Pleistocene sedimentary facies of the Gran Dolina archaeo-paleoanthropological site (Sierra de Atapuerca, Burgos, Spain)

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ABSTRACT

Gran Dolina is a cavity infill of the Sierra de Atapuerca, containing three important Early and Middle Pleistocene archaeo-paleontological layers, including hominin bones, fauna and lithic remains. Due to the relevance of this site to understand human evolution in Europe, it is essential to define in detail the sedimentary processes and environments associated with the archaeological remains. Gran Dolina has a 19 m thick sedimentary infill divided into 11 lithostratigraphic units. In this work, we describe the sedimentary facies of the Early and Middle Pleistocene units and we update its stratigraphy. For that purpose, we have studied the stratigraphic excavation profiles available, where we have combined field observations with laboratory sedimentary analysis (sieving, laser diffraction, and image analysis) to characterize the texture and structure of the sediments. Through these studies, 19 sedimentary facies have been distinguished, grouped as sediment gravity flow facies, fluvial facies and autochthonous facies. The facies associations indicate two main trends in the allochthonous sequence. During the Early Pleistocene (TD4–TD7), the cavity acted as a stream sink, where channel and floodplain facies migrated along the sequence, and were interbedded with lateral gravity sediment flows. On the other hand, the Middle Pleistocene sequence between TD7 and TD10 is dominated almost exclusively by gravity flows. At least three main entrances have been inferred from input directions of the sediments, which changed over time. Sediment characteristics have allowed us to preliminarily infer environmental conditions around the cavity.

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1. Introduction

Caves are natural sedimentary traps, accumulating and preserving sediments and archaeological remains. These tell us about the processes of cave formation and the relationship between the caves and their environment (Farrand, 2001). Sediments can have different origins, some derived from the interior cave dynamics (autochthonous sediments), and others coming from the outside and introduced into the cavity through natural entrances, so-called allochthonous sediments (Gillieson, 1998; Farrand, 2004). Cave sediments have been widely studied in many caves (Shaw, 1992; Lawson, 1995; Pérez-González et al., 1995, 2001; Polk et al., 2007; Kadlec et al., 2008; Fornós et al., 2009; Turk and Turk, 2010; Martini, 2011; Angelucci et al., 2013). Identifying the different sedimentary facies from karst infills is useful in reconstructing the sequence of processes that occurred in the formation of the cavities, their relationship with the environment and to interpret the relationship between archaeological accumulations and sediments (Farrand, 1975; Straus et al., 2001; Goldberg and Sherwood, 2006; Finlayson et al., 2008). Recent studies (Ford and Williams, 2007; White, 2007) on cave deposits divided sedimentary facies into three principal groups (allochthonous, autochthonous and chemical deposits), differentiating up to 23 principal origins for cave sediments.

The Sierra de Atapuerca karst infillings record impressive sequences dating from the Early Pleistocene (Gran Dolina, Sima del Elefante and Galería infillings). These sequences have thicknesses of 16–19 m, and include a rich and unique archaeo-
paleoanthropological record. Among these infillings, Gran Dolina has provided a great amount of archaeological and paleontological remains that document the human activity and environment during the last million years (Carbonell et al., 2008; Rodríguez et al., 2011; Ortega et al., 2014). This site includes TD4 unit, which contains lithic remains and fauna probably over 1 Ma, and TD6 yielded human remains, stones and fauna dated at about 0.8–0.9 Ma (Carbonell et al., 1999; Berger et al., 2008; Gómez-Olivencia et al., 2012; Pablos et al., 2012; Parés et al., 2013; Rodríguez-Gómez et al., 2013; Saladié et al., 2014). In the Middle Pleistocene, the TD10 unit is prominent, and includes two rich layers of stone tools and fauna interpreted as a human campsite of 0.35 Ma (Falguères et al., 1999, 2013; Óllé et al., 2013).

In this work, we describe and classify the sedimentary facies of Gran Dolina cave, filled during the Early and Middle Pleistocene (Parés and Pérez-González, 1999; Pérez-González et al., 2001), in order to define the processes characterizing the evolution of this cavity and the sedimentary dynamic operating during formation of the archaeological layer. For that purpose, we propose a new cave sediment classification for Gran Dolina, based on field observations, sedimentological laboratory analysis, and previous cave studies. Through this work, we hope that this new cave sediment classification might offer the possibility to establish a sedimentary facies classification that can be applied to other karst sites. At the same time, we have updated the stratigraphical sequence of this site, using information gathered from new areas excavated during recent years.

2. Background

2.1. Geological and geomorphological setting

The Sierra de Atapuerca is a gentle anticlinal ridge (Fig. 1, Benito-Calvo and Pérez-González, 2014), part of the most north-western outcrop of the Iberian Chain, situated in the NE Neogene Duero Basin (Pineda, 1997), and drained by the Arlanzón River. This anticlinal ridge consists mainly of folded Late Cretaceous limestones and dolostones in a NNW–SSE overturned anticlinal structure.

The phreatic levels related to the first fluvial terraces of the Arlanzón River were associated with the generation of a multi-level endokarst system in the Late Cretaceous carbonates of the Sierra de Atapuerca (Benito-Calvo, 2004; Ortega et al., 2013). The Sierra de Atapuerca multi-level system consists of 4.7 km of explored passages (Martín-Merino et al., 1981), composed mainly of three sub-horizontal levels (Ortega, 2009; Ortega et al., 2013). The Gran Dolina cavity is located in the intermediate level. This level is a sinuous subhorizontal phreatic passage about 500 m long and about 1000–1003 m in altitude, associated with the period of stability represented by terrace T3 (+70–78 m) (Ortega et al., 2013), during the Early Pleistocene (Benito-Calvo et al., 2008; Moreno et al., 2012). The vadose regime in this level was marked by incision of the Arlanzón River between T3 and T4 (+60–65 m). Gran Dolina is a WNW conduit with a keyhole or mixed morphology, that connects towards the WNW with the Penal cavity (Ortega, 2009). The opening of the caves to the outside during the Early Pleistocene resulted in allochthonous sediment input and the accumulation of archaeo-paleoanthropological remains.

