

# Gold-bearing Plio-Quaternary deposits: Insights from airborne LiDAR technology into the landscape evolution during the early Roman mining works in north-west Spain

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## ABSTRACT

This article focuses on the characterization of auriferous deposits, identification of hitherto unknown Roman mining infrastructure remains, and the early attempts of exploitation carried out in north-west Iberia. The research has combined airborne laser scanning (LiDAR) and field prospection to explore the geomorphological signature and landscape transformation resulting from Roman mining works in two unknown sectors of the western Duero Meseta. The integration of geological and remote sensing information contributed to extend the Roman's mining domains, traditionally focused on the river headwaters of the north-west. The article explores the complex hydraulic system developed in the Jamuz and lower sector of the Eria river valleys, as well as the evidence of open-cast mining and their relationship with the Roman army. The results suggest that the highly dispersed and reduced dimensions of the mining sites correspond to a selected method of gold prospection, employed for the identification of viable exploitation sectors. Thus, the initiation of the mining works could have started in the Jamuz valley and developed systematically in this area, to subsequently spread towards the up-stream sectors and nearby valleys. This research contributes to gain new insights into the extension and complexity of the mining infrastructure, indicating the importance of the gold-bearing raña deposits within the framework of Roman gold mining in north-west Spain.

## 1. Introduction

The north-west Iberian Peninsula contains a great variety of ore deposits, including gold, that were exploited since the ancient times (e.g. Fernández-Lozano, 2017). The early extraction works carried out by the pre-Roman settlers consisted of straightforward procedures based on panning free gold in river placers and other secondary occurrences (Sánchez-Palencia et al., 2018). The presence of auriferous deposits in north-western Iberia represented a major attraction for the Roman coinage production and contributed to this region becoming part of the Empire after the end of the Cantabrian Wars (19 BCE). The control and pacification of the auriferous territories led to the systematic exploitation of gold deposits in this area, which began in the early 1st AD century, under the direct control of the Roman State. Mining works were active until the 3rd century, when a strong political and economic crisis struck the Empire (Domergue, 1990; Sánchez-Palencia, 2000), a crisis that was enhanced by sudden climate changes (e.g. McCormick et al., 2012).

The Roman occupation contributed to a deep transformation of the territory, intensifying the exploitation and administration of the gold mines in north-west Iberia (Fig. 1A). These changes caused a strong impact on the landscape and social structures (Orejas-Saco, 1996; Sánchez-Palencia et al., 2006). It has been argued that such an intense landscape transformation has been the result of the imperative need for crop and tree cultivation together with the extensive impact provoked by mining activity (González-Gutiérrez, 1999; López-Merino et al., 2010, 2011; Reher et al., 2012; Hillman et al., 2017). Thus, the early stages of the Roman gold-rush may have had an important effect on the local economy. The early establishment of mining settlements in the area, characterised by a common pattern of semi-circular shaped

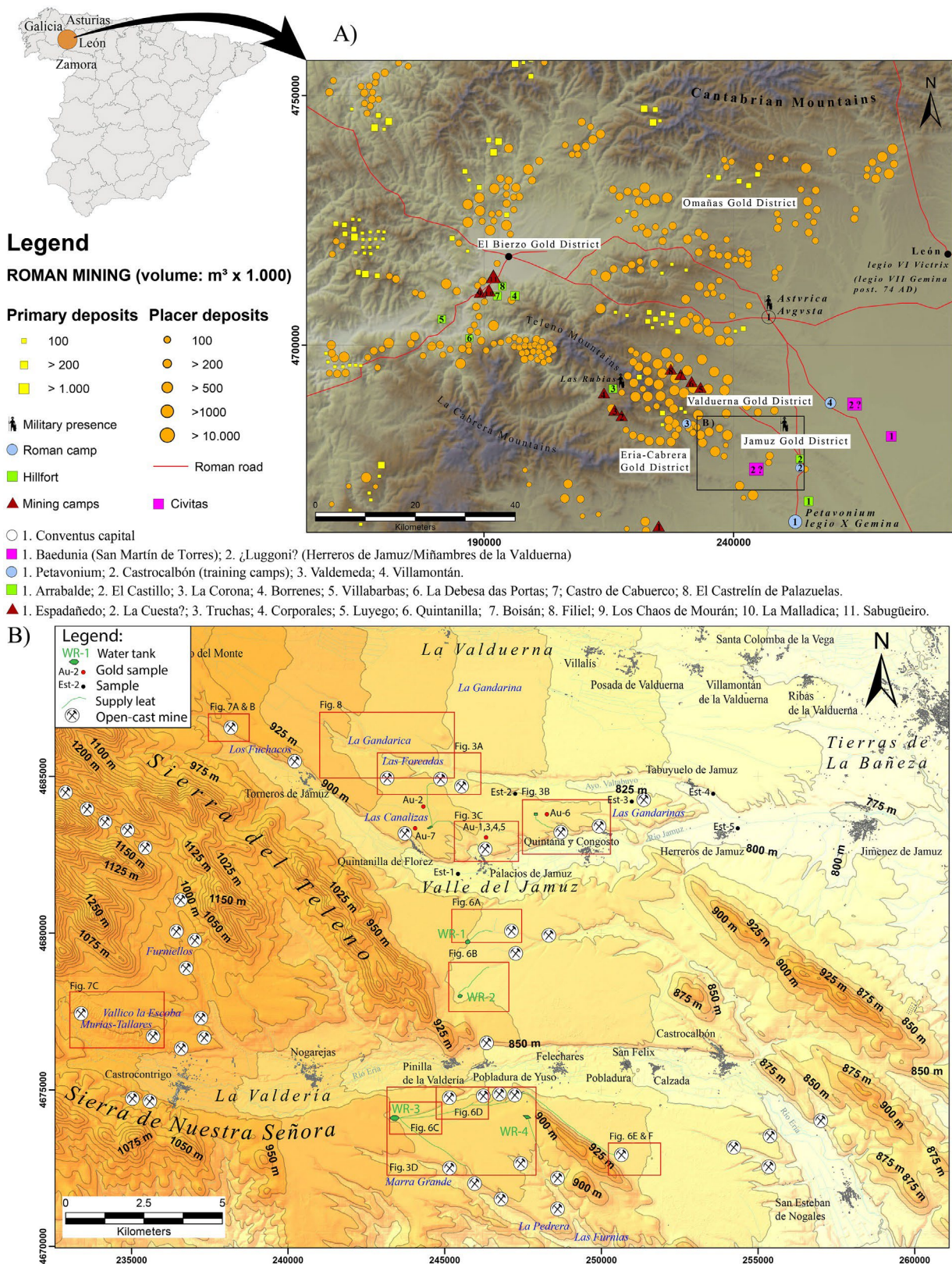


Fig. 1. General map of the study area and location of the gold samples shown in Fig. 4. A) Distribution of auriferous Roman works in north-west Spain both primary and secondary occurrences based on Pérez-García et al. (2000) and Fernández-Lozano et al. (2015). B) Distribution of the main mining sites across the Jamuz and the lower sector of the Eria river valley.

settlements protected with ditches —like the Quintanilla, Truchas, Boisan or Espadañedo examples (Esparza-Arroyo, 1983; Sánchez-Palencia, 1986; Currás-Refojos et al., 2012)—, suggests the importance that maintenance tasks and control of the main mines had in the *con-ventus Asturum*.

A notable effort has been made in the last 40 years to study the complex mining infrastructure developed in north-west Iberia (Sáenz-Ridruéjo and Vélez-González, 1974; Domergue and Hérail, 1978; Fernández-Posse and Sánchez-Palencia, 1988). Although major attention has been paid to the Las Médulas and Valduerna mining sites (Domergue, 1990; Sánchez-Palencia, 2000; Matías-Rodríguez, 2006), recent advances in LiDAR technology and UAV-derived DEMs have provided new findings in nearby areas, such as the Eria gold district and the Teleno mountains



(Fernández-Lozano et al., 2015, 2018; Fernández-Lozano and Gutiérrez-Alonso, 2016; Matías-Rodríguez and Llamas, 2018). Previous studies based on the scarce archaeological evidences in the area (Domergue and Sillières, 1977; Bird et al., 1984) suggest that Roman gold mining was initially developed in the Valduerna area. Unfortunately, there is little known about the Roman works carried out in the Jamuz valley and the nearby lower sector of the Eria gold district. During the past decades, agriculture and farming activities have modified the landscape leading to a poor conservation or loss of most of the mining remains. Moreover, the progressive destruction of the hydrographic network has hindered the investigation of the mining landscape. Besides that, the absence of archaeological remains and other epigraphic and literary sources does not allow the precise reconstruction of the Roman occupation in the area.

However, the geological and geomorphological analysis of mining landscapes may help to constrain and describe the style and extension of mining works in the region as well as to gain insights into the evolution of exploitation works. This article aims at: a) characterising the gold-bearing Plio-Quaternary *raña* deposits; b) identifying the mining infrastructure by application of visual enhancement techniques and tools to airborne LiDAR data; c) testing prospection works based on gold panning to identify mining sites and d) recognizing geomorphological features related to mining activity. This integrated approach was carried out in the south-west province of León, across the Jamuz and lower sector of the Eria river valleys (Fig. 1B). The results based on the geological prospection and remote sensing technology provide new insights into the Roman mining procedures used for exploration of ore deposits, adding new perspectives to the framework of the Roman gold mining in north-west Spain.

## 2. The gold-bearing Plio-Quaternary deposits of the western Duero basin

The term '*raña*', coined by Gómez de Llerena (1916), describes the peneplain surfaces located at the foothills of the Montes de Toledo and Extremadura mountain ranges—cored in the folded Ordovician Armorican Quartzite—. *Raños* represent, in fact, large alluvial fans resulting from the coalescence of individual fans developed in the transitional areas between these mountain ranges and the adjacent plains during the Plio-Pleistocene (Pérez-González, 1979). This type of sedimentary deposit is ubiquitous in the major basins of Iberia (Spain and Portugal), and is often found flanking their borders over Palaeozoic and Cenozoic bedrocks (Pereira, 2006; De Vicente and Muñoz-Martín, 2013).

The '*raña* deposits' can be identified in the landscape by the presence of a piedmont developed next to the main reliefs. They are characterised by gentle slopes (< 5%), with incised valleys and plateau morphologies constituted by coarse detrital materials mixed with a red, sandy-clayey matrix and abundant presence of weathered "black" and iron-coated pebbles (Espejo, 1988). The origin of these pebbles has been related to edaphic and hydromorphic processes that occurred in the *raña* under semi-arid conditions and rapid water-table oscillations (Martín-Serrano and Nozal-Martín, 2009). In fact, this rubefaction process has been often linked to the presence of gold (Pérez-González and Gallardo, 1987; Perea-Caveda and Sánchez-Palencia, 1995; Pérez-García and Sánchez-Palencia, 2000; Fernández-Lozano et al., 2016).

