**Appendix A. Sites description**

**A.1 VASCO-CANTABRIAN SITES**

**Axlor (Dima, Vizcaya, País Vasco)**

Axlor is a rock-shelter located in Dima (43.2706; -1.8905), with a continuous Middle Paleolithic sequence from the MIS5 to the MIS3 (DeMuro et al., 2023; Pederzani et al., 2023; Marín-Arroyo et al., 2018). It is placed on the southwestern slope of the Dima valley, with an elevation of approximately 320 m above sea level (a.s.l.), at 33 km straight from the present-day coastline, next to one of the lowest mountain passes linking the Cantabrian basins and the Alavese Plateau. The site was discovered in 1932 and initial excavations were performed by Barandiarán (1967-1974). J. M. Barandiarán undertook the excavations between 1967 and 1974, identifying eight Mousterian levels (I-VIII) (Barandiarán, 1980).

From 2000 to 2008, new excavations by González-Urquijo, Ibáñez-Estévez and Rios-Garaizar were achieved and, since 2019, these are ongoing by González-Urquijo and Lazuén. Due to the lack of chronology during Barandiarán excavations, among other aspects, work was focused on obtaining a detailed stratigraphy on the new excavation areas to correlate it with Barandiarán’s levels (González-Urquijo & Ibáñez-Estévez, 2021; González Urquijo et al., 2005). The new stratigraphic sequence is roughly equivalent to the previous one, but with additional levels, not previously identified or excavated by Barandiarán. Some of these levels were deposited before Level VIII (Gómez-Olivencia et al., 2018; 2020). The Middle Paleolithic sequence extends from layers VIII to III (or from N to B-C). Levallois production is predominant in the lower levels (VI to VIII), while Quina Mousterian technocomplex does in the upper ones (from III to V) (Rios-Garaizar, 2012, 2017). New chronological data by radiocarbon and OSL methods confirm that a sequence Axlor levels VI, VIII, and VIII probably accumulated during MIS5d–a (109–82 ka), while levels D to B probably were formed during the period encompassing the start of MIS 4 (71–57 ka) through to the beginning or middle of MIS 3 (57–29 ka) (Demuro et al., 2023) and upper Level III to 46,200 ±3,000 BP, which calibrates between 45,510 cal BP and the end of the calibration curve at > 55,000 cal BP (see Pederzani et al., 2023: Fig. 1).

The archaeozoological study indicate an anthropic origin of the faunal assemblage with scarce carnivore activity documented (Altuna, 1989; Castaños, 2005; Gómez-Olivencia et al., 2018). In lower layers, the most abundant taxa are *Cervus elaphus* (VIII) and *Capra pyrenaica* (VII), while in upper layers III-V, C*ervus elaphus* is substituted by *Bos primigenious/Bison priscus* and *Equus sp*. The material included in this work comes from the faunal collection of the Barandiarán excavation currently curated at the Bizkaia Museum of Archaeology (Bilbao) where teeth were sampled and the stable isotope analyses on enamel phosphate were included in Pederzani et al. (2023).

**El Castillo (Puente Viesgo, Cantabria)**

El Castillo is cave located in Puente Viesgo (43.2924; -3.9656), with an elevation of approximately 195m a.s.l., at 17 km straight from the present-day coastline. The cave belongs to the karstic system that was formed in the Monte Castillo, which dominates the Pas valley. The site was discovered in 1903 by H. Alcalde del Río. H. Obermaier carried out the first excavation seasons between 1910 and 1914, when many of the archeological remains were recovered, mainly from the hall of the cave. These interventions were done under the supervision of the “Institut de Paléontologie Humaine” (IPH) and of Prince Albert I of Monaco. From 1980 to 2011; V. Cabrera and F. Bernaldo de Quirós underwent new excavations focusing on the cave entrance, on the Middle to Upper Paleolithic transitional levels, mainly 16, 18 and 20 (Cabrera-Valdes, 1984). The site has yielded an important stratigraphic sequence, composed by 26 sedimentological units (1-26) related to different anthropic occupational units, often separated by archeologically sterile units: Eneolithic (2), Azilian (4), Magdalenian (6 and 8), Solutrean (10), Aurignacian (12, 14, 16 and 18), Mousterian (20, 21 and 22) and Acheulean (24) (Cabrera-Valdés, 1984).

