Unveiling Roman Mining Works: LiDAR Insights into Gold-Bearing Plio-Quaternary Deposits in Northwest Spain

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ABSTRACT

This article focuses on the characterization of auriferous deposits, identification of new Roman mining infrastructure remains, and the early attempts of exploitation carried out in northwest Iberia. The research has combined airborne laser scanning (LiDAR) and field prospection to explore the geomorphological signature and landscape transformation performed by the 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 northwest. The article explores the complex hydraulic system developed in the Jamuz and lower sector of the Eria River Valleys, as well as the evidences 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 upper 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 the Roman gold mining in northwest Spain.

Keywords: Gold Mining, Romans Mining, LiDAR, Geomorphologic Features, Raña

1. Introduction

The northwest Iberian Peninsula contains a great variety of ore deposits, among others gold, that were exploited since the ancient times (Fernández-Lozano, 2017). The early extraction works carried out by the pre-Roman settlements consisted of straightforward procedures based on panning free gold in river placers and other secondary deposits (Sánchez-Palencia et al., 2018). The presence of auriferous deposits in northwestern Iberia represented a suitable attraction for the Roman coinage production to thereby become part of the Empire after the end of the Cantabrian Wars (19 BC). Thus, the Astur territory, comprising part of the present-day provinces of Asturias, León and Galicia, became the conventus iuridicus Asturum. 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 till the 3rd century, when a strong political and economic crisis struck the Empire (Domergue, 1990; Sánchez-Palencia, 2000).

The Roman occupation contributed to a widely transformation of the territory, intensifying the exploitation and administration of the gold mines in northwest Iberia (Fig. 1A). These changes caused a strong impact in the landscape and social structures (Orejas, 1996; Sánchez-Palencia et al., 2006). Palaeoenvironmental data suggest that deforestation in the nearby Ancares Mountains started in 150 BC and subsequently advanced towards the Courel and central Asturias areas, which was responsible for a vegetation change from predominant oak and pine forests into shrub (Muñoz-Sobrino et al., 1995; Aira Rodríguez, 1986; López-Merino et al., 2014). 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 beginning 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 shapes protected with ditches −like the Quintanilla, Truchas, Boisan or Espadañedo examples (Esparza-Arroyo, 1983; Sánchez-Palencia, 1986; Currás et al., 2012)−, suggests the importance that maintenance tasks and control of the main mines had in the conventus iuridicus Asturum.

According to the description of Pliny the Elder in his Naturalis Historia (Plin NH, XXXIII), the mining infrastructure consisted in water reservoirs and supply canals that brought the water to the main mining sites.

A notable effort has been made in the last 40 years in the study of this complex network of mining infrastructure (Sáenz and Vélez, 1974; Domergue and Hérail, 1974; 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, Matias, 2008), recent advances in LiDAR technology and UAV-derived DEMs provided new findings in nearby areas, such as the Eria Gold District and the Teleno Mountains (Fernández-Lozano et al., 2015; Fernández-Lozano and Gutiérrez-Alonso, 2016; Matías and Llamas, 2017; Matías and Llamas, 2018; Fernández-Lozano et al., 2018). Unfortunately, little is known about the Roman works carried out in the Jamuz valley and the nearby lower sector of the Eria Gold District.

Raña deposits, a sedimentary red conglomerate configuring a topographic plateau, conserves most of the ancient record of mining elements hidden by the highly vegetation, although agriculture and farming activities have modified the landscape leading to a poor conservation or loss of the mining remains. So far, the destructed hydraulic network has obscured the investigation of this mining landscape. However, the geological and geomorphological analysis of the raña deposits may help to constrain and describe the style and extension of mining works in the area. This article aims at: a) characterising of the gold-bearing raña deposits; b) identifying of the mining infrastructure by application of visual enhancement techniques and tools to airborne LiDAR data; c) testing prospection works based on gold panning for identifying mining sites and d) recognition of geomorphological features related to mining activity. This integrated approach was carried out in the southwest 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 global framework of the Roman gold mining in northwest Spain.

