., 2006; Carbonell et al., 2008). These deposits display significant deformation in the central part generated by fracturing and subsidence processes caused by an underlying cave (Figs. 8C and 10B) (Rosas et al., 2006; Ortega et al., 2010).

The interior facies located at the base of Dolina display a reverse polarity (Parés and Pérez-González, 1995). Entries of sediments with fossils were produced during Early Pleistocene not older than 1 Myr, in the Cromerian (Carbonell et al., 1999b; Falguères et al., 1999; Berger et al., 2008; Rodríguez et al., 2011). The fill at Dolina and Elefante continues with the massive entry of debris flow and alluvial sediments. This phase coincides with the change from reverse to normal magnetic polarity in both sites (Dolina, TD7) and (Elefante, TE16–TE17) (Parés and Pérez-González, 1995; Parés et al., 2006), which can be correlated with the polarity change detected in the sediments of Silo–Baja passage (Parés et al., unpublished data), and with the tentative polarity change detected in terraces T4 and T5 (Benito-Calvo et al., 2008).

The Arlanzón terraces T4 and T5 are situated in the proximity of the Sierra de Atapuerca at 995 m (+63 m) and 993 m (+61 m), respectively. Base level stability during the formation of these terraces led to the formation of the Galería Complex (Figs. 10C and 13), and to the enlargement and downcutting in the distal parts of the intermediate level (e.g. Sala de los Cíclopes, Elefante and Dolina).

A third level of horizontal conduits located at about 990–985 m a.s.l. is correlated with the T5 (+50–54 m) and T6 (+44–46 m) Arlanzón River terraces, attributed to the early Middle Pleistocene (Benito-Calvo et al., 2008). This cave level is represented by the conduits in Sima de los Huesos, Cueva del Silo, Cueva Peluda and Cueva del Compresor (Figs. 5, 6A, B, and 11 to 14) (Ortega et al., 2005). Transport of cobbles and pebbles metamorphic in cavities has been observed in several of these conduits (Silo and Peluda caves) (Ortega et al., 2005; Rosas et al., 2006). This fluvial input from the Arlanzón River could be related to terrace T6 or an older level on the basis of their altitudinal distribution (Fig. 13). This event caused the erosion and enlargement of the conduits, causing the subsidence and deformation of the Elefante sedimentary units (TE7 to TE17), where the change to the Brunhes normal polarity is preserved (Parés et al., 2006). The latter suggests a Middle Pleistocene age for the deformation processes and the Cueva del Silo fluvial sediments (normal polarity), which could be correlated with terrace T6.

The stability of the Arlanzón River during the formation of terrace T7 (+38–40 m) can be associated with the development of a small cave sub-level represented by the lower passages in the Silo, Compresor and Peluda caves, at 978 m a.s.l. (Figs. 11, 13 and 14). In addition, the formation of this level would cause the incision of the fluvial deposits situated inside Cueva del Silo–Peluda. With the base level recorded by the T8 terrace (+26–35 m), attributed to the Middle Pleistocene (Benito-Calvo et al., 2008) and projected to an altitude of 972 m a.s.l. in the surroundings of the caves, the multilevel cave system became totally disconnected from and perched above the Arlanzón River network.

In consequence, the number of archaeological sites increased, owing to the abandonment of the caves by waters, and to the process of roof collapse that opened new entrances to the passages during the Middle Pleistocene. This favoured the formation of archaeological sites, mainly associated with caves of the intermediate level. The occupation by hominids of the upper levels in Elefante (TE19) and Dolina (TD10), together with new sites like the Galería Complex and Sima de los Huesos, is shown by the diversity of activities and industrial technocomplexes, together with faunal assemblages. These include some thirty *H. heidelbergensis* skeletons, indicating an intensification of human settlement during the middle part of the Middle Pleistocene (Arsuaga et al., 1993; Carbonell et al., 2001; Rodríguez et al., 2011; Ollé et al., in press).

Biostratigraphic studies have shown that entrance sectors in the intermediate level were filled to the roof in the late Middle Pleistocene (Falguères et al., 2001; Pérez-González et al., 2001; Berger et al., 2008). In the Upper Pleistocene, the karst of San Vicente Hill became inactive, with only minimal animal and human activity in the entrances of Cueva Mayor and Mirador rock-shelter (Ortega, 2009). A new phase of the general human occupation of the karst took place in recent Prehistorical times, when all the open caves in San Vicente Hill were used for diverse purposes (Vergés et al., 2008; Ortega et al., 2008, 2011).

6. Conclusions

The analysis of caves in karst areas may provide relevant clues for reconstructing the regional evolution of the landscape. This study has established the evolution of caves and base levels in the Sierra de Atapuerca area, based on the correlation between the levels of sub-horizontal conduits concentrated in the southwestern sector of the range and Late Cenozoic planation surfaces and terraces. A Miocene age has been inferred for the small conduit of Cueva Ciega–Paredeja, at about +115 m above the Arlanzón River, on the basis of its altitudinal match with the Middle Miocene Erosion Surface SE2. The reconstruction of the Quaternary palaeobase level markers in the Sierra has allowed us to perform a solid correlation between the Arlanzón River terraces and the cave levels, located between +90 and +60 m above the modern Arlanzón River.

The development of the Atapuerca caves involved the loss of water flow from the Arlanzón River, favouring rising groundwater in fractures along the contact between the host rock (Cretaceous carbonates) and the Neogene sediments. After, the groundwater resurged in springs at the head of the Pico River. The caves form a stepped system on three levels of sub-horizontal conduits genetically associated with Early to the Middle Pleistocene terraces T2 (+84–88 m) to T6 (+44–46 m) of the Arlanzón River. Fluvial downcutting led to a series of accessible dry caves whose entrances were used by hominids from the Early Pleistocene to the Upper Pleistocene. The ages of the sedimentary sequences near the cave entrances have been used to constrain the chronology of the terraces. Thus, a pre-Jaramillo age has been attributed to the intermediate cave level and the terrace T3 (+70–78 m), while T6 (+44–46 m), which left deposits in the lower level of the cave system, could be ascribed to the Middle Pleistocene.

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