Unit 21 is mostly sterile (Cabrera Valdés, 1984; Martín-Perea et al., 2023) and it was dated by ESR yielding a mean date of 69,000 ± 9,200 years BP (Rink et al., 1997). However, Martín-Perea et al. (2023) suggested some dating uncertainty arising from the interpretation of the initial stratigraphic nomenclature. They suggest that the ESR dates provided for level 21 by Rink et al. (1997) were erroneously attributed to this unit and it might correspond to 20E indicating that below that subunit the chronology is older than 70,000 years BP (Martín-Perea et al., 2023). The Mousterian Unit 20 cave is divided into several subunits (Martín-Perea et al., 2023). In Unit 20, a cave roof collapse took place transforming the cave system into an open rock shelter. This unit contains abundant archaeological and paleontological remains. Lithic industry consistent in sidescrapers, denticulates, notches and cleavers, the majority on quartzite and presents both unifacial, bifacial discoid debitage and Levallois debitage. Unit 20E was attributed to Quina Mousterian by Sánchez-Fernández and Bernaldo De Quiros (2009) and contains a Neanderthal tooth remain (Garralda, 2005). Considering the geochronological uncertainties for dates on 20E related with Rink et al. (1997), we have decided to solely rely on ERS date of 47,000 ± 9400 BP provided by Liberda et al. (2010) for this level. Unit 20C presents clear evidence of the Mousterian lithic industry and radiocarbon dates of 48,700±3,400 uncal BP (OxA-22204) and 49,400±3,700 uncal BP (OxA-22205) (Wood et al., 2018) and mean ESR date of 42,700 ±9900 BP (Liberda et al., 2010). Level 19 is archaeologically sterile and separates Unit 20 from Unit 18 (Wood et al., 2018).

Unit 18 is divided into three parts: 18A (archaeologically sterile), 18B, and 18C. Levels 18B and 18C were classified as Transitional Aurignacian, representing a gradual transformation from the Mousterian to the Aurignacian, which is unique to El Castillo cave (Cabrera et al., 2001; Maíllo and Bernaldo de Quirós, 2010; Wood et al., 2018). The dates and the cultural attribution of these levels have been the subject of much debate (e.g. Zilhao and D’Errico, 2003; Wood et al., 2018). According to Wood et al. (2018), the last dates of these levels range between 42,000±1,500 uncal BP (OxA-22203) and 46,000±2,400 uncal BP (OxA-21973), which is much earlier than the start of the Aurignacian period in the Cantabrian region (Marín-Arroyo et al., 2018; Vidal-Cordasco et al., 2023). The lithic assemblage of Unit 18 appears to be dominated by Discoid/Levallois technology (Bernaldo de Quirós and Maíllo-Fernández, 2009) but with a high percentage of "Upper Paleolithic" pieces. Additionally, punctual bone industry, as well as pieces with incisions and engravings, were discovered in Unit 18 (Cabrera-Valdés et al., 2001). Three deciduous tooth crowns attributed to Neanderthals were found in Unit 18B (Garralda et al., 2022). Above, Unit 17 is sterile but contains scarce lithic and faunal materials, while Level 16 was attributed to the Proto-Aurignacian, with dates of 38,600±1,000 uncal BP (OxA-22200) (Wood et al., 2018).