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

The term 'raña', coined by Gómez de Llarena (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―. Rañas 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 widely present in the major basins of Iberia (Spain and Portugal), and is often found flecking their borders over Paleozoic and Cenozoic bedrocks (Pereira 2006; De Vicente and Muñoz-Martín, 2013). In each case, the underlying bedrock was deeply incised before their deposition. After the sedimentation of these raña-type alluvial fans the fluvial network hierarchization and the individualization of a single main canal with tributaries took place. Both, the large alluvial fan and the subsequent fluvial incision and terrace aggradation, result from the important base level change experienced by the Duero River Basin. Furthermore, the final drainage network organization was accomplished by the dramatic change, from endorheic to exoreic conditions, occurred during the opening of the Duero Basin towards the Atlantic Ocean (Santiesteban et al., 1996).

This apparently simple puzzle has led to an important controversy on the origin, morphology and evolution of the raña deposits, with largely contradictory interpretations (Hernández-Pacheco, 1956; Pérez-González y Gallardo, 1987; Baena-Escudero y Díaz del Olmo, 1997). Raña deposits have been considered the relict expression of fluvial sources (Pérez-González and Gallardo, 1987; Delgado, 1988; Hacar y Alonso, 1999), convergence of alluvial fans (Cunha, 2008; De Vicente and Muñoz-Martín, 2013; Heredia et al., 2015) and structural forms in resistant levels affected by fluvial incision (Ferreiro, 1991)

Therefore, 'raña deposits' can be identified in the landscape by the presence of a piedmont developed next to the main reliefs. They are characterized 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-bearing pebbles (Espejo, 1988). The origin of these pebbles is not well known, but they have been related to the effect of edaphic and hydromorphic processes occurred in the raña under semi-arid conditions and rapidly changing water-table oscillations. In fact, this process of rubefaction has been often linked to the presence of gold (Pérez-González y Gallardo, 1987; Caveda y Sánchez-Palencia, 1995; Pérez-García y 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. (Figure 2). They are the result of the profound erosion of the mountain reliefs constituted by the Teleno Range, which feeds the piedmonts of the Eria, Duerna and Jamuz valleys. The Cenozoic sedimentary filling of these valleys has been related to the formation of relict fluvial terraces formed by vertical erosion in a staircase-like geometry (Delgado, 1988; Hacar et al., 1999). However, the geological mapping of these materials allows us to consider them as a terminal surface 'raña-type', similar to others described in the nearby sector of Zamora (Hérail, 1979; Martín-Serrano, 1986). In the Eria and Duerna valleys, the presence of these deposits have influenced the fluvial capture and incision of drainage networks, leading to the current hydrographic configuration of the rivers.

3. **Rañas 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 processes: i) by fluvial transport; and ii) by rubefaction or laterization processes that affect these sediments and are responsible for their reddening (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 upon 80-115 mg/m^3. A good example are 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). The Roman hydraulic supply system and the mining infrastructure in northwest Spain**

3.1 Hydraulic system

The hydraulic infrastructure established during the Roman Imperial period in northwest Spain comprises a series of canals and water reservoirs precisely designed to supply water to the main mining sites. This sumptuous engineering work outlines more than 600 km of canals 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 (Sánchez-Palencia and Pérez-García, 2000; Matías, 2006).

Canals were built directly over rock and their dimensions were thoroughly adapted to the slope roughness. Over irregular substrate, dry stone walls and wood-made aqueducts, were built to get across the uneven terrain (Pérez-García et al., 2000; Sánchez-Palencia and Pérez-García, 2000; Domergue, 2012). Canals were systematically established at different topographic levels. The upper structures carried out the water supplied by the snow thaw in the Aquiana and Teleno Mountains, active during the winter and most of the spring, whereas the lower canals used the river water, necessary for the mining works, from the Eria and Duerna valleys. In both cases, canal width varies between 1.2 and 1.5 m and discharge can be estimated in 0.2-0.7 m^3/s, considering a water depth of 0.4-0.6 m (Lewis and Jones, 1970; López, 1980; Sánchez-Palencia, 1980; Matías, 2006). The rock formations cropping out in the mountainous areas played an important role on the configuration of the hydraulic system. Thus, canals performed in slaty substrate were straightforward assembled rather than those outlined over the quartzites. The latter were generally avoided due to the hardness of the rock and, where necessary, tunnels were opened through to supply water to the main mining sites (Lewis and Jones, 1970; Jones and Bird, 1972; Sánchez-Palencia, 1980; Mañanes, 1988; Domergue, 1990; Sánchez-Palencia et al., 1999; Matías, 2004; 2006). Several authors observed the distinctive slope differences along the trace of the canals. Mean slopes would not exceed 0.5-1.2% according to detailed studies carried out in different sectors of the province of León (Sáenz-Ridruego and Vélez-González, 1974; Fernández-Posse and Sánchez-Palencia, 1988; Sánchez-Palencia and Pérez-García, 2000; Matías-Rodríguez, 2006; Fernández-Lozano et al., 2018).