The *raña* deposits mostly occur in the westernmost areas of the Duero Basin between 800 and 1200 m a.s.l. (Fig. 2). They are the result of the profound erosion of the mountain reliefs constituted by the Teleno range, which feeds, to the south, the piedmonts of the Eria, Valduerna and Jamuz valleys. *Raña* deposits constitute an important source of secondary gold deposits (placer). These sedimentary ore deposits result from the erosion and concentration of gold derived from the bedrock through two different geological processes: i) by fluvial transport; and ii) by rubefaction or laterization processes that affected these sediments and were responsible for their reddening (Perea-Caveda and Sánchez-Palencia, 1995; Pérez-García, 1977; Pérez-García and Sánchez-Palencia, 1992; Pérez-García et al., 2000; Ballesteros and Martín, 2002; Fernández-Lozano et al., 2016). Research carried out on similar deposits in the nearby valleys revealed gold grades amid 80–115 mg/m<sup>3</sup>. A similar case happens in the Cenozoic sediments of the Eria and Valduerna gold mining districts, especially in the lowermost part of the alluvial deposits, where ca. 85% of the total gold is concentrated (IGME, 1982; Pérez-García, 1991; Pérez-García et al., 2000).

## 3. Roman mining works

### 3.1. Hydraulic system

The hydraulic infrastructure established in north-west Spain during the Roman Imperial period comprises a series of channels and water tanks designed to supply water to the main mining sites (this work follows the terminology by Lewis and Jones, 1970; Jones and Bird, 1972, and Burnham, 1997). This sophisticated engineering work outlines > 600 km of channels widely spread over the mountainous territory of the Galaico-Leonese Mountains. The largest structure, built to supply water to the Las Médulas gold mine, exceeds 140 km (Pérez-García and Sánchez-Palencia, 2000; Matías-Rodríguez, 2006).

Channels were built directly over rock and their dimensions were adapted to the slope roughness. Dry stonewalls and wooden aqueducts were built over irregular substrate to get across the uneven terrain (Pérez-García et al., 2000; Pérez-García and Sánchez-Palencia, 2000; Domergue, 2012). Channel width varies between 1.2 and 1.5 m and discharge can be estimated in 0.2–0.7 m<sup>3</sup>/s, considering a water depth of 0.4–0.6 m (Lewis and Jones, 1970; López, 1980; Sánchez-Palencia, 1980; Matías-Rodríguez, 2006). In addition, several authors observed the distinctive slope differences along the trace of the canals, where average slope would not exceed 0.5–1.2% according to detailed studies carried out in different sectors of the province of León (Sáenz-Ridruejo and Vélez-González, 1974; Fernández-Posse and Sánchez-Palencia, 1988; Pérez-García and Sánchez-Palencia, 2000; Matías-Rodríguez, 2006; Fernández-Lozano et al., 2018).

Water tanks were important features in mountainous areas, where the water accessibility is reduced during most of the year. However, as we will point out below, they also played an important role in the large and remote plateau areas characterised by the presence of gold-bearing *raña* deposits. The distribution of water tanks in the Teleno Mountains and surrounding areas is similar to that observed in other *raña* deposits exploited in south-east Spain, where water was a very scarce resource (García-Pulido, 2009). Over these surfaces, the collection of water was dominated by the presence of springs or eventual raining periods (dew-ponds) and, when possible, by river captures and derivations.

### 3.2. Mining infrastructure in sedimentary gold placers

Roman gold mines caused a strong impact on the territory. Labours are sparse over Pleistocene sedimentary successions, whereas they tend to be grouped in the bedrock. Vertical changes in gold grade observed in placer deposits required a prospection solution to achieve profitable



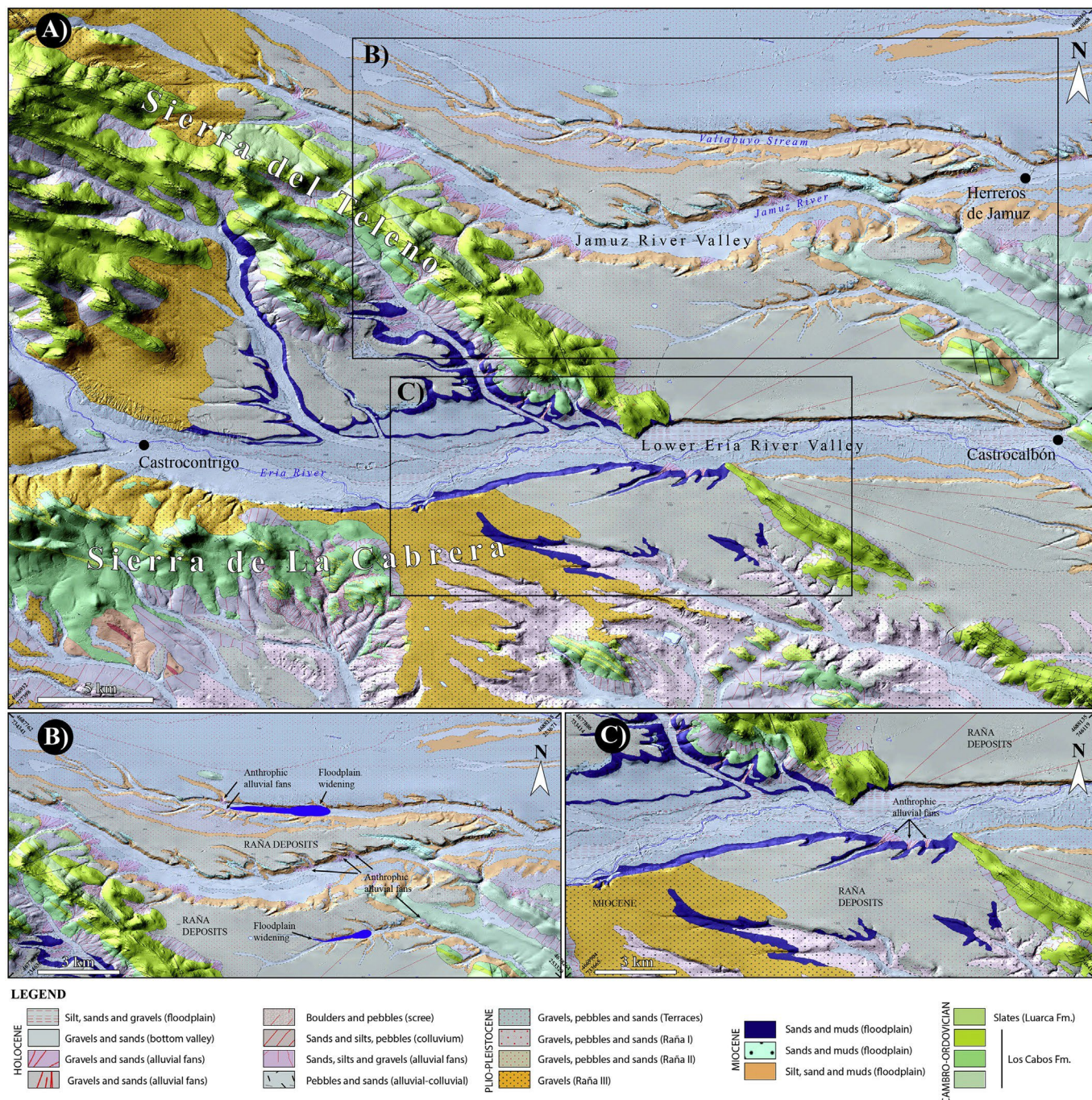


Fig. 2. A) Geomorphological map of the study area (modified after [Geode, 2018](#)). Insets illustrating the detailed geomorphological features used in this work within the Jamuz (B) and lower sector of the Eria river valleys (C). Fluvial landforms are hidden by the development of alluvial fan deposits. It is worth noting the presence of alluvial fans confining the lower part of some of the valleys.

mining. Thus, whereas primary deposits were exploited through ground-sluing, ditches, shafts and levels, there existed a wide variety of methods that the Romans applied to auriferous placers. Three different mechanisms depending on the thickness of the sedimentary deposit ([Domergue and Hérail, 1978](#)) and the mining method ([Pérez-García, 1977](#)) have been proposed in the literature for exploitation of placer deposits in Roman times: i) *hydraulicking* is the system that induced mass movements employed the *Ruina Montium (arrugia)* method when sedimentary thickness exceeded 30–100 m ([Sánchez-Palencia, 1983](#); [Pérez-García et al., 2000](#); [Bird, 2004](#)). Recent studies suggest that water and snow-melt water tanks were used to crumble the mountains by the gravitational action of water, a method more common than it was previously thought ([Fernández-Lozano and Andrés-Bercianos, 2018](#)); ii) *Ground-sluing* is the method that uses a continuous source of water to dismantle sedimentary debris (< 30 m) and iii) *hushing* is based on the use of large amounts of water collected from water tanks and leats, in a similar way as in other gold mines such as Dolaucothi in Britain ([Lewis and Jones, 1970](#); [Domergue and Hérail, 1978](#); [Burnham, 1997](#)). The spoil heaps produced during the hydraulic mining, called *murias*, are still recognizable as areas covered with quartzite boulders over the landscape.

#### 4. Material and methods

##### 4.1. Airborne LiDAR technology and principal components analysis



Airborne LiDAR technology has become increasingly used in the field of archaeology in the past years (Bewley et al., 2005; Crutchley and Crow, 2010; Chase et al., 2011). Also known as Light Detection and Ranging, LiDAR represents a suitable technology to acquire topographic information in remote or densely vegetated areas. Besides, it provides precise and reliable clouds of points representing the heights of the terrain surface in a fast and accurate mode. It is arguably that the most useful feature of LiDAR is the possibility of obtaining a complete surface visualization under vegetated areas and the generation of high-resolution digital terrain and surface models. The main difference between Digital Terrain Models (DTMs) and Digital Surface Models (DSMs) is the representation or not of elements situated over the ground, i.e. houses, trees (Hofton et al., 2002; Brovelli et al., 2004).

This rapidly evolving technology is often complemented with remote sensing methods for the identification and description of archaeological elements. However, it is important to bear in mind that the statistical analysis and filtering operations carried out for the generation and enhancement of maps, often assumes important scaling variations. As Bennett et al. (2012) argued, although the processed DTM models allow the feature recognition, visualization techniques, commonly based on shaded relief models, local relief or sky view factor modelling, cause metric geospatial shift of these features. In spite of these minor shifts, the relief visualization techniques have successfully helped researches to identify archaeological elements and it is widely used for such purpose (Zakšek et al., 2011; Štular et al., 2012; Doneus, 2013; Sánchez-Palencia and Currás-Refojos, 2015; Fernández-Lozano and Gutiérrez-Alonso, 2016).