According to Luret et al. (2020), there was a shift in hunting practices between the Late Mousterian (unit 20) and the Transitional Aurignacian (unit 18). During the Late Mousterian, hunting strategies were less specialized, and the species hunted included red deer, horses, and bovines. However, in Unit 18, a specialization in red deer hunting is observed. However, the explanation of this shift has been proposed as a response to a cultural choice or induced by climatic changes. The material included in this work comes from the faunal collection recovered during the Cabrera-Valdés and Bernaldo de Quirós excavations curated at Museo de Prehistoria y Arqueología de Cantabria (MUPAC, Santander).

**Labeko Koba (Arrastre, Guipúzcoa, País Vasco)**

Labeko Koba is a cave located in the Kurtzetxiki Hill (43.0619; -2.4833), at 246 m a.s.l. and 29 km straight from the present-day Atlantic coast. In 1987 and 1988, due to the construction of the Arrasate ring road, the site was discovered and a savage excavation was carried out (Arrizabalaga, 2000a). Unfortunately, the site was destroyed after that. The stratigraphic sequence identified nine different levels. The lower Level IX was attributed to the Châtelperronian, based on the presence of three Châtelperron points. Although there is a lack of human remains in few Cantabrian Châtelperronian sites, recent research has suggested that this techno-complex was produced by Neanderthals (Maroto et al., 2012; Rios-Garaizar et al., 2022). Level VII marks the beginning of the Aurignacian sequence, likely Proto-Aurignacian, with a lithic assemblage dominated by Dufour bladelets (Arrizabalaga, 2000a). Levels VI, V, and IV contain lithic assemblages that suggested an Early Aurignacian attribution (Arrizabalaga, 2000b; Arrizabalaga et al., 2009). This site is significant because it is one of the few sites with Châtelperronian assemblages and with both Proto-Aurignacian and Early Aurignacian separated (Arrizabalaga et al., 2009).

Initial radiocarbon dates were inconsistent with the stratigraphy of the site and much more recent than expected for the Early Upper Paleolithic (Arrizabalaga, 2000a). This incoherence was determined to be affected by taphonomic alterations (Wood et al., 2014). Later radiocarbon dates undertaken with an ultrafiltration pre-treatment provided a new regional framework for the regional Early Upper Paleolithic (Wood et al., 2014). The Châtelperronian layer is dated to 38,100±900 uncal BP (OxA-22562) and 37,400±800 uncal BP (OxA-22560). The Proto-Aurignacian levels cover a period from 36,850±800 uncal BP (OxA-21766) to 35,250±650 uncal BP (OxA-21793). The three Early Aurignacian levels are dated to 35,100±600 uncal BP (OxA-21778) for level VI, ~ 34,000 uncal BP (OxA-21767 and OxA-21779) for level V, and ~ 33,000 BP (OxA-21768 and OxA-21780) for level IV (Arrizabalaga et al., 2009).

Taphonomic studies indicate an alternation in the use of the cave between carnivores and humans, the latter ones during short occupation periods (Villaluenda et al., 2012; Ríos-Garaizar et al., 2012; Arrizabalaga et al., 2010). Labeko Koba is considered to have functioned as a natural trap where carnivores, mainly hyenas, accessed to animal carcasses. At least in the base of Labeko Koba IX, carnivore activity was higher, and they would have consumed the same prey as humans (Villaluenga et al., 2012). The presence of humans is linked to strategic use as a campsite associated with a small assemblage of lithic artifacts. The most consumed species by Châtelperronian groups were red deer, followed by the consumption of large bovids, equids, and woolly rhinoceros. During the Aurignacian period, there was some stability in human occupations, although still alternated with carnivore occupations (Arrizabalaga et al., 2010). Cold-adapted fauna such as reindeer and woolly rhinoceros were identified in association with the Châtelperronian. Reindeer were still present during the Aurignacian levels, as well as the woolly mammoth and arctic fox. The original sampling of the studied teeth by this work was performed in the San Sebastian Heritage Collection headquarters where the Guipuzcoa archaeological materials were deposited at that time.