As pointed out by Sánchez-Palencia (1980), according to the distribution of mining sites and the hydraulic system, roman gold works were hierarchically exploited, starting from the bottom of the valleys and then advancing towards the upper sectors located at high altitude in the mountains. This spatial pattern is generally preserved in elevated sectors, showing canals eventually destroyed by advancing mining works.

Tanks or water reservoirs are other archaeological elements preserved on the mining landscape. When they are empty, in the summer, they are broadly recognised in the landscape by the colour contrast produced by the present-day vegetation that grows over strongly hygroscopic decantation muds. Most of the tanks comprise semi-circular, V- or crescent-shaped, and nearly rectangular structures. These hydraulic infrastructures were used for the collection of water. Over elevations of 2000 m they were mostly used for accumulation of snow-melt water. However, in the bottom of the valleys water was collected from springs and rivers. Their dimensions vary greatly depending upon the water needs and bulk of material to be removed at the exploitation centres. According to literary sources, such as the Natural History by Pliny the Elder (NH, XXXIII), and information provided by archaeological finds, different authors suggest that the tank´s depth could vary between 2 and 3 meters (Fernández-Posse and Sánchez-Palencia, 1988; Sánchez-Palencia y Pérez-García, 2000).

Water reservoirs were important features in elevated areas, where the water accessibility is reduced during most part 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. Over these surfaces, the collection of water was constrained by the presence of springs or raining periods and, when possible, by river captures and derivations.

3.2 Mining infrastructure

Interspersed Roman gold mines provoked a strong impact on the territory. Labours are sparse over Pleistocene sedimentary successions, whereas they tend to be grouped in the bedrock. This systematic mining method responds to the broad variations observed in gold grades between primary and secondary deposits, but also within the sedimentary sequence itself. As pointed out by Pérez-García (1977), in the secondary deposits of Las Médulas, the average proportion of gold decreases from the bedrock contact to the top of the Cenozoic sediments, from 30 mg/m^3 to more than 300 mg/m^3. These vertical changes in gold grade obliged to establish a prospection solution suitable to achieve a profitable benefit. Thus, whereas primary deposits were exploited through ground-sluicing, ditches and underground passageways, there exists a wide variety of methods that the Romans applied to auriferous placers. Depending on the thickness of the sedimentary deposit (Domergue and Herail, 1978) and the mining method (Pérez-García, 1977), different mechanisms have been proposed in the literature:

- Induced mass movements. This method was used where sedimentary thickness exceeded 30-100 m (Sánchez-Palencia, 1983; Pérez-García et al., 2000). The induced mountain collapse or *Ruina Montium*, partially described by Pliny in his Naturalis Historia (also known as *arrugia*). Las Médulas, declared World Heritage Site by UNESCO in 1997 and Natural Monument in 2002, represents the best-preserved example of this method. Recent studies suggest that water and snow-melt water tanks were used to crumble the mountains by the gravitational action, a method more common than previously thought (Fernández-Lozano and Andrés-Bercianos, 2018). An alternative method was proposed by Sáenz-Ridruejo and Vélez-García (1974). It consists in the erosion of the bottom of the mountain, provoking the subsequent hillside instability.