2.2. Gran Dolina stratigraphic sequence

Gran Dolina has a 19 m thick cave infilling divided into 11 lithostratigraphic units (Gil et al., 1987; Parés and Pérez-González, 1999). The units named TD (Trinchera Dolina) are numbered from bottom to top. The first two units (TD1–TD2) are autochthonous sediments and are archaeologically sterile. The rest of the units (TD3–TD11) are allochthonous sediments, mainly mass flows and fluvial sediments, including an important collection of human remains, fossils and lithic remains. The infilling processes finished with the formation of terra rossa soils in roof chimneys (Fig. 2).

The first stratigraphical study of Gran Dolina was conducted by Gil et al. (1987). In this work, Gran Dolina was differentiated into 11 lithostratigraphic units which have been used thereafter. Subsequent studies tried to relate the sedimentary record to the climatic record of the Quaternary using indirect dating methods such as fauna, geomorphology and paleomagnetism (Carracedo et al., 1987; Aguirre, 1992; Aguirre and Hoyos, 1992; Hoyos and Aguirre, 1995). Later, Pérez-González and Pares published several studies on Gran Dolina and its magnetostratigraphy (Pares and Perez-Gonzalez, 1995, 1998, 1999; Perez-Gonzalez et al., 2001).

Later stratigraphic contributions for the Gran Dolina site are limited. Canals et al. (2003) published an archaeostratigraphic study on TD6, containing a stratigraphic section of TD6.1 and TD6.2. Later, Bermúdez de Castro et al. (2008) presented a new stratigraphic column for TD6.1 and TD6.2, where the Aurora archaeostratigraphic set was defined as containing at least six sedimentary layers of gravel, silt and clay situated in TD6.2.

Although the principal stratigraphical units of the Gran Dolina site have remained the same since Gil et al. (1987), some nomenclature modifications have occurred during the progress of the excavation. A revision of these changes can be found in Rodríguez et al., 2011 where TD8–9 unit was introduced. On the other hand, some confusion persists about the nomenclature of the lower units, especially with regard to the presence of two sections separated by a limestone wall. In this area, different names have been used for the same unit, such as TDW4b, TD3–TD4 or TD3–4 (Cuenca-Bescós et al., 2001; Pérez-González et al., 2001; Van der Made, 2001; Rodríguez et al., 2011). In the present work, we have decided to use the name of TD4 for this unit, considering that TD3 has not been preserved.

Regarding geochronology, several dating methods have been used to date the Gran Dolina site, namely paleomagnetism, biostratigraphy, TL and ESR (Parés and Pérez-González, 1995, 1999; Falguères et al., 1999; Cuenca-Bescós et al., 2001, 2010; Berger et al., 2008; Parés et al., 2013). These studies have provided chronological data that are not always in agreement. The Matuyama–Brunhes boundary is situated at the top of TD7 (Parés and Pérez-González, 1995, 1999), with Dolina spanning from Early Pleistocene (TD1–TD7) to Middle Pleistocene (TD8–TD11). Below TD7 lies TD6 including the Aurora Stratum, famous for its artifacts and human remains (Carbonell et al., 1995; Bermúdez de Castro et al., 2008). This important layer is dated at 0.78–0.85 Ma (Falguères et al., 1999, 2013), with 0.77 ± 0.08 Ma as a more realistic date (Duval et al., 2012). A more recent study suggests a 0.936 Ma date for Aurora Stratum, and possibly formed during marine isotope stage (MIS) 25 (Pares et al., 2013). The lowest unit of the Gran Dolina site (TD1) has a date of 1.18 ± 0.15 Ma (Falguères et al., 2013) and the top has been dated at 0.2–0.24 Ma (Berger et al., 2008), so Gran Dolina represents a range of about 1 million years. A possible Jaramillo and Cobb Mountain subchron presence has been described in the TD1 unit (Parés and Pérez-González, 1999; Parés et al., 2013), according to ESR ages from quartz (Moreno García, 2011; Moreno et al., 2015).

3. Methodology

The study and classification of the different facies and sedimentary environments of Gran Dolina required a detailed description of the available stratigraphic excavation profiles (Fig. 6). This fieldwork has been combined with laboratory analyses aimed
at describing the texture of the sediments. Particle size sieving and laser diffraction techniques have been used. For sieving techniques, a \( \phi \) size sieve, range \(-3\phi \) to \(4\phi \), was used. Larger sizes have not have been analyzed because a large amount of sample would have been required to obtain a representative analysis. A Beckman Coulter LS13 320 laser diffraction particle size analyzer was used to measure the particle size of the silt and clay fraction. Particle size has been classified following the classification of Blott and Pye (2012). Percentages of matrix and clasts were also calculated through image analysis using photogrammetry.

The survey of the stratigraphic profiles and facies maps of the sections was performed using 3D laser scanning techniques (Leica C10), total stations and photogrammetry, which have served to obtain a 3D model of textures with a RGB image of Gran Dolina. This model was useful for identifying the continuity and geometry of the sedimentary layers and the stratigraphic architecture of the site.

4. Sedimentary facies of the Gran Dolina site

The most recent studies (Ford and Williams, 2007; White, 2007) about cave deposits divide sedimentary facies into three principal groups: allochthonous sediments, autochthonous sediments and chemical sediments. Taking into account the characteristics of Gran Dolina, chemical sediments can be assumed as autochthonous sediments. Based on these classifications, fieldwork descriptions and textual analysis, we have distinguished the following sedimentary facies in the Gran Dolina sequence (Table 1):

### Table 1

**Classification of sedimentary facies described in this work.**

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<tr>
<th>Allochthonous facies</th>
<th>Sediment gravity flow</th>
<th>Debris fall</th>
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<th>Autochthonous facies</th>
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4.1. Allochthonous facies

In the Gran Dolina sequence, we have identified two kinds of allochthonous facies: sediment gravity flow facies and fluvial flow facies, which are the most common deposits found in the cave.