Recent studies using a combination of Aerial Laser Scanning technology (ALS) and relief visualization techniques have shown the improvements in the recognition and description of the Roman gold-mining infrastructure in north-west Spain (Fernández-Lozano et al., 2015; Fernández-Lozano and Gutiérrez-Alonso, 2016). The analytical processing of LiDAR-derived DEMs highlights the topographic features of the mining landscape, which comprises leats and water tanks. Even the processing of low-resolution DEMs (i.e. 5 m interpolation) provides an important improvement, sharpening minor topographic variations caused by leat destruction or anthropic modification of the ground (Fernández-Lozano and Gutiérrez-Alonso, 2016). LiDAR image processing techniques can produce a large number of derived images that can be reduced to a limited number of suitable figures for interpretation by means of the principal component analysis techniques. We have implemented the LiDAR DTMs by using three different visualization methods: Sky-View Factor, Multihillshading and Simple Local Relief Model (SLRM) functions (Fig. 3). Visualization techniques improve the identification and description of a wide variety of archaeological remains. In the north-west of Spain, this approach has been used in the past years to document and relate different settlements with the presence of the Roman army (Sánchez-Palencia and Currás-Refojos, 2015; Costa-García and Casal-García, 2015; Costa-García and Fonte, 2017; Vidal-Encinas et al., 2018). Moreover, the potential for the analysis and identification of the Roman hydraulic system and mines, due to their important imprint left on the landscape, has provided great improvements in prospection works and detailed mapping of these archaeological remains (Fernández-Lozano and Gutiérrez-Alonso, 2016).

In this study, we first performed a 0.5 m interpolated mesh based on LiDAR point clouds provided by the Spanish Instituto Geográfico Nacional (IGN at [www.ign.es](http://www.ign.es)). Data were filtered to remove vegetation and housing for the generation of reliable DTMs. The acquisition of high-resolution models allowed the processing with relief visualization techniques to identify the dispersed hydraulic system and mining infrastructure of different sectors of the Jamuz and lower Eria river valleys. The identified mining sectors, where geomorphological changes were observed on the processed DTMs, were prospected by panning for the extraction of gold that confirmed the potential presence of mining works in the area.

#### 4.2. Gold prospection works and geomorphological analysis

Once the interpretation of processed LiDAR DTMs was carried out, we performed a series of prospection works to sample the auriferous material. Prospection tasks consisted in panning the *raña* deposits and a few samples from the Jamuz river sands, where no known previous prospection works existed. In the Eria valley, data was obtained from previous prospection studies carried out in the area by the Spanish Geological Survey and gold mining companies (IGME, 1982; Pérez-García, 1991). Ancient prospection works are interpreted to have consisted in the identification of gold positives along the river, in the *raña* sediments and riverbeds, searching for the location of the main gold ores, close to the primary deposits. This technique is similar to that used by present-day mining companies (Pérez-García and Sánchez-Palencia, 2000; Sánchez-Palencia et al., 2018), and allows the identification of deposits that are potentially most viable for exploitation: the higher the gold grade, the higher the possibilities for exploitation. Thus, during the Roman times, the finding of high-gold grade areas led to the development of large mining sectors such as those found in the upper sector of the Eria and the Valduerna gold districts (Sáenz-Ridruejo and Vélez-González, 1974; Domergue and Hérail, 1978; Sánchez-Palencia, 1980; Fernández-Lozano et al., 2015).

A total of 12 samples covering the *raña* deposit of the Jamuz valley, over 300 kg, were panned in the river (see location in Fig. 1B): 7 samples provided small gold particles (Au-1 to 7), whereas no gold was found in the other 5 (Est-1 to 5). Gold particles were observed on a binocular magnifying glass to determine shape and size. Most of the samples present rounded morphologies between 0.2 and 1.5 mm (Fig. 4). Additionally, the areas where gold was found were geomorphologically analysed using both DTMs and fieldwork. Observations consisted in the definition of mining geometries, dump deposits and erosion patterns and aggradation effects suffered by the drainage network. The latter provides a remarkable clue to the presence of mining works in the area. In general, the studied valleys are characterised by ephemeral or inactive streams with wide flood plains when compared to larger river floodplains in the region. The increased size of the floodplains suggests that they could have been intentionally flooded during the mining works. So far, archaeological works carried out in the western Duero Basin have paid little attention to geomorphological changes in drainage system (Pérez-García, 1977; Domergue and Hérail, 1978; Perea-Caveda and Sánchez-Palencia, 1995; Pérez-García et al., 2000), which have been investigated in this work.

### 5. Results

The south westernmost auriferous deposits of the province of León represent a complex system of mining infrastructure developed over a large area affecting the shallow *raña* sediments, which rarely exceeds 15 m in thickness (Fig. 5). In the Jamuz and lower Eria river valleys, *raña* deposits are characterised by the presence of truncated erosive surfaces overlying the Miocene red argillites, although in some sectors, they unconformably overlay the Palaeozoic low-grade metamorphic basement, which comprises quartzites and slates of the Cambrian-Ordovician Los Cabos Fm. Towards the south-west, near the Eria river valley, the Palaeozoic is located at ca. 100 m depth, and the Miocene argillites reach a total thickness of ca. 80 m (De Mingo, 1987). The overlying continental *raña* deposits comprise heterometric red fanglomerates with quartz to quartzite gravel within a sandy-clayey matrix. It is characterised by the presence of black and red pebbles indicating a strong subsurface alteration under dry conditions. The upper level often comprises a well-developed brown soil. In general, palaeocurrents show W-NW (N150°) SW directions, which are interpreted to indicate the

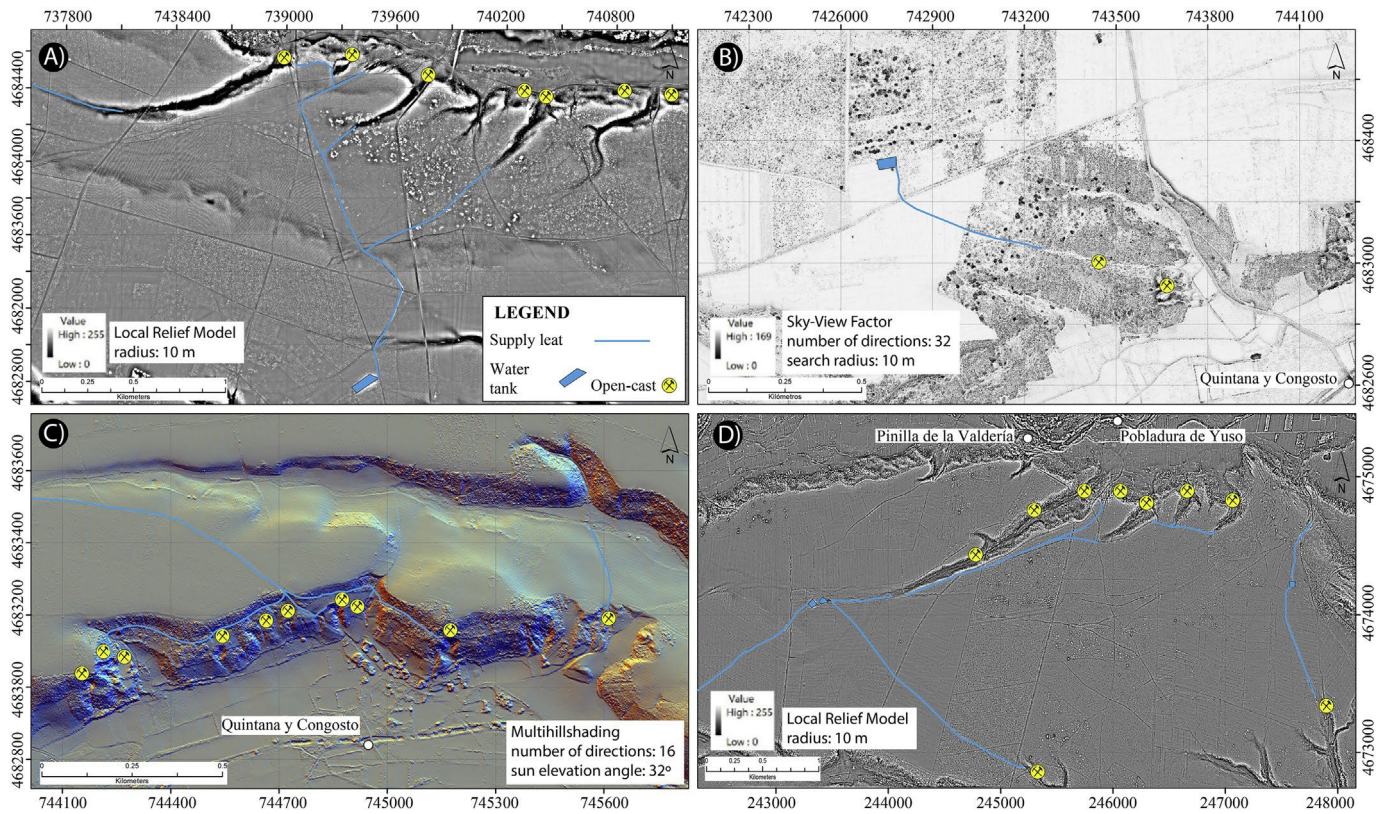


Fig. 3. Image enhancement components calculated after filtering and processing airborne LiDAR data from different sectors of the Jamuz (A, B and C) and Eria (D) river valleys.

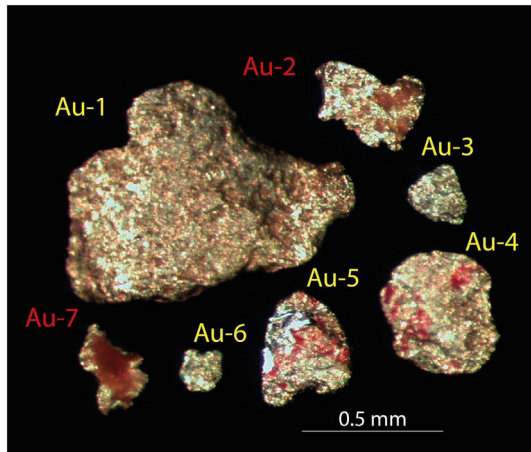


Fig. 4. Different gold particles obtained during the panning works that were carried out over 300 kg of sediments, and performed at the main mining sites. Size and geometry (i.e. roundness) vary from one particle to another, suggesting its secondary origin (Au-2, Au-7). See Fig. 1 for sample location.

location of the source area. Hence, the formation of the *raña* piedmont is directly related to the mountain front uplift and erosion of the Sierra del Teleno (Fig.1). The Roman mining works developed over the *raña* deposits represent a series of open pits and a broad hydraulic network, used for ore deposit washing, and mainly consisting of supply leats and water tanks. Mining activity was responsible for the extensive impact observed in the adjacent valleys due to the intense erosion caused during sediment hushing.

