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Landscape evolution and chronostratigraphic correlations of the cave entrance depositional environments and palaeosols of the Gran Dolina unit TD10 (Sierra de Atapuerca, Spain)

Lila Warnitz [a,b], David Manuel Martín-Perea [a,c,d], Andreu Ollé [a,b], Palmira Saladié [a,b,e], Antonio Rodríguez-Hidalgo [a,f], Marina Mosquera [a,b], Josep Maria Parés [g], Eudald Carbonell [a,b,h], Josep Vallverdú [a,b,e,*]

[a] Institut Català de Paleoecologia Humana i Evolució Social (IPHES-CERCA), Zona Educacional 4, Campus Sescelades URV (Edifici W3), 43007 Tarragona, Spain
[b] Departament d'Història i Història de l'Art, Universitat Rovira i Virgili, Avinguda de Catalunya 35, 43002 Tarragona, Spain
[c] Department of Geodynamics, Stratigraphy, and Palaeontology, Faculty of Geology, Complutense University of Madrid, Madrid, Spain
[d] Institute of Evolution in Africa – IDEA, University of Alcalá de Henares, Madrid, Spain
[e] Unit Associated with CSIC, Departamento de Paleobiología, Museo Nacional de Ciencias Naturales (CSIC), Calle José Gutiérrez Abascal, 2, 28006 Madrid, Spain
[f] Consejo Superior de Investigaciones Científicas, Instituto de Arqueología-Mérida (CSIC-Junta de Extremadura), Plaza de España 15, 06800 Mérida, Spain
[g] Centro Nacional de Investigación Sobre la Evolución Humana (CENIEH), Paseo Sierra de Atapuerca 3, Burgos 09002, Spain
[h] Fundación Atapuerca. Carretera de Logroño, 44 - 09198 Ibeas de Juarros, Burgos, Spain

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ABSTRACT

Gran Dolina Unit TD10 is a sedimentary succession located at the cave entrance depositional environment of the Sierra de Atapuerca multilevel cave complex (Burgos, Spain). Its lithostratigraphic units include four archaeostratigraphic subunits (TD10.1, TD10.2, TD10.3, TD10.4) dating to the Middle Pleistocene, which have been the focus of numerous multidisciplinary studies. This research is based on the examination of large-format thin sections (14 x 6 cm) cut from monolith samples of undisturbed sediments, combined with field descriptions of TD10. We divide unit TD10 in three lithostratigraphic units: TD10a, TD10b and TD10c.

Our detailed description and interpretation of the TD10 microfacies classification is guided by facies models and sedimentary process of slope deposits. The primary findings support the identification of distinct sedimentary processes, illustrating the evolution of cave entrance talus scree deposits into stratified slope deposits. Field and microscopic observations of cave entrance deposits are closely integrated with palaeoecological reconstructions, particularly concerning the vanished middle Pleistocene soils of the slopes of Gran Dolina prehistoric site.

Additionally, analogies with other archaeological sites and soil formation processes provide insights into palaeosol profiles and the formation processes of the archaeological record. Finally, we discuss and formalize depositional and palaeoenvironmental units, correlating them with marine isotopic stages and substages using Bayesian chronostratigraphic modelling and TD10 palaeosols. Chronological uncertainties arise in TD10b between Bayesian dates and permafrost and (paleo-argillic) brown earths buried horizons, which are correlated with MIS 12 and MIS 11 in north-western Europe. TD10a Bayesian chronology aligns with MIS 9 in agreement with a interglacial palaeosol record. This research emphasizes the complexity of cave entrance stratigraphy and its pivotal role in reconstructing past environments.

1. Introduction

Gran Dolina (GD) Unit TD10 is a lithostratigraphic unit in a cave entrance environment (Ford and Williams, 2007). Palaeoecological studies of the GD site have characterised its surroundings as a stable environment, consisting of a savannah-like open woodland during the Early and Middle Pleistocene (Rodríguez et al., 2011). Moreover, environmental proxies from Atapuerca micromammal record suggest typical

* Corresponding author at: Unitat de Geoarqueologia. Responsable de la Unitat de Làmina Prima. Institut Català de Paleoecologia Humana i Evolució Social (IPHES-CERCA), Zona Educacional 4, Campus Sescelades URV (Edifici W3), 43007 Tarragona, Spain.