4.1.1. Sediment gravity flow facies

Middleton and Hampton (1973) defined sediment gravity flow as the flow of sediments or sediment fluid mixtures under the action of gravity. This facies corresponds to isolated sediment inputs, which are deposited only short distances inside passages. Sedimentary gravity flows form cone-shaped deposits from vertical and sub-vertical entries, which may result in the entries silting up. A sufficiently large entrance is necessary for the occurrence of this type of facies, and which allows large sedimentary inputs. In Gran Dolina, three main sediment gravity flow types are distinguished, depending on the clast/matrix ratio.

4.1.1.1. Debris fall. Debris falls are sediments which have fallen under the action of gravity and where no fluid is necessary. These sedimentary deposits are of heterometric clast accumulations, usually angular, piled, and with little or no matrix. The Gran Dolina site has recognizable debris fall facies in the TD8 unit. They occur as cone-shaped clast-supported deposits of medium sized boulders to very coarse gravel, with about 50 cm maximum thickness in the center, decreasing towards the sides. Clasts are rectangular limestones and little or no matrix is observable. They are associated with a near sub-vertical entry and subsequent entries of debris flow facies. At least four debris fall events have been identified in the TD8 unit. Above the TD8 unit, debris fall facies decrease in size.

4.1.1.2. Debris flow. Dasgupta (2003) defined debris flow as a high-density clastic flow and laminar flow. Debris flow can also be defined as one-phase flow in which the whole mass undergoes continuous deformation (Cousset and Meunier, 1996). It represents a sudden moment when heterogeneous sediment slides because of dip and interstitial fluid. These facies deposits are unbedded sediment masses formed by the chaotic mixture of different particle sizes from clay to boulders. Two main phases can be separated: a matrix that consists of a mixture of fine sediment and water, and clast particles transported by it. Cave debris flow facies has a cone-shape where the large clasts are situated near of the tip of the cone and with grain size decreasing towards the distal zone, which has only silt and clay particles.

Six debris flow facies have been identified in the Gran Dolina sequence:

Facies A: Matrix-supported tabular boulders with muddy matrix: A breccia formed by medium to very small boulders surrounded by a muddy matrix rich in manganese oxide. Clasts are sub-angular and generally planar and elongate, situated in parallel to bedding planes (Fig. 3A), indicating different layers of deposits. Clasts represent about 30–40% of the facies. The muddy matrix is composed of 25% sand and 75% mud (Fig. 4A). This facies appears at the base of the allochthonous sediment sequence of Gran Dolina, in the TD4 unit. It has a 1–2 m thickness because of the accumulation of subsequent entries of sediment. Laterally, larger clasts are observed, losing the parallel orientation.

Facies B: Muddy matrix with small boulders: This facies shares many common characteristics with facies A, but has less than 20% boulders and these are not arranged parallel to bedding planes. Facies B has 0.1–0.3 m thick layers intercalated with gravel layers (Fig. 3B). The muddy matrix has the same composition as facies A, with 25% sand and 75% mud (Fig. 4B).
Clasts are subangular. This facies has a larger amount of gravel than facies A, between 5% and 20% mass weight. The similarity of facies B to facies A and its proximity in the Gran Dolina sequence indicate a common sedimentary process.

**Facies C: Clast-supported boulders with muddy matrix:** This facies is characterized by medium and small boulders in close contact with muddy matrix (Fig. 3C). Clasts in the section represent >30% of the facies, and are medium to small subangular elongate boulders, with a low content of gravel (Fig. 4C). The general characteristics of this facies are poor sorting, and its massive and ungraded nature. Facies C occurs in TD6 and TD10 units, with a 0.5–1 m thickness, with more boulders towards the NW and less towards the SE, where the layer changes to mud flow facies.

**Facies D: Matrix-supported boulders and gravels with muddy matrix:** Facies D is one of the most common facies in the Gran Dolina site. It is characterized by a mixture of chaotic and unsorted sediments from medium boulders to gravels, sands and mud, in a homogenous deposit (Figs. 3D, 4D). It is present in TD5, TD6, TD8 and TD10 forming layers of 0.3–1 m thickness that change to mud flow facies towards the SE. Clasts are subangular and elongate. Locally, there are zones which are clast-supported.

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**Fig. 3.** Debris flow facies. A, TD4 unit detail where debris flow facies A is observed. B, Debris flow facies B between two channel facies A (TD4.1). C, Debris flow facies C observed in the upper zone of TD6.3. D, TD6.3 where debris flow facies D is observed. Note heterogeneous clast size and matrix-supported fabric. E, Debris flow facies E located in the lower section of TD8. On the left side of the image, matrix-supported fabric occurs, meanwhile in the center, clast-supported fabric is observed showing the heterogeneous nature of this facies. F, TD10 detail where debris flow facies F is observed. This kind of facies is the most common in this unit. Scale bar: 10 cm.
**Facies E: Clast-supported boulders and gravels with muddy matrix:**
This facies is generally unsorted and ungraded, forming a massive deposit of clastic sediment. The clasts range from very fine gravel to small boulders and they are mostly in close contact. Matrix-supported areas are also observed (Fig. 3E). Facies E occurs overlying debris fall facies, at the base of TD8, and it is mainly cemented by carbonate.

**Facies F: Grain-supported boulders:**
This facies is generally massive and ungraded. Clasts are mostly medium to small boulder sized (Fig. 3F), representing 10%–30% by weight and supported by a gravel–mud matrix (Fig. 4E). Facies F is thought to represent a non-cohesive debris flow. A non-cohesive or granular debris flow is a high density and laminar flow (Dasgupta, 2003), characterized in the field by matrix-supported clasts and a gravel–sand matrix. This facies is distributed mainly in the upper sequence as thick beds dipping to the east and it usually contains archaeological remains.