In this work we have selected the most representative areas in order to illustrate the strength of the methods used to unravel and enlighten the different types of structures found in the Roman works studied in the *raña*. The different selected zones covering the relevant aspects to the studied mining framework are illustrated in Fig. 1.

### 5.1. Mining hydraulic complexes

The hydraulic network is scarcely preserved in the area. The intense anthropic activity and the presence of dense vegetation hinder the location of the supply leats and derivations. However, the hydraulic infrastructure remains can be identified at both the open-casts and the water tanks, which are often preserved on the landscape. Unlike nearby mountainous areas, where channels are preserved in the bedrock, the deposits were mostly destroyed in the *raña* sediments. There are two types of leats in the area: those used for filling the water reservoirs, or *corrugi* according to Pliny's *Naturalis Historia*, and supply leats or *emi-saria*, which carried the water to the main mining sites (Fig.6). The latter are best preserved in the area, because the distance between the water tanks and the mining sites is often small.



Water tanks are mostly preserved due to their dimensions (Fig. 6A). They represent the putative biggest tanks preserved in the north-west of Iberia, exceeding the hitherto largest La Horta water tank, located in Las Médulas gold district. Table 1 shows the water volumes of the main reservoirs described in the area. Although they have been subsequently modified, their connection to the main mining sites and the nearby spoil heaps reveals their presence since Roman times. They were used for the accumulation of water that was used for hushing the auriferous sediments. Water to fill the tanks was likely brought from rivers and natural springs from the nearby areas. In addition, their large dimensions suggest that they could have been active for long periods of time. Due to the broad extension of the *raña*, the distribution of water tanks shows a common pattern in both the Jamuz and lower Eria areas. The development of this method of exploitation, based on isolated water tanks connected to the mining sites, is common in large plateaus, where water is scarce. A similar method of exploitation is found in south-east Spain

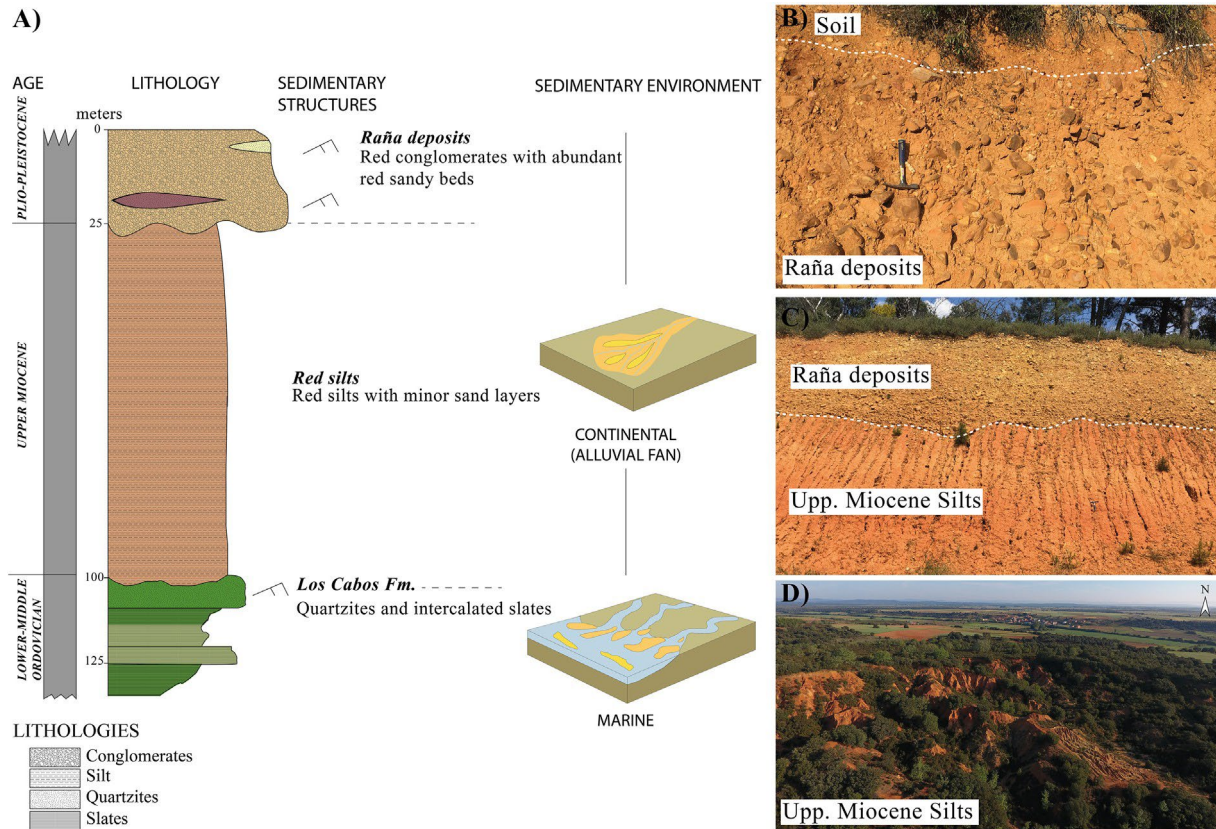


Fig. 5. Stratigraphic column of the Jamuz Valley. A) Development of a soil layer over the *raña* deposit. B) Erosive contact between the *raña* and underlying Miocene sediments. C) Panoramic view of the Jamuz *raña* deposit forefront. The Miocene argillites are affected by gullies, as a result of weathering processes.

(Baza-Los Filabres basin near the Ibero-Roman civitas Basti), reported by Strabo in the I a.C., although in that area, early works may trace back to the II BC. i.e. Republican period (García-Pulido, 2008, 2009). In general, they are closely related to the main mountain fronts and in clear connection with the valleys and juxtaposed streams, suggesting that ephemeral streams were flooded during the mining works. In addition, water reservoirs appear located close to the main mining sites. For instance, the gold mine of Los Fuchacos (Fig. 1B and 7), has a nearby water tank that supplied water for the hushing of the alluvial sediments.

## 5.2. Style and geometry of mining sites

One of the most significant features for the recognition and description of Roman mining infrastructure is the presence of geometric patterns, which are characteristic of a diversity of exploitation techniques. The results obtained in the areas described in the Jamuz and lower Eria sector comprise a series of open-cast mines represented by ground-sluicing and hush-like structures. It is worth noting that, in general, open-casts appear isolated and dispersed over a broad territory. Their dimensions are often limited by the available space and thickness of the *raña* deposits. Ditches rarely exceed a few meters deep. However, aggradation structures in valleys may extend to dozens of meters. In those areas where the *raña* deposits are > 10 m thick, hush-like structures are dominant; whereas where the auriferous sedimentary cover is thin (< 10 m), mining works were laterally extended to work as much surface as possible. This is the case of Los Fuchacos, a fan-like structure in the Jamuz area. As observed in Fig. 7A and B, the use of visual enhancement tools applied over the LiDAR-generated DTM images, improves the archaeological element visualization (i.e. location of a water tanks not seen from the oblique aerial image).

A prospection panning carried out over the *raña* occurrences provided an ore grade upon 32 mg/m<sup>3</sup>. This is a rather low gold grade compared to other similar deposits in the Valduerna and upper Eria sector, where grades, ranging from 80 to 115 mg/m<sup>3</sup> have been reported by recent prospection works (IGME, 1982; Pérez-García, 1991; Pérez-García et al., 2000; Fernández-Lozano and Gutiérrez-Alonso, 2017). The digital terrain model obtained from LiDAR data allowed the characterization of the exploitation volumes by using cut-and-fill algorithms. Therefore, for a mining sector, such as that shown in Fig. 7A and B, Los Fuchacos, the total amount of gold (using the above mentioned gold grade) obtained by the Romans was < 10 kg.

### 5.3. Geomorphological features

LiDAR data provide a useful picture of the significant impact of mining activity over the landscape. The close proximity of water tanks to the main valleys and their connection through a complex irrigation system define a systematic procedure for prospecting and mining based on ground-sluicing mining of the *raña* sediments. The distribution of a well-established natural fluvial network configuring a pinnated drainage over the *raña* plateau is juxtaposed to the mining hydraulic system, which in some areas, uses these river courses for recharging. Anthropogenic transformations have led to the establishment of a series of obsequent streams, where the river stream course runs opposite to the original slope of the land surface leading to a reversed drainage pattern (Fig. 3).

The presence of large flood plains in the area that cannot solely be explained by the presence of ephemeral streams, such as the Valtabuyo stream, is worth mentioning (Figs. 2 and 8). For instance, this stream is characterised by a longer than 300 m flood plain, similar to those present in the adjacent everlasting Eria river, which varies between 300 and 1.500 m in its widest part. Fig. 8 shows the presence of farming lands in the central part of the flood plain, indicating that the Valtabuyo



Fig. 6. Roman mining infrastructure comprising water tanks and supply leats in the Jamuz area (A and B); C) water tank, leat (D) and *murias* deposits (E, F) in the lower sector of the Eria river valley.

stream is mostly inactive ever since (i.e. a geomorphologically called underfit stream) We interpret the presence of such a wide flood plain in the Valtabuyo creek as the result of human-induced landscape modification caused by the nearby Roman gold mines. This is in agreement with the presence of unpaired terraces, usually linked to tectonic or anthropic activity. However, since no record of active tectonics has been identified in the *raña* deposits, the observed differences in terrace height are mostly due to anthropic activity related to gold mining activity.

Other geomorphological elements configure a landscape of undulated streambanks or structural banks that define a series of anthropic terraced surfaces caused by the parallel retreat of slopes during landscape denudation by lateral erosion of scarp slopes (Fig. 2). Minor valleys are characterised by the presence of headward erosion that produced lateral aggradation of the stream channel. In addition, the geomorphological interpretation of alluvial fans developed at the valley outlets suggests a strong relation to the gold mining works (Fig. 2). This is supported by the deep incision suffered by small valleys at the headwaters stream and the presence of spoil heap deposits, called *murias*, highlighting the location of the mining sites (Fig. 6D, E and F). Particularly interesting is the presence of anthropic funnel-like valleys attached to the structural benches of the *raña* hillsides. They were formed as a result of the ground-sluicing labours performed over the auriferous deposits. These typical gully-like morphologies, comprising minor wadis or coulees, suggest an ephemeral stream channel, like those formed in arid regions. Usually, they comprise a rounded and open surface upwards, narrowing towards the lower part of the hillside, where the fine material would have been channelled for an eventual extraction of gold.