**Aitzbitarte III (Renteria, Guipúzcoa, País Vasco)**

Aitzbitarte III is an archaeological site located within a karstic system comprising of nine caves in Renteria (43.270; -1.8905). The cave is situated 220 m.a.s.l. and is 10 km away from the present-day coastline. Initial archaeological interventions were carried out at the end of the 19th century by P.M. de Soraluce (Altuna, 2011). Recent excavations were initially conducted in the deep zone inside the cave between 1986 and 1993, and later focused on the cave entrance between 1994 and 2002, by J. Altuna, K. Mariezkurrena, and J. Ríos-Garaizar (Altuna et al., 2011; 2017).

While the cave's entrance area contains a sequence comprising Mousterian, Evolved Aurignacian, and Gravettian layers (Altuna et al., 2011; 2013), the stratigraphy in the inner cave presents eight levels: level VIII (some tools with Mousterian features), VII (sterile), VIb, VIa and V (Middle Gravettian technocomplex with abundance of Noailles burins), IV-II (disturbed archaeological levels) and I (surface) (Altuna et al., 2017). Levels V have dates of 24,910 uncal BP (I-15208) and 23,230 uncal BP (Ua-2243); whereas level VI extends from 23,830 ± 345 uncal BP (Ua-2628) and 25,380± 430 uncal BP (Ua-2244) (Altuna, 1992; Altuna et al., 2017), with a possible outlier dated at 21,130 uncal BP (Ua-1917).

The Gravettian occupation in the inner part of the cave was originally thought to be more recent than the ones in the cave entrance. However, it was difficult to correlate the two excavation areas due to different sedimentation rates. The rich human occupations took place during a singular cold phase in the Middle Gravettian with a specialized paleoeconomy focused on the hunting of *Bos primigenius* and *Bison priscus* (85% in level VI and 68% in level V), which is unusual in the Cantabrian region mostly focused on red deer and ibex. Other ungulates present are *Cervus elaphus* and *Rupicapra rupicapra*, and to a lesser extent *Capra pyrenaica, Capreolus capreolus, Rangifer tarandus*, and *Equus ferus* (Altuna et al., 2017; Altuna & Mariezkurrena, 2020). There is a scarce representation of carnivores. The tooth studied was sampled at the Gordailua Center for Heritage Collections of the Provincial Council of Gipuzkoa.

**El Otero (Secadura, Voto, Cantabria)**

El Otero cave is located in Secadura (Voto) (43.3565; -3.5360), at 129 m.s.a.l and 12 km straight from the present-day coastline. Near the Matienzo valley in a coastal plain environment covered by meadows and gentle hills. The discovery was made in 1908 by Lorenzo Sierra. The site was excavated in 1963 by J. Gonzalez Echegaray and M.A. García Guinea, in two different sectors (Sala I and Sala II) with an equivalent stratigraphic sequence (González Echegaray, 1966). A total of nine levels were identified in Sala I, from level IX to level I. Levels IX and VIII were originally related to the “Aurignacian-Mousterian, based on lithics assemblages with a combination of both technocomplex features. The overlying levels VI-IV were separated by a speleothem crust (level VII) and were initially related to Aurignacian, due to the presence of end-scrappers, bone points, blades, or burins on truncation (Freeman, 1964; Rios-Garaizar, 2013). Also, perforated deer, ibex, and fox teeth were found in levels V and IV. This site lacked chronological dating methods, until a selection of material from levels VI, V and IV revealed a difference chrono-cultural attribution (Marín-Arroyo et al., 2018). Radiocarbon results yielded younger dates for such a cultural attribution and show significant stratigraphic inconsistency. Level VI gave a result of 12,415±55 (OxA-32585), two dates in Level V are 12,340±55 (OxA-32509) and 10,585±50 (OxA-32510) and a date in Level IV is 15,990±80 (OxA-32508). All these results fall into the range of the Late Upper Paleolithic (Magdalenian-Azilian initially identified in levels III-I), eliminating attribution of these levels to the Aurignacian, despite the presence of apparently characteristic artefacts.