- Erosion works. Sedimentary deposits less than 30 m thick were excavated using the ground-sluicing technique, also known as *chantier-ravine* by Domergue and Herail (1978). Water was used to erode the unconsolidated material to get through the underlying auriferous layers. These authors mention also the presence of a mining camp, from which maintenance and preservation works of the hydraulic system would have been performed in the area. This is a common feature in most of the mining sites. Recently, Currás-Refojos et al. (2012) showed the functionality of a similar mining camp in the nearby province of Zamora, further south, indicating the strong correlation between living and mining settlements in the area as a widely established practice in northwest Spain. Large ditches with running water were used for working on thick layers along steep slopes (chantier piriforme, Domergue and Herail, 1978).

  Shallow auriferous deposits were laterally exploited and extended over large surfaces. Ponytail canals were used in flat areas, whereas inclined surfaces used fan (convergent) or comb (straight) canals ending into a washing canal, where gold was directly recovered. Erosion of shallow deposits was also carried out using a side-trawling method: water was supplied from tanks through canals following the sinuosity of the reliefs or straight according to the topography. In general, the shape is similar to a natural ditch, but the bottom tends to narrow out instead and the canals converge one another. Domergue and Herail (1978) referred to *chantier-friffe* and *ruisellement*.

The accumulation of waste material resulting from the above-mentioned mining operations depends on the granulometry of the exploited deposits. Therefore, Cenozoic red conglomerates and Plio-Quaternary rañas contributed to provide a large amount of waste material, called in the area *murias*, but the fine-grained sediments are not preserved.

4. Material and methods

a. 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; Cruchley and Crow, 2010; Chase et al., 2011). Also known as Light Detection and Ranging, LiDAR represents a challenging 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. Among its best characteristics, stands out the possibility to obtain 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 growing 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 colourful and astonishing maps, often assumes important scaling variations. As Bennet 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. Besides these minor shifts, the relief visualization techniques have successfully helped researches to the rapid an accurate identification of archaeology 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 northwest 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 canals and water reservoirs. Even the processing of low resolution DEMs (i.e. 5 m interpolation) provide an important improvement, sharpening minor topographic variations caused by canal 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 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 northwest 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 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 signature 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 firstly performed a 0.5 m interpolated mesh based on LiDAR point clouds provided by the Spanish Instituto Geográfico Nacional (IGN at 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 confirms the presence of mining works in the area.

b. 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 pan the raña deposits and a few samples from the Jamuz river, where no previous prospection works exist. 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 consisted in the identification of gold positives along the river direction in 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 the Roman miners and present-day mining companies (Pérez-García and Sánchez-Palencia, 2000; Sánchez-Palencia et al., 2018), and allows the identification of the most successful deposits: the higher the gold grade, the more successful possibilities for exploitation. Thus, during the Roman times, high gold grades led to the development of large mine sectors such as those found in the upper sector of the Eria and the Valduerna Gold Districts (Sánz-Ridruejo and Vélez-González, 1974; Domergue and Hèrail, 1978; Sánchez-Palencia, 1980; Fernández-Lozano et al., 2015).

A total of 12 samples covering the entire raña deposit of the Jamuz valley, over 300 kg, were panned in the river (see sample location in Figure 1B): 7 samples provided small gold particles (Au-1 to 7), whereas no gold was found in other 5 (Est-1 to 5). Gold particles were observed on a binocular magnifying glass to determine shape and size.

Most of the samples are represented by rounded morphologies between 0.2-1.5 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 suffered by the drainage network. The latter provides a remarkable clue on the presence of mining works in the area. In general, the studied valleys are characterised by ephemeral or inactive streams but wide flood plains compared with those from larger rivers, which suggests that they were probably flooded during the mining works. So far, archaeological works carried out in the western Duero Basin payed little attention to geomorphological changes in drainage system (Pérez-García, 1977; Domergue and Hérail, 1978; Perea-Caveda, A., & Sánchez-Palencia, 1995; Pérez-García et al., 2000), which have been investigated in this work.