## 6. Discussion

Remains of Roman gold mining are broadly represented in NW Spain, which holds some of the major gold occurrences in Europe: Las Médulas



Table 1  
Size and volumes of the study water tanks. See Fig. 1 for location.

Name	Perimeter (m)	Surface (m2)	Diameter (m)	Depth (m)	Volume (m3)
La Laguna (WR-1)	400	12,900	130	2.5	32,250
La Panera (WR-2)	270	6118	81	2.5	15,295
La Sopera I (WR-3)	200	2900	62	2.5	7250
La Sopera II (WR-3)	130	1424	47	2.5	3560
La Cigüeña (WR-4)	130	1429	40	2.5	3572.5

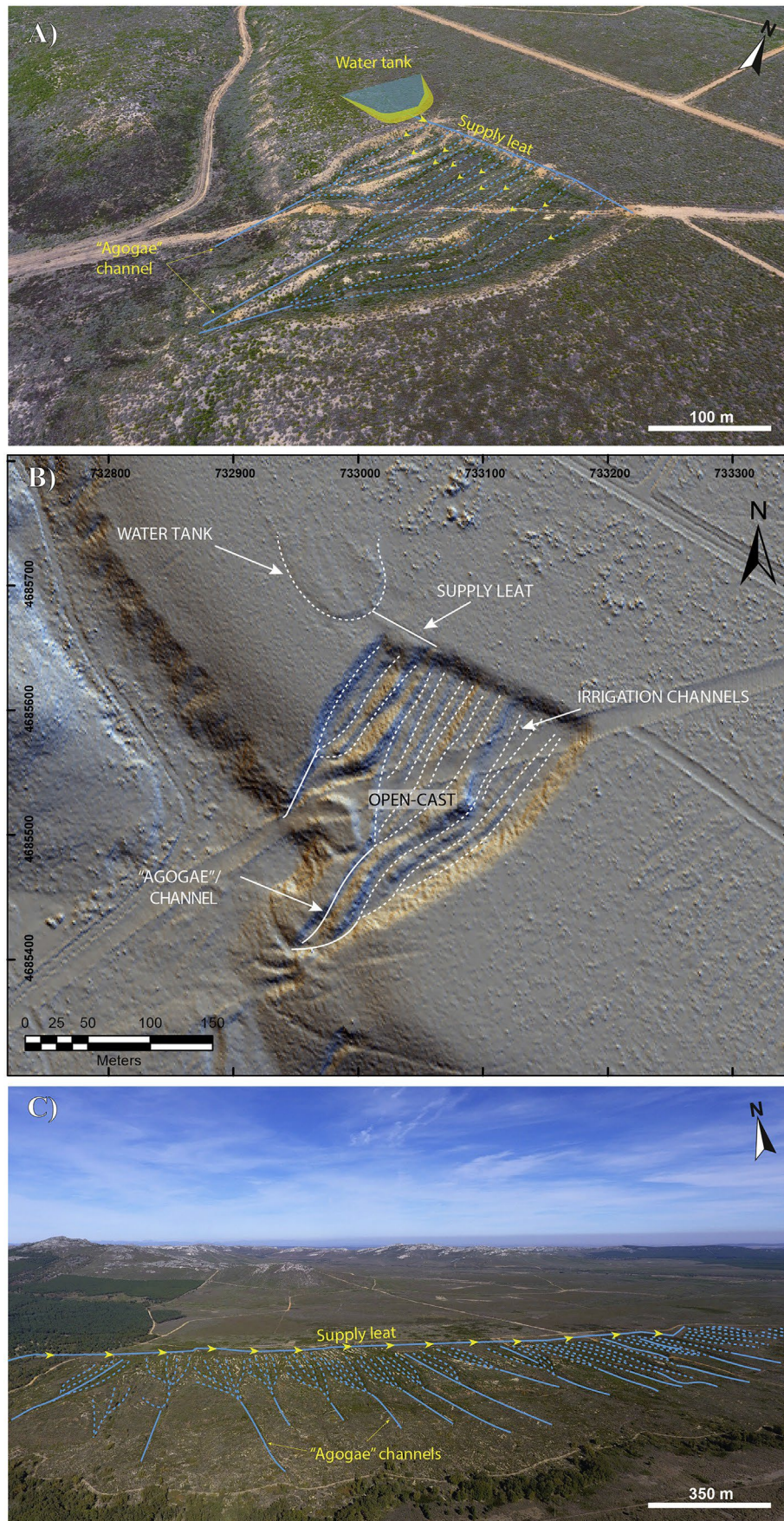


Fig. 7. Large size variations observed among the Los Fuchacos mine in the Jamuz area and the upper sector of the Eria district at Las Murias-Tallares mining site. A) Small-scale open-cast at Los Fuchacos site ( $\approx 200$  m). B) Multihillshading digital terrain model obtained from LiDAR data showing the main mining infrastructure and C) large-scale mining works carried out in the upper sector of the Eria river valley at Las Murias-Tallares gold mine (4.7 km long). See Fig. 1 for location.



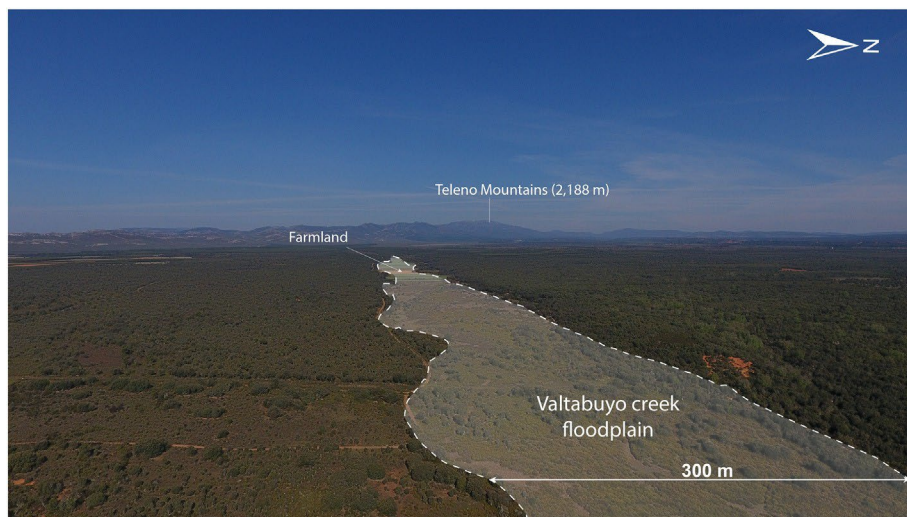


Fig. 8. Oblique aerial image of the Valtabuyo stream, showing the large alluvial floodplain formed by the Roman mining activity (> 300 m), and indicating the abundant amount of water that should have drained the area to give rise to such a valley extent. Nowadays the headwater area is turned into farmland, indicating the absence of seasonal streams. See the text for further explanation.

and Sánchez-Palencia, 1988; Fernández-Lozano et al., 2015; Fernández-Lozano and Gutiérrez-Alonso, 2016; Matías-Rodríguez and Llamas, 2018; Fernández-Lozano et al., 2018) and Valduerna gold districts (Domergue and Hèrail, 1978; Domergue, 1990). However, little is known about the mining activity carried out by the Roman Empire in the nearby Jamuz and lower sector of the Eria valleys.

The gold mining infrastructure established on these sectors, as shown in this work, consist in the development, on the *raña* deposits, in a precise system of irrigation represented by water leats that connect the tanks to the mining sites. The establishment of this irrigation system—which is certainly different from other valleys where supply leats are more relevant—, lies on the large dimensions acquired by the *raña* deposits, together with the reduced amount of water available from nearby ephemeral rivers and streams, which forced the construction of an extensive network of water tanks. The identification of Roman's infrastructure has been improved by the combination of airborne LiDAR technology and image enhancement techniques and tools. Both methods provide good results for the identification of ancient mining elements (Hesse, 2010; Bennett et al., 2012; Lasaponara and Masini, 2012; Fernández-Lozano and Gutiérrez-Alonso, 2016), although the spatial resolution and the eventual landscape transformation by anthropic activity reduce their applicability.

Despite the important contribution of the geological knowledge to the identification of gold ore deposits, little attention has been paid to understanding its weight on the Roman's mining legacy. Previous studies argued that Cenozoic auriferous deposits in the north-west are mostly confined to ancient river terraces, Miocene in age (Pérez-García, 1977; Hèrail, 1984; Pérez-García et al., 2000). However, the sediments that configure the proximal alluvial fan deposits of the Jamuz and Eria represent one of the best-preserved examples of Plio-Pleistocene *raña* deposits worked for gold extraction. These sediments display strong similarities with others located in the western Duero Basin (Zamora and Salamanca, El Bierzo), such as the presence of ferruginous and black pebbles, well-sorted soils and a well-developed drainage system, (Martín-Serrano, 1986; Heredia et al., 2015). The *raña* deposits comprise a series of alluvial fans, sourced from the Teleno Mountains, with W to NE directed palaeocurrents building up a wide plateau that rises over the Duero Basin.

Due to the broad extension of these sedimentary deposits and its reduced thickness, mining works were confined to the upper part of the *raña*. Prospection works based on gold panning indicate a low gold grade ( $\approx 32 \text{ mg/m}^3$ ). This is consistent with the little interest shown by the Roman Empire for the exploitation of this area, as well as the dispersion of the mining sites. In general, the bottom of the Miocene sedimentary deposits provides the highest gold grades (IGME, 1982; Pérez-García, 1991; Pérez-García et al., 2000). This is supported by the mining extension that comprises the upper sector of the Eria gold district at Los Tallares mining site (4.7 km and 168 ha) in comparison with the Los Fuchacos in the Jamuz area (200 m and 5.62 ha) (compare both sectors in Fig. 7). However, due to the nature of the *raña* deposits, which includes a particularly low gold grade and reduced thickness in the study area, Romans had to establish a methodology based on isolated prospection works. Thus, both the geometry and style of the mining works seems controlled by the thickness and the gold grade oscillations. In the light of the above, these factors can explain the high dispersion of open-casts and the differences in mining style (i.e. from ground-slucing to hushing). This observation supports the idea suggested in previous studies that the widespread “mining sites” and their reduced dimensions mostly correspond to prospection works carried out before exploitation s.s. started (Pérez-García et al., 2000; Sánchez-Palencia, 2012). Conversely, the broad dimensions of the *raña* deposits involve a well-established hydraulic infrastructure. This is confirmed by the presence of large-scale water tanks and dew-ponds connected with valleys, where the main exploitation sites are located. The use of this irrigation system is well known in other areas with similar characteristics. For instance, in El Cabaco gold mines (Salamanca), Sánchez-Palencia (2012) and Ruiz del Árbol et al., 2014 suggest that nowadays these reservoirs could have also played an important role for the livestock watering.