Red deer dominate the assemblage, except for level IV where horses are more abundant. Wild boar, roe deer, and ibex are also present, but large bovids are relatively rare (González Echegaray, 1966). Level IV is the richest and most anthropogenic level, with evidence of butchering in red deer (captured in winter and early summer) and chamois (in autumn) The formation of this level involved humans and carnivores, and although certain data may suggest an anthropogenic predominance, the limited sample analyzed taphonomically and the pre-selection of preserved pieces do not allow for a definitive conclusion (Yravedra & Gómez-Castanedo, 2010). The material included in this work is curated at the Museo de Prehistoria y Arqueología de Cantabria (MUPAC, Santander).

**A.2 MEDITERRANEAN SITES**

**Terrasses de la Riera dels Canyars (Gavà, Barcelona, Cataluña)**

Terrasses de la Riera dels Canyars (henceforth, Canyars) is an open-air site located near Gavà (Barcelona) (41.2961;1.9797), at 28 m.s.a.l and 3 km straight from the present-day coastline. The site lies on a fluvial terrace at the confluence of Riera dels Canyars, a torrential stream between Garraf Massif, Llobregat delta and Riera de Can Llong (Daura et al., 2013). Archaeo-paleontological remains were discovered during quarries activities in 2005 and was complete excavated on 2007 by the *Grup de Recerca del Quaternari* (Daura and Sanz, 2006; Daura et al., 2013). This intervention determined nine lithological units. The paleontological and archaeological remains come exclusively from one unit, the middle luthitic unit (MLU), and specifically from layer I. The MLU is composed of coarse sandy clays and gravels, filling a paleochannel network named lower detrital unit (LDU) (Daura et al., 2013). Five radiocarbon dates were obtained on charcoals from layer I, which yield statistically consistent ages from 33,800 ±350 uncal BP to 34,900 ±340 uncal BP, which results in mean age of 39,600 cal BP (from 37,405 to 40,916 cal BP) (Daura et al., 2013).

The layer I of the site has yielded a rich faunal assemblage, consisting of over 5,000 remains. Among the herbivores, the most common species found are *Equus ferus*, *Bos primigenius, Equus hydruntinus*, and *Cervus elaphus* (Daura et al., 2013; Sanz-Royo et al., 2020). *Capra* sp. and *Sus scrofa are* also present, although in lower frequencies. The carnivores found at the site are also noteworthy, with *Crocuta crocuta* and *Lynx pardinus* being the most frequent. Presence of cold-adapted fauna associated to stepped environments is recorded, such as cf. *Mammuthus* sp., *Coelodonta antiquitatis*, and *Equus hydruntinus*. Small mammal analysis, pollen, and use-wear analysis have provided further evidence that a steppe-dominated landscape surrounded the Canyars site, supporting a correlation with the Heinrich Event 4, in coherence with the chronology obtained for the layer (López-García et al. 2013; 2023; Rivals et al., 2017). However, the presence of woodland is also attested by forest taxa within charcoal and pollen assemblages (Daura et al., 2013).

Taphonomic study is ongoing. But several evidences point that hyenas have played an important role in the accumulation of the faunal assemblage (Daura et al., 2013; Jimenez et al. 2019). However, sporadic human presence is documented by few human modifications found in faunal remains (cutmarks and fire alterations). Although the paucity of the lithic assemblage in the site, it shows a clear attribution to Upper Palaeolithic technocomplex, most likely the Early Aurignacian (Daura et al., 2013). Recently, it was documented a perforated bone fragment, which has been identified as a perforated board for leather production (Doyon et al., 2023). All teeth included in this work were sampled in *Laboratori de la Guixera* (Ajuntament de Casteldefels) where the material is stored.

**Complementary information**

Detailed information on dates in Appendix B and Figure 1; sites’ locations are in Figure 2.

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