**4.1.1.3. Mud flow.**
This facies is frequently found in the SE of the section of the Gran Dolina site, related to distal sediments or low energy flows. Mud flow is characterized by 5–30 cm thick tabular layers of normally unsorted structureless fine sediments (Fig. 4F). Particle size is about 20% sand, varying from fine to very fine grain size (Fig. 4F), and 80% mud, more silty in the proximal zone and more clayey towards distal zones. Mud flow facies can appear as differentiated layers or as the distal zone of debris flow.

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facies. In the latter case, mud flows show a gentle southward slope.

4.1.2. Fluvial flow facies

Fluvial flow facies in the Gran Dolina site are mainly composed of gravels and mud. Gravels are deposited in channel flows, while muddy sediments are found at its limits or as a last deposit of water flow. Three main fluvial facies types are distinguished.

4.1.2.1. Channel. Channels are the principal fluvial facies. They are represented in Gran Dolina as grain-supported and grain-size decreasing gravel layers often having a lenticular-shape. Gravels are well sorted, subangular limestones. Cross-stratification is often observed. The largest particle sizes that appear at the base of lenticular-shaped sediments are named lags. Lag layers indicate periods of migration of the main channel which are identified by grain-size decreasing cycles that end in a layer of clay. As in sub-aerial rivers, inside caves it is common to see several channel migrations arranged one on top of each other. In the Gran Dolina site, this is clearly observed in TD6 and TD11 channel facies. This facies is distributed in the Early Pleistocene units and in the upper unit (TD11) of Gran Dolina. Channels located in the lower units develop along the NW wall of the passage. Depending on the amount of matrix, two channel facies are differentiated.

Facies A: Grain-size decreasing gravels: This facies forms 10–30 cm thick layers, located in the lower sequence (TD4 and TD5). It is characterized by a low amount of matrix, less than 40% of the total weight. In facies A, lag and lenses are frequent, where different channel migrations could be observed in the same layer. Decantation facies are often found on top of this facies, marking the final period of water flow.

Facies B: Gravels with muddy matrix: This facies refers to thin layers of gravel whose grains are either supported by a muddy matrix or in loose contact. The matrix is composed of sands and mud and represents more than 40% of total weight. This facies occurs in the lower layers of TD6 and TD11, associated with debris flow facies.

4.1.2.2. Floodplain. These facies are silts and clay layers near channel sediments. They are yellowish red homogenous layers composed of coarse and fine silt, including between 10% and 30% clay (Fig. 5) and about 20% or less of sands. Clasts are scarce in this facies, but they are occasionally present. This facies frequently shows prismatic breaking and manganese oxide precipitation, mainly in the lower units. In TD7, floodplain facies show millimeter laminations and yellow colors. As a result of its aspect and particle size, floodplain facies can be locally confused with decantation facies or mud flow facies, but it is identified by its association with channel facies. Floodplain facies always appears in the SE of the section.

4.1.2.3. Decantation. Decantation facies are yellowish red clayey silt layers with horizontal laminations and are very thin. They usually contain less than 20% of sands and no clasts or gravel. Particle size analyses of the mud fraction reveal a 70:30 silt/clay ratio (Fig. 5), and coarse silt as the principal particle size. These results are variable between different decantation layers and do not allow differentiation between this facies and floodplain facies. Decantation facies often show prismatic breaking and manganese oxide precipitation. The most important decantation facies are in TD6, TD7 and TD10 where they do not exceed 10 cm thickness. This facies is interpreted as suspended sediment transported into the cave and deposited by decantation. Normally, they are located at the top of a fluvial sequence, where the lowest energy associated with the end of the flow allows the deposition of the finest materials. Regardless of channel facies distribution, they only occur in certain places marking important sedimentary dynamic changes.

4.2. Autochthonous facies

Autochthonous sediments are generated within the karst, as a result of cave processes such as weathering or breakdown. These kinds of sediment are usually produced when the cave is closed to the outside, since the cave sedimentation rate is slower than with allochthonous deposition, and the latter prevents autochthonous sediment accumulation. Autochthonous facies occur at the base of the stratigraphic record, before opening of Gran Dolina to the outside. In the Gran Dolina site, we have differentiated five autochthonous facies, although new excavation ongoing at the base of Gran Dolina will allow us to study autochthonous deposits in more detail.

4.2.1. Speleothem

Speleothems are chemical precipitation deposits formed inside caves. The Gran Dolina site has two well developed carbonate speleothems in TD1 and TD2 units and minor growths in TD5, TD7 and TD8–9. The TD1 and TD2 speleothems are 50 cm thick lenticular-shaped layers, located in the northern section of Gran Dolina, before allochthonous facies input. They are well crystallized and show several phases of crystallization. The speleothem layers whose growth over allochthonous facies is discontinuous and thin (0.5–10 cm thick), show poorer and smaller crystal formation. The formation of speleothems implies cessation of allochthonous sedimentation and slow autochthonous sedimentation. Thus, cave entrances were closed.

4.2.2. Breakdown

Breakdown facies are characterized by large and angular boulders breaking off from the ceiling and walls of caves. In Gran Dolina, breakdowns appear in the TD2 unit and in TD10, and are included...
in debris flow facies. The rock falls have caused sediment deformation in the underlying layers, as in the TD1 unit, where laminated layers are folded because of TD2 breakdown. Causes of collapse can be because of undermining of the underlying support, loss of hydrostatic pressure caused by transition from phreatic to vadose conditions, cryo-clastism, secondary mineral wedging, or earthquakes (Sasowsky, 2007).