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temperate fauna reflecting minimal influence from Pleistocene glaciation (Domínguez-García et al., 2024).

Considering the site's formation, previous lithostratigraphic studies of GD Unit TD10 have provided different interpretations. For instance, early research by Hoyos and Aguirre (1995) and Mallol and Carbonell (2008) suggested that a rockfall triggered by cryoclastism was responsible for its origin. On the other hand, Campaña et al. (2017) have proposed that TD10 was formed through a rockfall that was subsequently modified by debris flows. Interestingly, the low variability in sedimentary facies within Unit TD10 is notable, especially considering the significant Quaternary climatic fluctuations documented in the Marine Isotope Stages (MIS) record (Cohen and Gibbard, 2019; Lisiecki and Raymo, 2005; Railsback et al., 2015).

Cave entrances, and associated alluvial and colluvial sedimentary facies, are complex systems shaped by various sedimentary processes (Bertran, 2004; Blair and McPherson, 2009; Karkanas and Goldberg, 2019; Van Steijn, 2011). These reference frameworks for describing alluvial and colluvial deposits form the basis of this study's primary objectives: (1) a palaeoenvironmental reconstruction dealing with the landscape evolution of the GD cave entrance; (2) correlating soils and vegetation with the past slope deposits preserved in the sedimentary record of Unit TD10 (Beverly et al., 2018; Fédoroff, 1986; Fédoroff and Courty, 1987; Holliday, 2004; Mandel and Bettis, 2001; van Vliet-Lanoë, 1998). Furthermore, this paper also aims to develop a detailed microstratigraphy of GD Unit TD10, identifying sedimentary processes through microfacies associations and proposing depositional sequence units.

Colluvial deposits, including lithostratigraphic Unit TD10, are characterised as accumulations of material transported downslope by various sedimentary processes (Blikra and Nemec, 1998; Catt, 1986; Karkanas and Goldberg, 2019). These deposits, known today as stratified slope deposits, are heterogeneous and typically found on rocky slopes in high mountain and hilly environments (Selby, 1993). They are generally mapped at the base of mountain slopes, formed primarily by sediment-gravity flows (Bertran and Texier, 1999; Blikra and Nemec, 1998; Collcutt, 1979).

Initially, stratified slope deposits were defined as *éboulis ordonné* or screes (Cailleux, 1946). The term *grèze litée* later emerged, linking these deposits to periglacial conditions (Guillien, 1951). Stratification in *grèze litée* was attributed to intense gelifraction, sparse vegetation, and snowmelt-driven slope-wash processes (Guillien, 1951; Van Steijn, 2011). By the 1990 s, research demonstrated that stratified slope deposits could result from diverse sedimentary processes, not exclusively periglacial conditions (Blikra and Nemec, 1998; Van Steijn, 2011).

The sedimentary structures and microfacies associations of Unit TD10 suggest multiple sedimentary processes such as grainflow, solifluction, frost creep, debris flow, and overland flow. Microscopic analyses of sedimentary petrography and soil micromorphology have provided valuable insights into the taphonomy of TD10′s Pleistocene sediments (Bertran et al., 2019). Microfacies descriptions and interpretations characterise TD10 sediments as consistent with slope deposit models (Bertran and Texier, 1999).

In this study, microscopic observations are integrated with field analyses of the lithology and the geometric shapes of TD10 deposits to reconstruct depositional sequences. Additionally, distinct types of buried soil profiles (palaeosols) and relict pedogenic features in cave sediments have been classified (Fédoroff and Courty, 1987; Tabor and Myers, 2015; Vieira de Sousa et al. 2023), enabling the determination of sedimentary accumulation modes and contextualizing the formation processes of TD10′s archaeological record (Bailey, 2007; Bertran et al., 2017).