5. The beginning of mining operations in the Jamuz valley and their arrangement across the territory

It is difficult to accurately establish when the start of mining on these sites took place. Attempts are hindered by a lack of studies and the absence of supporting archaeological literary and epigraphic material. Nevertheless, there is certain indirect evidence that makes it possible to set the likely commencement of work on such sites and their articulation across the territory. Different studies frame the beginning of mining works in Valduerna and Eria valleys in the early imperial period (Sánchez-Palencia et al., 2006; Orejas-Saco et al., 2012; Sánchez-Palencia, 2012a; Orejas-Saco and Sánchez-Palencia, 2016; Domergue and Sillières, 1977; Domergue and Herail, 1978). The proximity of the gold mines of Jamuz valley to the former two, 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.

According to a report by Floro (Flor., 2.33.59-60), the Romans would have started the gold extraction activities under Augustus' rule, immediately after the conquest of the peoples of the peninsular north in 19 B.C. Such date is consistent with the urgent need to exploit rich mining resources that the Romans were already aware of even before their arrival to such lands. However, everything suggests that large-scale exploitation had to be postponed until peace and control over such territories had been achieved, as well as the organization of the land and its inhabitants within the Roman legal framework, (Sastre et al., 2010; Orejas-Saco and Sánchez-Palencia, 2016). The Roman army played an essential role in both tasks.

To achieve both goals, Roman authorities deployed the bulk of the army in the northwestern area of the Iberian Peninsula, where Cantabrians and Astures—the last two peoples to be conquered— were settled and where the main gold deposits of Hispania were located. Although territorial control must have varied according to the different areas and the opposition of their dwellers, everything seems 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'. 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 peoples. This period also yields the first data referring to large-scale mining development undertaken by Rome. Proof of this seem to be the proliferation of hospitality pacts between Roman authorities and different communities in the area during Tiberius' rule. Such documents have been considered evidence of the transformations in the organization and dealings of native peoples with Rome after the establishment of peace needed to start mining (Sastre et al., 2010). This is further supported by the date of the start of the mining activities in La Corona de Quintanilla, located in the heart of Valduerna, in the year 15 A.D. (Domergue and Sillières, 1977).

During this process, the Roman army took on different roles, which varied according to the times and circumstances. Nevertheless, it is reasonable to assume that the first activities carried out by these 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), 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 mining. The location at some point between the end of Augustus' rule and the beginning of Tiberius' of legion X Gemina's camp in Petavonium (Rosinos de Vidriales, Zamora), quite far to the south from the Astures and barely twenty kilometres away from the Jamuz or Eria valleys, can be partly explained by the mining wealth of the area. The identification of what clearly seem camps in the very middle of mining sites has also been associated with the beginning of activities in such deposits. This is assumed to be the case of the camp of Valdemeda (Pozos, León), which has been linked to the waterworks required to extract the material (Sánchez-Palencia, 1986). The recent discovery of structures identified as camps in the locality of Villamontán de la Valduerna, in the heart of the mining valley of the same name and very close to the mines of the Jamuz valley, seems to further support this association. However, evidence of mining structures is not always synonymous with military presence associated with mining. This is the case with the group of camps in Castrocalbón (León), which are identified as operation areas that did not accommodate troops (Le Roux, 1982 and 1992). 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 mining complex of Vipasca (Portugal) and the deposit of Las Rubias (Corporales, León) (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. Quite significant in this regard is the confirmation of the presence in Asturica Augusta of soldiers in active duty belonging to legions X Gemina and VI Victrix dated to Julio-Claudian times. The presence of soldiers stationed outside their main headquarters is explained by the political and administrative weight gained by this city, but also by its role in relation to the mines in the area. From this point of view, it seems more than likely that the troops were expected to carry out tasks of surveillance and supervision of the deposits, the opening of pathways for the output of the material, controlling the output of material and supporting the civilian personnel sent from Asturica or even Tarraco. Although belonging to a later period (between 163 and 191 A.D.), the inscriptions of Villalís and Luyego illustrate said association between military troops and civilian personnel in this area (Palao Vicente, 2006). The aforementioned case of the deposit of Las Rubias (Corporales, León), dated as belonging to the Julio-Claudian period, points in the same direction. Especially interesting among the structures found in diggings are what seem to be a thermal building with a double-headed apse, a compartmentalized building of a functional nature and what could be an aedes (Dieulafait et al., 2011). Among the findings is a bolt that could be linked to a scorpio dart. Archaeologists who have been digging the site argue that this site to have been a post devoted to the surveillance and management of the mining operations conducted on the southern slope of the Teleno, where military staff and government personnel sent from the nearby Asturica Augusta would have coexisted(Dieulafait et al., 2011).