4.2.3. Phosphatic accumulation

Inside caves, it is usual to find white or yellow deposits from phosphatic precipitation (Hill and Forti, 1997; Karkanas et al., 1999; Weiner et al., 2002; Shahack-Gross et al., 2004). In the Gran Dolina site, there are specific areas of precipitation of phosphates, probably associated with hyena coprolites, and a unit of bat guano, TD9 (Pérez-González et al., 2001). Phosphates appear as millimetric and centimetric crusts formed around weathered limestones. These crusts show a brown–white lamination. Mineralogical analysis reveals that phosphates in Gran Dolina are hydroxyapatites, with a variable amount of carbonate radical in their structure. This variability and the difference in crystallization explain the laminations observed in some crusts. Phosphatic growths are concentrated in the SE of the section, where TD6 hyena coprolites are located and the section is affected by a cut-and-fill, which carries sediments from TD9.

4.2.4. Weathering detritus

Weathering detritus are silt and clay deposits formed by the dissolution of host rock (White, 2007). The contact of sediment
4.2.5. Fluvial

Autochthonous fluvial layers are sediments deposited by the action of a more or less constant stream of groundwater that selects and concentrates particles of similar size. It is formed by well sorted sands, which display a unimodal particle size distribution and usually include a very high percentage of quartz grains. As with allochthonous fluvial facies, the grain size depends on stream energy. This facies can have an influence from outside since stream groundwater is usually related to outside river losses through karst features. Three sub-facies are differentiated depending on granularity and structure.

**Facies A: Laminated sandy silt with soft nodules:** This facies is observed at the top of TD1 and TD2 and is composed of well sorted laminated sandy silt, with dark-pale brown layer alternations. Soft nodules are present in some layers. The morphology, internal laminations and vertical position of these nodules indicate its diagenesis. Speleothem facies commonly overlies this facies. This facies shows increased thickness towards the northern section.

**Facies B: Laminated clayey silt with cemented layers:** Facies B shares many characteristics in common with facies A, having laminated layers, but with a more clayey texture. In fact, this facies always occurs under facies A, in TD1. An alternation of cemented and non-cemented layers is found, where cemented layers develop discontinuous hard surfaces.

**Facies C: Sands and clays:** Facies C only occurs in TD1 and represents the lowest layers found in the Gran Dolina site. It is characterized by well sorted sand layers and clay layers where limestone clasts are often found. The sand layers are lenticular and thin. Clay nodules are often observed within the sand layers. It is a heterogeneous facies where no internal structures can be differentiated.

5. Discussion

5.1. Sediment source area

The form and type of sediment gravity flow depend on the available sediment from the source area, energy flow and cave entrance type. Sources of sediment inside Gran Dolina are the southern slopes of the Sierra de Atapuerca. The main type of soil formed in Sierra de Atapuerca is terra rossa, a red silty clay soil characteristic of the Mediterranean region, and which forms on limestones and dolostones (Durn et al., 1999; Schaezl and Anderson, 2005). These soils are characterized by red muds with less than 10% sand, and about 70% silt and 30% clay. They are mainly composed of quartz, phyllosilicates and iron oxides. Because these soils are formed by weathering processes in the epikarst zone, the formation of significant amounts of terra rossa should be related to warmer and more humid climatic conditions. Slope failures would produce mud and debris flows, which would be introduced into Gran Dolina cave depending on the cave entrance size. Soil erosion on the Sierra de Atapuerca slopes could also be produced by fluvial processes, which involve a hydrologic reactivation inside the karst system, somehow related to an increase in relative humidity in the nearest environment.

5.2. Site formation processes and depositional environments

Unit TD1 is the oldest sedimentary unit known in Gran Dolina cave and is formed by autochthonous fluvial facies. The first sedimentological events of Gran Dolina (autochthonous fluvial facies C) were marked by small and discontinuous sheet water flows which eroded the previous clay layers. Subsequently, water flows were formed inside, the energy system increased and classified the sediment, giving rise to autochthonous fluvial facies B and facies A. The change from facies B to facies A meant an increase in flow energy and sorting of larger particles. The top of TD1 is defined by a speleothem, which coincides stratigraphically with a breakdown of large boulders. The latter have generally been used to define the TD2 unit (Pàrs and Pérez-González, 1999). Within TD2 and overlying the large boulders, autochthonous floodplain facies A is deposited, reactivating a similar environment to TD1. In the same way, TD2 also ends with a notable speleothem. This cyclic sedimentation is associated with vadose discharge variations in the cave, perhaps related to seasonal humidity variations (e.g. minor cycles), or to large recurrent periods (e.g. TD1 and TD2 cycles).

Nevertheless, no available chronological indicators allow precise dating of the recurrence of this stratigraphical sequence. A normal polarity excursion is described in autochthonous fluvial facies A, below the TD2 speleothem (Pàrs and Pérez-González, 1999; Pàrs et al., 2013).

TD3 described by Gil et al. (1987) is not preserved in the current section at Gran Dolina, suggesting that this unit was a locally restricted clayey unit. In the section, TD2 is overlain by TD4.

TD4 is the earliest autochthonous unit currently observable at Gran Dolina. This infill is a silty clay matrix debris flow (Debris flow facies A and Debris flow facies B, Fig. 3), formed by inputs from the SE towards the NW, through a high gradient entry (Gillieson, 1986; Bosch and White, 2004). The debris flow has around 70–75% silty-clay matrix (Fig. 10), greater than in TD5 and TD6.3 debris flows, indicating soil formation outside perhaps related to a relatively warm and more humid climate. Afterwards, water flow coming from outside introduced gravel sediments, indicating that Gran Dolina began to work as a sink, in a similar way to other railway trench sites (Ortega et al., 2013). Grain-size decreasing gravels (Channel facies A) mark the beginning of the TD4.1 sequence (Fig. 7) and indicate stream flow (Deckers and Riehl, 2007), which lies along the passage NW wall, coming from a general western direction. Thus, the input directions are different between gravity flow facies and fluvial facies, suggesting the existence of two different kinds of cave inputs. At least four cycles of alternating gravity flows and channels were distinguished in TD4.1 (Figs. 8 and 9).