Water drainage provoked a deep geomorphological impact on the *raña* deposits. The amplitude of the valleys developed by ephemeral streams does not correspond with that of the perennial rivers in the area. Thus, it is necessary to consider a permanent drainage caused by the long-term activity initiated during the mining works. As shown above, seasonal streams, such as the Valtabuyo stream, have also present-day farming activity on the flood plain, indicating the lack of natural drainage. The presence of mining spoil heaps (*murias*)—characteristics of Roman gold mining activity—within the valleys, confirms the large-scale impact of gold extraction over the *raña*. This method of exploitation caused backward erosion at the river headwaters, leading to the subsequent aggradation of the valley flood plains.

Notwithstanding the little amount of open-cast mining works compared to other nearby areas like the Valduerna gold district, the Jamuz and the lower sector of the Eria are established at 825 m of elevation, and they represent the lowermost mining infrastructure of the western Duero basin. As previously pointed out by Pérez-García and Sánchez-Palencia (2000) and Matías-Rodríguez (2006), Roman works commonly started in the lower sectors and subsequently moved up towards the mountains. This mechanism prevents the destruction of the upper mining sectors, facilitating a better management of the hydraulic resources.

Given the strong transformation of the landscape due to farming activity and the intense revegetation, it is difficult to identify the complete hydraulic network and mining infrastructure developed in the area. The lack of archaeological remains impeded further interpretations, but the use of geomorphological features provides new evidences that improve the knowledge and impact of the Roman gold mining activity in western Europe. It is important to remark that this activity caused a dramatic transformation in the north-west, which led to a profound economic change. According to López-Merino et al. (2010), the transformation did not only affect the lifestyles, but also the entire landscape as a result of the control of resources forced by the Roman's policy (Sánchez-Palencia, 2000). The construction of the hydraulic network and the intensive exploitation of resources had a deep impact in the reorganization of the territory (Ruiz del Árbol et al., 2000). The mining activity was developed thanks to the military control in the north-west after the consolidation of the *Pax Romana* by Augusto (27 BCE-14 CE).

In order to achieve this target, the Roman authorities deployed an important military contingent throughout the Spanish north-western area, which reached three legions and a significant number of auxiliary troops. Once the peace and control of these territories and their native population (Astures) was achieved, the army participated in early mining operations —mainly gold, but also other metals such as iron— (Palao-Vicente, 2017). The maintenance and mining work was carried out from the main mining camps with an indigenous occupation in the environment (Esparza-Arroyo, 1983; Sánchez-Palencia, 1986; Currás-Refojos et al., 2012).

Although territorial control must have varied according to the different areas and the opposition of their dwellers, different signs seem to indicate that it must have been gained more or less completely towards the end of Augustus' rule or in the early days of Tiberius' (Palao-Vicente, 2017). A series of changes in the distribution of the legions and *auxilia* in the region and the structural modifications that were carried out in camps seem to confirm this. These adjustments are proof of the permanent posting of troops whose primary mission was no longer to subjugate northern people. This period also yields the first data referring to large-scale mining development undertaken by Rome. Different studies frame the beginning of mining works in Valduerna in the year 15 C.E. (Domergue and Sillières, 1977; Domergue and Hérail, 1978; Bird et al., 1984; Sánchez-Palencia et al., 2006; Orejas-Saco et al., 2012; Sánchez-Palencia, 2012; Orejas-Saco and Sánchez-Palencia, 2016). The proximity of the gold mines of Jamuz valley to the former one, alongside the strong presence of Roman troops in the area in the early imperial period, could also suggest an early start of the exploitation of the Jamuz valley mining sites. Another argument in favour of this idea is the proliferation of hospitality pacts between Roman authorities and different communities in the area during Tiberius' rule. Such documents have been considered an evidence of the transformations in the organization and dealings of native people with Rome after the establishment of peace needed to start mining (Sastre-Prats et al., 2010).

It is reasonable to assume that the first activities carried out by the Roman troops must have been related to exploratory drilling in search of the most profitable veins and deposits, as well as to the immediate commencement of their exploitation. Part of the information would be obtained from the conquered and subjugated peoples, who had already been exploiting such deposits since earlier times. Another would be the result of the exploration activities undertaken by the Roman troops, under the guidance of their engineers and experts, in different areas. This stage would begin in the early days of Roman occupation, immediately after the consolidation of control over the lands. Camp locations or evidence of troops nearby or in the vicinity of mining regions would prove this relationship (Sánchez-Palencia and Currás-Refojos, 2015; Muñoz-Villarejo and Celis-Sánchez, 2016), although other possible roles that cannot be identified due to documentary weakness should not be ruled out (Hirt, 2010). The case of the deposits of the mining sectors of La Valduerna, Eria and the Jamuz valley confirm such association between the presence of troops and the beginning of mining activities. This is assumed to be the case of the camp of Valdemeda (Pozos, León), which has been linked to the waterworks required for mining (Sánchez-Palencia, 1986). Likewise, the Roman army's intervention in mines is not exclusively associated with camps. There is knowledge of small groups of soldiers who were displaced from their main units and accommodated in other types of establishments, as seems to be proved by the case of the Las Rubias site (Corporales, León, dated in the Julio-Claudian period) (Dieulafait et al., 2011). Epigraphic testimonies support this marked presence of soldiers in the area, probably carrying out mining-related functions among their possible responsibilities, in the initial years of the imperial period.

The maintenance and mining work was carried out from the main mining camps with an indigenous occupation (Esparza-Arroyo, 1983; Sánchez-Palencia, 1986; Currás-Refojos et al., 2012). However, as far as the relationship between mining sites and communities in the area is concerned, the available data do not allow a detailed analysis. Contrary to what has been found for other areas of the Leonese province and peninsular north-west (Sastre-Prats et al., 2010), there is no research available on settlements in the Jamuz area and their relationship with the described mining sites. Nevertheless, this handicap can be bridged by using the model of nearby areas for the Jamuz mining sector. We know that an administrative system structured around the *civitas* as an entity with administrative, political and economic functions, was implemented in the north-west after the Roman conquest. Such organization turned out to be an essential tool to control the territory and plan work in the mines, a role that the mentioned pacts of hospitality found in different mining areas seem to confirm (Sastre-Prats, 2010). To date, there is knowledge of the existence of two *civitates* in the area surrounding the Jamuz, as stated in the termini of Claudius' times of the *cohors IIII Gallorum* and *legio X Gemina* found in the vicinity of La Bañeza (Cortés-Bárcena, 2013) mentioning the *civitas* of the *Luggoni*, whose accurate location still remains unknown (although the localities of Herreros de Jamuz and Miñambres de la Valduerna have been suggested) and that of the *Baediunienses*, identified with present-day San Martín de Torres, in León (Fig. 1A). Both *civitates* must have played a key role in the territorial planning and exploitation of mining sites in the area, as can be observed in other mining regions (Orejas-Saco et al., 2012), although the data gap prevents any further development of such theory. Therefore, it is reasonable to assume that there were mining camps linked to these exploitations, as exemplified in the nearby Valduerna (Quintanilla, Boisán, Filiel, and Luyego) and Eria valley (Truchas, La Cuesta?, and Corporales) (Fig. 1A). However, it has not been possible to identify any of them. Future works on the area may perhaps reveal the location of such settlements associated with this type of mining exploitations.

Within this context, our findings suggest that the Jamuz and lower sector of the Eria river valleys could represent an important starting point for the establishment of a mining activity for the extraction of ore deposits. Therefore, data support that the initiation of the Roman gold mining works in the western Duero Meseta was probably located in this area, that was strongly controlled by the Roman military forces. These valleys represent a topographic plateau (*raña* deposits rarely exceed < 5% of slope), easy to access and well connected to the western mountainous region. At this point, mining works would have started in the Jamuz area, and were rapidly extended towards the nearby headwaters of the Eria and Valduerna Valleys, where a large amount of auriferous materials were dismantled. The observed pattern and dispersion of mining sites, together with the characteristics and style of exploitation labours, suggest that mining operations represented a group of small prospection open-casts that served for gold extraction. The technique implemented by the Roman miners aimed at the development of a complex mining system involved in the exploitation of similar geological deposits in other adjacent auriferous areas. These results confirm that the dense and complex mining infrastructure, established by the Roman Empire, is much broader than it was previously thought, indicating the importance of the *raña* deposits, the most accessible and easy to exploit, within the framework of the Roman gold mining in north-western Spain.



## 7. Conclusions

The *raña* deposits of the western Duero Basin have been hitherto assigned a discreet role within the Roman “gold-rush” context of the Spanish north-western area, that goes largely unnoticed owing to their hidden and partially destroyed evidences of gold mining infrastructure. A good example is the Jamuz and lower sector of the Eria river valleys, which share significant similarities on style and dispersion of Roman mining works and the complexity of the hydraulic systems. However, the combination of image enhancement techniques and new technologies, such as airborne LiDAR, together with the geological and geo-morphological characterization of the valleys aimed at the identification and description of a broad mining sector. It comprises a dispersed but extensive system of open-cast mining, with leats and water tanks that supplied water to benefit the auriferous sedimentary deposits. The examples of headwater erosion observed along the valleys, over the *raña* deposits, and the large alluvial plains that characterize the ephemeral streams, suggest their correlation with an important mining activity carried out in the area. Overall, the new findings in the *raña* deposits of the Jamuz area may represent an early prospection activity due to its large dispersion and short-term exploitation. Moreover, the flat topography and accessibility across the *raña* plateau towards the adjacent valleys, reinforces the idea of upstream erosion due to gold mining activity, which would have extended from the Jamuz to the head of the adjacent Valduerna and Eria valleys.