The TD10 soil micromorphological research further explores palaeoenvironmental units through different development stages of the palaeosols and relict soil features (Bronger and Catt, 1998; Duchaufour, 1984; Fédoroff and Courty, 1987; Kubiëna, 1970). Finally, correlations between these palaeoenvironmental units (palaeosols) and MIS have help to constrain the chronostratigraphy of the Unit TD10 (Blackwell and Schwarcz, 1993).

Our microstratigraphic research demonstrates that employing sedimentary slope deposit models as a reference framework enhances the identification and interpretation of sedimentary processes within Unit TD10 of GD. This approach has revealed evidence of sedimentary processes previously overlooked in the GD geological studies. Our findings highlight the effectiveness of combining field and microscopic observation for analysing palaeoenvironments and fossil assemblage formation processes.

2. Regional setting

The Sierra de Atapuerca is located 15 km east of Burgos in the region of Castilla y León, Spain (Benito-Calvo et al., 2017). This Mesozoic range is situated at the northwestern edge of the Iberian System. It covers an area of approximately 25 km^2 and reaches an elevation of about 1,000 m above sea level, with San Vicente peak rising to 1,085 m. The Sierra de Atapuerca cave system features three levels of sub-horizontal, inactive subterranean passages. The Trinchera del Ferrocarril archaeological complex includes the Elefante (E), Gran Dolina (GD), and Galería (G) cave entrances, all completely infilled with Pleistocene sediments (Ortega et al., 2014).

Geographically, the Sierra de Atapuerca forms the southeastern boundary of the Bureba Corridor, which connects the Duero and Ebro basins (Fig. 1a, b). The Pleistocene deposits of the Sierra de Atapuerca have provided invaluable evidence of early human evolution in western Europe (Carbonell et al., 1999, 2008).

3. Material and methods

GD cave is in the middle level of the Sierra de Atapuerca karst system (Campaña et al., 2017; Carbonell et al., 1999; Ortega et al., 2014). GD contains 19 m of sedimentary infill dating to the late Early to late Middle Pleistocene and is made up of 11 lithostratigraphic units (Campaña et al., 2017; Gil et al., 1987; Hoyos and Aguirre, 1995; Parés and Pérez-González, 1999; Pérez-González et al., 2001). Two types of sediments are present within the GD infills: autochthonous sediments (TD1 and TD2) and allochthonous sediments (TD3 to TD11). The excavation of Unit TD10 has covered over 80 m^2. Two TD10 stratigraphic profiles are available for field observations and sampling (Fig. 1c): the north panel (magnetic east), which is 10 m long and 3 m deep; and the east panel (magnetic south), which is 8 m long and 4 m deep.

The biostratigraphy of Unit TD10 suggests it was formed during the mid to late Middle Pleistocene based on Faunal Unit 6 (313–430 ka) (Cuenca-Bescós et al., 2016). TD10 is divided into four archaeostratigraphic units (TD10.4-TD10.3-TD10.2-TD10.1) from the bottom to the top. The lithic assemblages of Unit TD10 contain late Acheulean and early Middle Palaeolithic industries (de Lombera-Hermida et al., 2020; Mosquera et al., 2024). TD10 archaeological assemblages have remarkable knapped lithic refittings and skeletal remains with reliable spatial integrity for *in situ* behavioural research (Arteaga-Brieba et al., 2023; Rodríguez-Hidalgo et al., 2015, 2017).

Fig. 2 shows the stratigraphic panel for Unit TD10, constructed from field observations, which delineates the sedimentary successions TD10a, TD10b, and TD10c as lithostratigraphic subunits of TD10. The illustration includes rock fragments larger than small boulders, lithological boundaries, and the positions of sediment samples in monoliths, all recorded using total station and photogrammetry. The inclination of the boulders was analysed using ArcGIS, with the results represented in rose diagrams. Only boulders with a length-to-width (L/W) ratio greater than 2 were considered in the rose diagrams (Fig. 2) (Bertran, 2004).

Bayesian modelling using the OxCal programme applies an internal distribution of geochronometric dates, delimited by uninformative prior beliefs (uniform boundary type), based on the boundaries of lithologic and archaeostratigraphic units of TD10 (Bronk Ramsey, 2009). Code