During the archaeological excavation, fallen flowstone sheets were found at the top of TD4. The positions and morphologies of these speleothem fragments suggest the existence of a flowstone floor around this height attached to the southern limestone wall. This floor had to be developed over the old surface of sediments, which were eroded later.

TD5 unit was divided into TD5.2, mainly a gravity flow sub-unit situated at the base, and TD5.1, basically a channel facies sub-unit characterizing the top of TD5 (Fig. 8). TD5.2 is a fining upwards debris flow sequence of facies D, finishing with mud flow facies. As debris particle size is constrained by the entrance size (Bull, 1981), this fining upward sequence probably reflects the silting up of this entrance. This entry would be situated in close proximity as indicated by the presence of large clasts.

The lack of channel facies in TD5.2, unlike TD4, could indicate a drier environment in the cave, and perhaps also in the outside.
environment, but the silty mud matrix of debris flow facies D suggested a good subaerial soil development outside, associated with a warm and humid climate. On the other hand, TD5.1 is composed exclusively of channel and floodplain fluvial facies (Fig. 7). Channel facies developed along the NW wall of the passage, in the same way as TD4 channel facies (Fig. 7), indicating a similar input area from the west. At least five fluvial cycles are differentiated (Fig. 9). Each cycle represents a humid–dry change, where dry periods are defined by no sedimentation. During these events, micromorphological studies have revealed high sedimentation rates indicated by poor development of soil-formation processes (Vallverdú, 2002), suggesting that humid sedimentation periods may have dominated. This is supported by the squamate and amphibian fossil

Fig. 7. Sedimentary facies distribution and revised stratigraphic section of Gran Dolina site. The site has been separated into each excavation section actually observable. Scale in cm.
record in this sub-unit (Blain et al., 2009), which indicates a climatic evolution towards colder humid conditions at the top of TD5. This climatic change is consistent with the facies change in TD5.1, where fluvial facies are a proxy for more humid environments. This increasing humidity is also indicated by the presence of small mammal faunas (López-Antoñanzas and Cuenca-Bescós, 2002).

An important sedimentary change is recorded between TD5 and TD6. Fluvial facies decrease and gravity flow facies are predominant. The base of TD6 (sub-unit TD6.3) begins with an anomalous debris flow facies D (Fig. 7), which includes very small clast-supported boulders. This layer marks the reactivation of the cave after a stable period. The sub-unit continues with normal debris flow facies D, and channel facies B overlying the debris flows, which
smooth the paleorelief created by those flows (Fig. 7). Debris flow facies D was formed by sudden inputs of washed sediment, meanwhile channel facies B was deposited by a small ephemeral flow with poorly sorted grain size that moved over the debris flow, similar to a braided river (Hassan et al., 2009).

A decantation clay layer is found within TD6.3 (Fig. 9), which could indicate a flooding event to the SE of the cavity and slow sedimentation rates or sub-aqueous debris flow input. The dip of the debris flow facies and the decrease in coarse sediment southward indicate a new sediment entry point in the cave, from the NW towards the SE, opposite to that observed in previous units (Fig. 7). This new entry dominates the rest of the Gran Dolina infilling, and is located near the current Penal karst infilling. The TD6.3 sub-unit is completed by debris flow facies C (Fig. 3C), defined by large clasts, currently placed in the center of the stratigraphic section. These large clasts imply a large entry zone and higher energy than in lower units. In addition, the central position of the large clasts suggests other input directions for the deposits, nearly perpendicular to the current stratigraphic section. This new direction could denote another entry position or the existence of paleorelief which controlled the sedimentation.

Sedimentary processes in subsequent TD6 sub-units (TD6.2 and TD6.1) are different from TD6.3. In TD6.2 and TD6.1, channel facies A dominate with wider channels than in previous layers (Fig. 8). Channel facies change laterally to floodplain silts, defining an environment with rapid flooding events as a result of water level oscillations, as also suggested by micromorphological analysis (Valverdú, 2002).

TD6.2 sub-unit includes hominid remains, both in channel facies and in its associated floodplain facies (Carbonell et al., 1995; Bermúdez de Castro et al., 1997, 2008, 2012). The new entrance location of TD6 could have allowed hominid access to the interior of the cave and use of the cave by hominids as a home base (Carbonell et al., 1999; Saladie et al., 2011, 2014). In previous work, this section has been defined as the “Aurora archaeostratigraphic set” (AAS) (Bermúdez de Castro et al., 2008). AAS consists of six layers of clay, silt and gravel correlating with the Aurora Stratum defined in 1995 in the SE area (Parés and Pérez-González, 1995, 1999). Their lithology, morphology and interrelationship suggest a fluvial environment with lateral floodplain development. Three lag layers have been differentiated within TD6.2 channel facies, indicating respective reactivation layers of the fluvial flow. In addition, TD6.2 includes two decantation layers, with thicknesses increasing up to 30 cm towards the excavated area, where the lowest local topography should be situated. These layers represent a cessation of stream flow in this area, characterized by low sedimentation rates and energy (White, 2007). In the upper part of TD6.2, a thick debris flow facies D enters from the NW, as with other debris flows in TD6.3 (Fig. 3D). This input formed a paleorelief in slope towards the SE that prevented the formation of a floodplain to the NW of Gran Dolina.

Therefore, TD6.1 and TD6.2 show discontinuous events that may be associated with environmental changes. These two sub-units indicate fluvial reactivation events where the main environment is a stream inside a passage, passing through the center of the passage with southward lateral floodplain development (Fig. 7). These fluvial reactivations may be related to a more humid environment in the Sierra de Atapuerca with drier moments represented by debris flow facies D previously described. This interpretation is in agreement with the pollen data that postulate a drier climate at the base of TD6 and becoming more humid towards the top (García-Antón, 1995), but in disagreement with a study of herpetofauna that showed the opposite, with a drier environment increasing to the top (Blain et al., 2008). TD6 finishes with a hyena coprolite layer and a red decantation facies indicating a slow sedimentation rate. Both indicate a moment of stability inside the cave at the end of TD6, and a major temporal hiatus between TD6 and TD7 (Fig. 10).