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## References

- Ballesteros, E.M., Martín, M.C., 2002. Study of weathering processes developed on old piedmont surfaces in Western Spain: new contributions to the interpretation of the “Raña” profiles. *Geomorphology* 42 (3–4), 279–292.
- Bennett, R., Welham, K., Hill, R.A., Ford, A., 2012. A comparison of visualization techniques for models created from airborne laser scanned data. *Archaeol. Prospect.* 19 (1), 41–48.
- Bewley, R.H., Crutchley, S.P., Shell, C.A., 2005. New light on an ancient landscape: lidar survey in the Stonehenge World Heritage Site. *Antiquity* 79 (305), 636–647.
- Bird, D., 2004. Pliny's arrugia water power in roman gold-mining. *Mining History: The Bulletin of the Peak District Mines Historical Society* 15, 58–63.
- Bird, D.G., Blagg, T.F.C., Jones, R.F.J., Keay, S.J., 1984. Pliny and the gold mines of the north-west of the Iberian Peninsula. *Papers in Iberian Archaeology* 193, 354.
- Brovelli, M.A., Cannata, M., Longoni, U.M., 2004. LIDAR data filtering and DTM interpolation within GRASS. *Trans. GIS* 8 (2), 155–174.
- Burnham, B.C., 1997. Roman mining at Dolaucothi: the implications of the 1991–3 excavations near the Carreg Pumsaint. *Britannia* 28, 325–336.
- Chase, A.F., Chase, D.Z., Weishampel, J.F., Drake, J.B., Shrestha, R.L., Slatton, K.C., Awe, J.A., Carter, W.E., 2011. Airborne LiDAR, archaeology, and the ancient Maya landscape at Caracol, Belize. *J. Archaeol. Sci.* 38 (2), 387–398.
- Cortés-Bárcena, C., 2013. Epigrafía en los confines de las ciudades romanas. In: *Los Termini Publici en Hispania. Numidia, Mauretania y* (321 pp).
- Costa-García, J.M., Casal-García, R., 2015. Fotografía aérea histórica, satelital moderna y LiDAR aéreo en algunos recintos militares romanos de Castilla y León. *Portvgalia, Nova Série*, vol. 36, Porto, DCTP-FLUP. pp. 143–158.
- Costa-García, J.M., Fonte, J., 2017. Scope and limitations of airborne LiDAR technology for the detection and analysis of Roman military sites in north-west Iberia. V. Mayoral-Herrera, C. Parcero-Oubiña and P. Fábrega-Álvarez (Eds.). In: *Harvesting the Benefits of 10 Years of Training in the Iberian Peninsula (2006–2015)*. Sidestone Press, Leiden, pp. 55–71.
- Crutchley, S., Crow, P., 2010. The light fantastic: using airborne lidar in archaeological survey. Swindon: English heritage. W. Wagner and B. Székely, (Eds.). In: *ISPRS TC VII Symposium – 100 Years ISPRS*, Vienna, Austria, July 5–7, 2010, IAPRS, Vol. XXXVIII, Part 7B, 160–164.
- Currás-Refojos, B., Romero, D., Sánchez-Palencia, F.J., Pecharrromán, J.L., Reher, G., Alonso, F., 2012. Minería de oro antigua en la cuenca del río Negro (Zamora). In: Sánchez-Palencia, J.F. (Ed.), *Minería romana en zonas interfronterizas de Castilla y León y Portugal (Asturia y NE de Lusitania)*. Junta de Castilla y León, Consejería de cultura y Turismo. Documento Pahis, pp. 217–229.
- De Mingo, A.G., 1987. Prospección geofísica por el método SEV en el valle del río Eria (León). Informe elaborado por RENASA para el IGME. pp. 19.
- De Vicente, G., Muñoz-Martín, A., 2013. The Madrid Basin and the central system: a tectonostratigraphic analysis from 2D seismic lines. *Tectonophysics* 602, 259–285.
- Dieulafait, Chr., Dieulafait, F., Domergue, C., Fincker, M., Picard, V., 2011. L'établissement romain de Las Rubias dans les mines d'or de la Sierra del Teleno (Corporales, province de León, Espagne). In: Mata Perelló, J.M., Torró i Abat, L., Fuentes Prieto, M.<sup>a</sup>N. (Eds.), *Actas del Quinto Congreso Internacional sobre minería y metalurgia históricas en el suroeste europeo*. León, 2008. Libro en homenaje a Claude Domergue, pp. 59–98.
- Domergue, C., 1990. Les mines de la Péninsule Ibérique dans l'antiquité romaine. *Ecole française de Rome. Publications de l'École Française de Rome* (127 pp).
- Domergue C. (2012). De l'utilisation de l'eau pour le transport des matériaux: le cas des mines romaines de Las Médulas (province de León, Espagne). J. P. Bost (Ed.). In: *L'eau: usages, risques et représentations dans le Sud-Ouest de la Gaule et le Nord de la péninsule Ibérique, de la fin de l'âge du Fer à l'Antiquité tardive (II<sup>e</sup> s. a.C.-VI<sup>e</sup> s. p.C.)*. Aquitania 21.
- Domergue C. and Hérail G. (1978). Mines d'or romaines d'Espagne. Le district de la Valduerna (León). Etude géomorphologique et archéologique. Publications de l'Univ. De Toulouse-Le Mirail. Serie B, T. IV, 303.
- Domergue C. and Sillières P. (1977). Minas de oro romanas de la provincial de León. I. La Corona de Quintanilla: Excavaciones 1971-1973. Las Coronas de Filiel, Boisan, Luyego 1 y 2: exploraciones de 1973. (183 pp).
- Doneus, M., 2013. Openness as visualization technique for interpretative mapping of airborne lidar derived digital terrain models. *Remote Sens.* 5 (12), 6427–6442.
- España-Arroyo, Á., 1983. Los castros de Zamora occidental y Tras-os-Montes oriental: Habitat y cronología. *Portvgalia* 1983, 131–146.
- Espejo, R., 1988. Evolución geomorfológica y procesos erosivos en las formaciones de raña relacionadas con las sierras de las Villueras y Altamira (W de España). *Ecología* 2, 39–51.
- Fernández-Lozano, J., 2017. Minería antigua en el valle del Eria (León). J. Fernández-Lozano (Ed.). In: *Prehistoria y romanización, sociedad y minería antigua*. Diputación de León, León (188 pp).
- Fernández-Lozano, J., Andrés-Bercianos, R., 2018. Natural or induced mass movements: new insights into slope instability recognition in the province of León. *Geogaceta* 64, 99–102.
- Fernández-Lozano, J., Gutiérrez-Alonso, G., 2016. Improving archaeological prospection using localized UAVs assisted photogrammetry: an example from the Roman gold district of the Eria river valley (NW Spain). *J. Archaeol. Sci. Rep.* 5, 509–520.
- Fernández-Lozano, J. and Gutiérrez-Alonso, G. (2017). Geomática aplicada a la prospección y valoración arqueológica de yacimientos auríferos romanos en el Noroeste peninsular (Distrito Aurífero del Valle del Eria, León). O. Puche Riart, M. Ayarzagüena Sanz, J. Fernando López Ciudad and J. Pous de la Flor (Eds). In: *Minería y metalurgia históricas en el sudoeste europeo. Nuestras Raíces Mineras*. 105–113.