Unit TD7 starts with a thick silt deposit interpreted as floodplain facies (TD7.3 and TD7.4) (Fig. 9), with microlaminations (Valverdú, 2002) and very low angle cross-bedding (Parés and Pérez-González, 1999). The oscillation in percent sand
observed in particle size analysis (Fig. 10) reveals fluctuations in the water flow (Springer and Kite, 1997; Ford and Williams, 2007). The particle size and chemistry of TD7.3 and TD7.4 (Fig. 10) are similar to autochthonous fluvial facies A, which also had cemented layers and a low iron concentration. These similarities could be the result of a more restricted sediment entry in the cave during this period, supported by few microfossil remains being found (Cuenca-Bescós et al., 2001), although the presence of large mammalian fossils (Van der Made, 2001) indicates an entrance in close proximity. In any case, we explain TD7.4 and TD7.3 as slow flooding events, showing flow velocity oscillations and cyclic drying events.

Overlying these sediments and with a possible lateral relationship, TD7.2 was deposited. This sub-unit has been described as clast-supported breccias with gravel texture and little cementation (Parés and Pérez-González, 1999). A new exhaustive examination reveals many layers of clast-supported gravels, subangular and subrounded, which display channel facies characteristics, including some larger subangular clasts. Thus, TD7.2 is mainly a channel facies, probably related to TD7.3 and TD7.4 floodplain facies. TD7 finishes with speleothem growth. The speleothem indicates a relatively stable period in the cave after the TD7 fluvial sedimentation. Nevertheless, this speleothem is laterally interbedded with a debris flow (facies E), which recorded the beginning of a new vertical entry in the NW. The geometry and texture of this debris flow are more related to TD8 unit than TD7 unit, with cone-shape and similar particle sizes.

Early Pleistocene allochthonous sediment in the Gran Dolina site is about 8 m thick. Near the base, a normal paleomagnetism is observed, within the autochthonous facies and below a speleothem. This normal polarity is described as the Jaramillo subchron (0.99–1.07 Ma) (Parés and Pérez-González, 1999; Parés et al., 2013), although the Cobb Mountain subchron (1.22–1.24 Ma) is also possible (Pérez-González et al., 2001) and this would agree with an ESR dates of 1.18 ± 0.15 Ma (Falguères et al., 2013) and 1.24 ± 126 ka (Moreno et al., 2015). Using this subchron and the Brunhes–Matuyama boundary of TD7, a tentative sedimentation rate could be postulated. If we assume the Jaramillo subchron, the general sedimentation rate would be about 3.8 cm/ka. With the Cobb Mountain subchron, the general sedimentation rate would be about 1.8 cm/ka. These are minimum sedimentation rates because, above the TD1 subchron, there is a speleothem that represents an important hiatus. An important discontinuity exists among TD4, TD5 and TD6 units (Fig. 10) and a more rapid sedimentation rate in sediment gravity flows is expected because the sedimentation rate in continuous layers (TD5.1, TD6.2 and TD6.1) should also be faster.

The change from TD7 to TD8 entailed an important lithostratigraphic change in Gran Dolina, since fluvial facies disappears until TD11 (with the exception of small channel facies in TD10) (Fig. 8), as environmental conditions became drier, as indicated by small

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**Fig. 10.** Summary table of principal analyses done in Gran Dolina site. Facies – Blue: Fluvial facies, Red: Sediment gravity flow facies, Grey: Other facies. Discontinuities – Solid bold line: major discontinuity, Discontinuous bold line: medium discontinuity, Discontinuous line: small discontinuity. Clast/Matrix – Blue: Clasts, Dark brown: Matrix. Particle size – Blue: gravel, Light brown: sand, Dark brown: mud. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
verbatimes (López-Antonanzas and Cuenca-Bescós, 2002; Cuenca-Bescós et al., 2011). This change could be controlled by climatic conditions and/or by the deeper incision of the regional fluvial network during the Early–Middle Pleistocene boundary (Benito-Calvo et al., 2008; Moreno et al., 2012).

As already mentioned, TD8 brought the re-opening of the cavity, through an entry situated near to the earlier TD6 sediment input area. Lower sub-units of TD8 have been dated. ESR dates are about 602 ± 52 ka (Falguères et al., 1999) and 525 ± 26 ka (Moreno et al., 2015), while the TL date is about 820 ± 140 ka (Berger et al., 2008). On the one hand, if we use the ESR date, the difference of this date with the 780 ka age of TD7 is important (178 ± 52 ka and 255 ± 26 ka respectively) and could be related to the upper speleothem of TD7, indicating the time period when the cave was closed. On the other hand, the TL date indicates a very short time lapse. TD8 has three main sedimentary facies: debris fall, debris flow facies E and debris flow facies F (Fig. 7). Debris flow facies E are found at the base of the unit (TD8.4, TD8.5), with a large associated debris fall facies (Fig. 3E). The clay concentration in debris flow facies E is similar to the cohesive debris flow proposed byDasgupta (2003) whose lack of turbulence and high flow viscosity prevented bedload traction and explained the sorting and the size sorting of the facies (Mazza and Ventró, 2011). In the NW, a decantation facies is observed overlying the upper debris fall deposits. This decantation facies suggests a longer time interval and a sedimentary change separating debris flow facies E from debris flow facies D. This change is characterized by an increase in the debris matrix (Fig. 10), which implies more soil formation outside during deposition of the upper TD8 unit. Accordingly, a climate variation to more humid and warmer conditions upwards could be suggested.