- Fernández-Lozano, J., Gutiérrez-Alonso, G., Fernández-Morán, M.Á., 2015. Using air-borne LiDAR sensing technology and aerial orthoimages to unravel roman water supply systems and gold works in NW Spain (Eria valley, León). *J. Archaeol. Sci.* 53, 356–373.
- Fernández-Lozano, J., Blanco-Sánchez, J.A., García-Talegón, J., Franco, P., 2016. Rubefaction process as prospection criteria within the roman goldmining context of the Eria gold mining district (León, NW Spain). *Geo-temas* 16 (2), 371–374.
- Fernández-Lozano, J., González-Díez, A., Gutiérrez-Alonso, G., Carrasco, R., Pedraza, J., García-Talegón, J., Remondo, J., Bonachea, J., Morellón, M., 2018. New perspectives for UAV-based modelling the Roman gold mining infrastructure in NW Spain. *Minerals* 8 (11), 518.
- Fernández-Posse, M.D., Sánchez-Palencia, F.J., 1988. La Corona y el Castro de Corporales II: campaña de 1983 y prospecciones en la Valdería y la Cabrera (León). In: Ministerio de Cultura, Dirección General de Bellas Artes y Archivos, Junta de Castilla y León. Educación y Cultura, Consejería de (262 pp).
- García-Pulido, L.J., 2008. El Hoyo de la ampana. Un enclave idóneo para la valorización del patrimonio minero aurífero de Granada. In: *Actas del V Congreso Internacional sobre Minería y Metalurgia Históricas en el Suroeste Europeo*. León, pp. 661–684.
- García-Pulido, L.J., 2009. Estudio preliminar de las estructuras mineras antiguas existentes en cuatro sectores de explotación aurífera del territorio de Basti (Baza). *Arqueología y Territorio* 6, 179–197.
- Geode. n.d. Mapa Geológico Digital continuo de España [online]. [Date consulted: 11/05/2018] Available at: [www.igme.es](http://www.igme.es)
- Gómez de Larena, J.M., 1916. Bosquejo geológico de los Montes de Toledo. *Trab. Museo CC. Naturales (Geología)* 15, 1–74.
- González-Gutiérrez, R.B., 1999. Las explotaciones auríferas romanas del río de las Huelgas y su influencia en la transformación del paisaje (El ejemplo de Vegelina de Cepeda, León). *Cuadernos de Investigación Geográfica* 25, 111–123.
- Hérail, G., 1984. Géomorphologie et géologie de l'or détritique. Piémonts et bassins in-tramontagneux du Nord-Ouest de l'Espagne. *Éditions du CNRS, Centre de Toulouse, Sciences de la Terre* (450 p).
- Heredia, N., Fernández, L.P., Martín-González, F., Bahamonde, J.R., 2015. Depositional style and tectonostratigraphic evolution of El Bierzo tertiary sub-basin (Pyrenean orogen, NW Spain). *Geologica Acta: An International Earth Science Journal* 13 (1), 1–23.
- Hesse, R., 2010. LiDAR-derived local relief models—a new tool for archaeological prospection. *Archaeol. Prospect.* 17 (2), 67–72.
- Hillman, A.L., Abbott, M.B., Valero-Garcés, B.L., Morellón, M., Barreiro-Lostres, F., Bain, D.J., 2017. Lead pollution resulting from Roman gold extraction in north-western Spain. *The Holocene* 27 (10), 1465–1474.
- Hirt, A.M., 2010. Imperial mines and quarries in the Roman world. In: *Organizational Aspects 27 BC–AD 235*. Press, Oxford University (551 pp).
- Hofton, M.A., Rocchio, L.E., Blair, J.B., Dubayah, R., 2002. Validation of vegetation canopy lidar sub-canopy topography measurements for a dense tropical forest. *J. Geodyn.* 34 (3–4), 491–502.
- IGME, 1982. Inventario de las labores romanas de prospección y explotación de oro en el NO de la Cuenca del Duero. (63 pp).
- Jones, R.F.J., Bird, D.G., 1972. Roman gold-mining in north-west Spain, II: workings on the Rio Duerna. *The Journal of Roman Studies* 62, 59–74.
- Lasaponara, R., Masini, N., 2012. Image enhancement, feature extraction and geospatial analysis in an archaeological perspective. R. Lasaponara and N. Masini (Eds). In: *Satellite Remote Sensing*. Springer, Dordrecht, pp. 17–63.
- Lewis, P.R., Jones, G.D.B., 1970. Roman gold-mining in north-west Spain. *The Journal of Roman Studies* 60 (1), 169–185.
- López, D.G., 1980. Las Médulas. Nebrija, León, pp. 159.
- López-Merino, L., Peña-Chocarro, L., Ruiz-Alonso, M., López-Sáez, J.A., Sánchez-Palencia, J., F., 2010. Beyond nature: the management of a productive cultural landscape in Las Médulas area (El Bierzo, León, Spain) during pre-Roman and Roman times. *Plant Biosystems* 144 (4), 909–923.
- López-Merino, L., Cortizas, A.M., López-Sáez, J.A., 2011. Human-induced changes on wetlands: a study case from NW Iberia. *Quat. Sci. Rev.* 30 (19–20), 2745–2754.
- Martín-Serrano, Á., 1986. El relieve de la región occidental zamorana. Un modelo de evolución geomorfológica del borde Hespérico. Tesis Univ, Complutense de Madrid, Madrid (517 pp).
- Martín-Serrano, Á., Nozal-Martín, F., 2009. Fluvial network, raña deposits and appalachian relief of the Iberian Massif. In: García-Cortés, Á. (Ed.), *Spanish Geological Frameworks and Geosites*, Instituto Geológico y Minero de España, pp. 184–191 (215 pp).
- Matías-Rodríguez, R., 2006. El agua en la ingeniería de la explotación minera de Las Médulas (León-España). *Lancia: revista de prehistoria, arqueología e historia antigua del noroeste peninsular* 7, 17–112.
- Matías-Rodríguez, R., Llamas, B., 2018. Use of LIDAR and photointerpretation to map the water supply at the Las Murias-Los Tallares Roman gold mine (Castrocontrigo, León, Spain). *Archaeol. Prospect.* 25 (1), 59–69.
- McCormick, M., Büntgen, U., Cane, M.A., Cook, E.R., Harper, K., Huybers, P., Litt, T., Manning, S.W., Mayewski, P.A., More, A.F.M., Nicolussi, K., Tegel, W., 2012. Climate change during and after the Roman Empire: reconstructing the past from scientific and historical evidence. *J. Interdiscip. Hist.* 43 (2), 169–220.
- Muñoz-Villarejo, F., Celis-Sánchez, J., 2016. Nuevos Campamentos Romanos en Villamontán de la Valduerna (León). *El Adelanto Bañezano* [online]. [Date consulted: 01/02/2018]. Available at: <http://adelantobanezano.com/?p=37631>.
- Orejas-Saco A. (1996). Estructura social y territorio: el impacto romano en la cuenca noroccidental del Duero (Vol. 15). Editorial CSIC-CSIC Press. (270 pp).
- Orejas-Saco A. and Sánchez-Palencia F.J. (2016). Del final de la conquista al inicio de la explotación minera: Augusto y el control del Noroeste hispano. M.<sup>a</sup> Dolores Dopico Caínzos, M. Villanueva Acuña (Ed.). In: *Clausus est Ianus. Augusto e a transformación do noroeste hispano*. 341–359.
- Orejas-Saco A., Sastre-Prats I. and Zubiarre E. (2012). Organización y regulación de la actividad minera hispana altoimperial. M. Zarzalejos Prieto, P. Hevia Gómez, L. Mansilla Plaza (Ed.). In: *Paisajes mineros antiguos en la Península Ibérica. Investigaciones recientes y nuevas líneas de trabajo*. 31–46.
- Palao-Vicente, J.J., 2017. La res militar in Hispania durante la época de la Naturalis Historia de Plinio. In: Ciprés, P. (Ed.), *Plinio el Viejo y la construcción de Hispania Citerior*. Universidad del País Vasco, Vitoria-Gasteiz, pp. 153–197.
- Perea-Caveda, A.P., Sánchez-Palencia, F.J., 1995. Arqueología del oro Astur: orfebrería y minería. Caja de Asturias, Obra Social y Cultural. Asturias (120 pp).
- Pereira, D.I., 2006. Depósitos Cenozóicos. E. Pereira (Coord.). In: *Notícia Explicativa da Folha 2 da Carta Geológica de Portugal na escala 1:200000*. Inst. Geol. Mineiro, pp. 43–48.
- Pérez-García L.C. (1977). Los sedimentos auríferos del NO de la Cuenca del Duero (Provincia de León, España) y su prospección. Oviedo (Universidad de Oviedo) (tesis inédita).
- Pérez-García L.C. (1991). Métodos de prospección de oro en diferentes depósitos aluviales en España. *Actas del Congreso Gisements alluviaux d'or*. La Paz 1–5 junio, 325–355.
- Pérez-García, L.C., Sánchez-Palencia, F.J.S., 1992. Los yacimientos de oro de Las Médulas de Carucedo (León). In: Sánchez-Palencia, F.J. (Ed.), *Recursos minerales de España*. Consejo Superior de Investigaciones Científicas, CSIC, pp. 861–873.
- Pérez-García, L.C., Sánchez-Palencia, F.J., 2000. El yacimiento aurífero de Las Médulas: situación y geología. In: Sánchez-Palencia, F.J. (Ed.), *Las Médulas (León). Un paisaje cultural en la «Asturia Augustana»*. Instituto Leonés de Cultura, León, León, pp. 144–188.
- Pérez-García, L.C., Sánchez-Palencia, F.J., Torres-Ruiz, J., 2000. Tertiary and quaternary alluvial gold deposits of north-west Spain and Roman mining (NW of Duero and Bierzo basins). *J. Geochem. Explor.* 71 (2), 225–240.
- Pérez-González, A., 1979. El límite Plio-Pleistoceno en la Submeseta Meridional en base a los datos geomorfológicos y estratigráficos. *Trab. sobre Neógeno/Cuaternario*, (9), 23–36. Madrid 9, 23–36.
- Pérez-González, A., Gallardo, J., 1987. La Raña al sur de la Somosierra y Sierra de Ayllón: un piedemonte escalonado del Villafranquense medio. *Geogaceta* 2, 29–32.
- Reher, G.M., López-Merino, L., Sánchez-Palencia, F.J., López-Sáez, J.A., 2012. Configuring the landscape: Roman mining in the conventus Asturum (NW Hispania). In: Kluiving, S., Guttman-Bond, E. (Eds.), *Landscape Archaeology between Art and Science*, Amsterdam, pp. 127–136.
- Ruiz del Árbol, M.R., Sastre-Prats, I., Plácido, D., 2000. El nuevo modelo de ocupación del territorio. F. J. Sánchez-Palencia (Ed.). In: *Las Médulas (León). Un paisaje cultural en la Astura Augustana*. León, Instituto Leonés de Cultura, pp. 229–252.
- Ruiz del Árbol, M., Sánchez-Palencia, F.J., Sastre-Prats, I., Orejas-Saco, A., 2014. Water networks of Roman gold mines of north-western Iberian Peninsula. *Water History* 6 (1), 95–113.
- Sáenz-Ridruéjo, C., Vélez-González, J., 1974. Contribución al estudio de la minería primitiva del oro en el Noroeste de España. Ediciones Atlas, Madrid 190.



- Sánchez-Palencia, F.J., 1980. Prospecciones en las explotaciones auríferas del NO de España (Cuencas de los ríos Eria y Cabrera y Sierra del Teleno). *Noticiario Arqueológico Hispánico* 8, 214–289.
- Sánchez-Palencia, F.J., 1983. La explotación del oro de Asturia y Gallaecia en la Antigüedad (Doctoral dissertation, Tesis doctoral inédita, Universidad Complutense de Madrid, Facultad de Geografía e Historia).
- Sánchez-Palencia, F.J., 1986. El campamento romano de Valdemeda, Manzaneda (León): ocupación militar y explotación aurífera en el NW peninsular. *Numantia: Arqueología en Castilla y León* 2, 227–235.
- Sánchez-Palencia, F.J., 2000. Las Médulas (León). Un paisaje cultural en la Asturia Augustana. Instituto Leonés de Cultura, León (362 pp).
- Sánchez-Palencia, F.J., 2012. La minería romana de la Sierra de la Peña de Francia. Las zonas arqueológicas de Las Cavenes de El Cabaco y del Pinalejo y Tenebrilla (Salamanca). In: Sánchez-Palencia, F.J. (Ed.), *Minería romana en zonas inter- fronterizas de Castilla y León y Portugal (Asturia y NE de Lusitania)*. Junta de Castilla y León, pp. 135–180.
- Sánchez-Palencia, F.J., Currás-Refojos, B., 2015. Campamentos romanos en zonas mineras del cuadrante noroeste de la Península Ibérica. *Las Guerras Astur-Cántabras*, Gijón, KRK Ediciones, pp. 273–283.
- Sánchez-Palencia, F.J., Orejas-Saco, A., Sastre-Prats, I., Pérez-García, L.C., 2006. Las zonas mineras romanas del noroeste peninsular: infraestructura y organización del territorio. I. Moreno-Gallo (Ed.). In: *Nuevos elementos de ingeniería romana: III Congreso de las Obras Públicas Romanas*. Consejería de Cultura y Turismo, pp. 265–285.
- Sánchez-Palencia F.J., Romero D. and Beltrán A. (2018). *Geoarqueología del oro en la zona minera de Pino del Oro (Zamora)*. *Mélanges de la Casa de Velázquez. Nouvelle série*, (48-1), 63–87.
- Sastre-Prats, I., 2010. Clientela y dependencia social en el Occidente y Noroeste hispanos: pactos y minería. In: Orejas-Saco, A., Rico, C. (Eds.), *Minería y metalurgia antiguas. Visiones y revisiones*. Madrid. Casa de Velázquez, pp. 255–260.
- Sastre-Prats, I., Beltrán-Ortega, A., Sánchez-Palencia, F.J., 2010. Ejército y comunidades locales en el noroeste peninsular: formas de control y relaciones de poder en torno a la minería del oro. In: Palao-Vicente, J.J. (Ed.), *Militares y civiles en la antigua Roma: dos mundos diferentes, dos mundos unidos*, pp. 117–134.
- Štular, B., Kokalj, Ž., Oštir, K., Nuninger, L., 2012. Visualization of lidar-derived relief models for detection of archaeological features. *J. Archaeol. Sci.* 39 (11), 3354–3360.
- Vidal-Encinas, J.M., Costa-García, J.M., González-Álvarez, D., Menéndez-Blanco, A., 2018. La presencia del ejército romano en las montañas de el Bierzo (León): novedades arqueológicas. *An. Arqueol. Cordobesa* 29, 85–110.
- Zakšek, K., Oštir, K., Kokalj, Ž., 2011. Sky-view factor as a relief visualization technique. *Remote Sens.* 3 (2), 398–415.