Later, TD8.1, TD8.2 and TD8.3 were partially eroded (Fig. 7). Above the erosion surface, a new stable period is recorded by a speleothem, preceding an episodic input which infills the paleoorelief. This input is the unit TD8–9, which is composed of debris flow facies D. After this process, the entrance is closed again with further thin speleothem growth. The erosion surface and speleothem growth suggest an important hiatus in sedimentation, supported by a change in fauna (Cuenca-Bescós and Forti, 1997) or it represents a distal position of a debris flow. Channel facies is observed in lower areas, indicating water flow during this time. In any case, TD10.4 shows a high percentage of matrix, suggesting soil formation outside under relatively warm and humid conditions, coincident with the climate deduced from faunal and pollen studies (García-Antón, 1995; Cuenca-Bescós et al., 2005; Blain et al., 2009). On the other hand, TD10.3, TD10.2 and TD10.1 are units especially poor in clay matrix, dominated by debris flow facies C and F (Figs. 7, 9), which suggest poor soil development outside restricted by slightly colder and drier climatic conditions, also suggested by the faunal and pollen association (García-Antón, 1995; López-Antonanzas and Cuenca-Bescós, 2002). Other studies indicate the lack of glacial vertebrates in the fossil remains (Rodríguez et al., 2011; Blain et al., 2012) and suggest that glacial climates are not registered in Gran Dolina. The lack of soil does not necessarily implicate a glacial climate, but a not hot and humid climate. TD10.3 has at least three debris flow facies F events, which imply normal reactivation of the cave, and finished with a debris flow facies C (Fig. 7), which includes large tabular boulders coming from breakdown processes affecting the cave walls or ceiling. This event could cause the enlargement of pre-existing openings or new openings. Thus, a new secondary entry can be suggested after these fall events, recorded by SE inputs of debris flow facies F.

TD10 yielded two important archaeological assemblages containing more than 30,000 lithic remains and 99,000 faunal remains (Ollé et al., 2013). These archaeological layers have been interpreted as being the result of high intensity occupations, where the hominids undertook various activities in a stable environment (Carbonell et al., 2001; Márquez et al., 2001; Blasco et al., 2010, 2013a, 2013b; Ollé et al., 2013). These assemblages are placed in the period between two debris flows. This period can be very variable, years or thousands of years (Gilleson, 1986; Kovanen and Slaymaker, 2008; Matthews et al., 2009), but much larger than the debris flow events, which are instantaneous and sudden inputs.

Middle Pleistocene sediments of Gran Dolina are about 7 m thick up to the top of TD10. The date of the top of TD10 is 244 ± 26 ka by the TL method (Berger et al., 2008), 337 ± 28 ka by the U-ESR method (Falguères et al., 1999) and 393 ± 77 ka by the ESR quartz grain method (Moreno et al., 2015). If the TL date is used, we can estimate a sedimentation rate of 1.3 cm/ka. Using the U-ESR date, the sedimentation rate is 1.58 cm/ka. The ESR quartz grain...
method indicates a sedimentation rate of 1.8 cm/ka. However, we have to be cautious with this value because of the hiatus represented by the TD8–9 and TD9 units.

Finally, the TD11 stratigraphic unit represents an important facies change with regard to previous units. This is probably because Gran Dolina cave was now almost completely filled and this restricted input from the outside, as also indicated by the lack of fossils. This unit date range from 240 ± 44 ka to 55 ± 14 ka by TL (Berger et al., 2008). In TD11, layers of channel and floodplain facies developed, showing a hydrologic reactivation which silted up the Gran Dolina cavity. At the top, sediments in contact with the carbonate host rock were subjected to precipitation of carbonate. The last process recorded inside Gran Dolina infill was terra rossa soil formation in the two chimneys currently visible (Pérez-González et al., 2001).

6. Conclusion

The Gran Dolina site has functioned as a sediment trap since its opening to the outside in the Early Pleistocene, until the cave silted up in the Middle Pleistocene. During this time, the cave has been filled with clastic sediment containing paleontological and archaeological remains. Nineteen sedimentary facies have been differentiated in the Gran Dolina site, twelve of which are allochthonous facies and seven are autochthonous facies. Regarding the allochthonous facies, the cave is filled by two principal sedimentary processes: fluvial and sedimentary gravity flow. During the Early Pleistocene, Gran Dolina acted as a stream sink, where occasional and rapid gravity sediment flows occurred, giving general sedimentation rates of 1.8–3.8 cm/ky. Stream facies show a migration from TD4 to TD5, where the channel developed close to the NW cavity wall, until TD6, where the stream channel developed in the middle of the cavity. At the beginning of the Middle Pleistocene, an important change is recorded in the sedimentary sequence. Fluvial facies decreased drastically, and the sequence is dominated by gravity flows from TD8 until TD10, with mean sedimentation rates of 1.3–1.8 cm/ka. The allochthonous sequence in Gran Dolina has at least two important hiatuses represented by speleothem growth (one at the top of TD7 and two above TD8 and TD8–9) and an erosive surface (TD8–9). Despite the presence of TD8–9 and the cut-and-fill observed, erosive processes are limited in the Gran Dolina site.

At least three principal entries have been present at the Gran Dolina site. The main change in sediment direction occurred in TD6, where the sediments migrated from a NW input direction to an E input direction until TD11. Secondary entrances were also present in the Gran Dolina site, using chimneys and wall fissures.

Paleo-environmental interpretations from clastic deposits must be viewed with caution. Sedimentary deposits depend on various factors, not only the environment, although this is one of the most important factors. To make paleo-environmental interpretations in the Gran Dolina cave, we must assume that the source of sediment is soil development on the Sierra de Atapuerca slopes, and that these soils were sensitive to local and regional climate change. Paleo-environmental interpretation of Gran Dolina facies has been combined with existing geomorphological, faunal and pollen data.

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