Alongside technical support and administrative functions, it should not be ruled out that the soldiers could have played supervising roles, or even participated in the very engineering tasks, which they were more familiar with than the native population. It seems improbable that the mission of the troops posted at such sites was the surveillance of those doomed to work in the mines. Research conducted in this part of the Iberian Peninsula confirms that the extraction tasks were carried out by the free native population under a system supervised by Roman authorities (Sánchez-Palencia and Orejas, 2012).

As far as the relationship between mining sites and communities in the area is concerned, the data available do not allow any attempt to conduct a detailed analysis. Contrary to what has been found for other areas of the Leonese province and peninsular northwest (Sastre et al., 2010), there is no research available on settlement in the Jamuz area and its relationship with mining sites. Nevertheless, this handicap can be bridged by using the model of those other 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 northwest 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, 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 Barcena, 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 Baedunienses, 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. It is logical, therefore, to assume that there were mining camps linked to these exploitations, as confirmed 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 reveal the location of such settlements associated with this type of mining exploitations.

6. Results and discussion

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 deep (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 directly unconformably overlay the Palaeozoic low-grade metamorphic basement, which comprises quartzites and slates of the Cambrian-Ordovician Los Cabos Fm., with marine affinity. Towards the southwest, near the Eria River Valley, the Palaeozoic is located at ca. 100 m depth, and the Miocene argillites reach a total thickness upon 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, which explains their aging. The upper level often comprises a well-developed brown soil. In general, palaeocurrents show W-NW (N150º) and SW directions, interpreted to indicate the location of the source area. Hence, the formation of the raña piedemont 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 deposits washing, and mainly consisting of supply canals and water reservoirs. Mining activity was responsible for the extensive impact observed in the adjacent valleys due to the intense erosion caused during sediment washing.

a. Mining hydraulic complex

The hydraulic network is scarcely preserved in the area. The intense anthropic activity and the presence of dense vegetation make difficult the location of the supply canals and derivations. However, the hydraulic infrastructure remains can be identified at both the open-casts and in connection with some of the water reservoirs, which are often preserved on the landscape. Unlike nearby mountainous areas, where canals are preserved in the bedrock, in the raña sedimentary deposits they are mostly destroyed. There are two types of canals in the area: canals used for filling the water reservoirs, or *corrugi* according to Pliny´s Naturalis Historia, and supply canals or *emisaria*, which brought the water to the main mining sites (Fig.6). The latter are best preserved in the area, because the distance between the water reservoirs and the mining sites is often small.

Water reservoirs are mostly preserved due to their dimensions (Fig. 6A). They represent the putative biggest reservoirs preserved in the northwest of Iberia, exceeding the hitherto largest La Horta water reservoir, located in Las Médulas Gold District. Table 1 shows the water volumes of the main reservoirs described in the area. Although they have been eventually modified, their connection to the main mining sites and the nearby tailings reveals their presence since roman times. They were used for the accumulation of water that was subsequently used for the washing of the auriferous sediments. Water to fill the reservoirs 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 dimensions of the raña, the distribution of water reservoirs shows a common pattern in both the Jamuz and Eria areas. 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 (Figure 1B and 7), has a nearby water reservoir that supplied water for the washing of the alluvial sediments.

b. 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 Jamuz and lower Eria sector comprises a series of open-cast mines represented by ground-sluicing, spoon and fan-like structures. It is worth noting that, in general, open-cast appears isolated and dispersed over a broad surface. Their dimensions are often limited by the available space and depth of the raña deposits. Trenches rarely exceed a few meters deep. However, aggradation structures in valleys may extend to dozens of meters. In those areas where the raña deposits have more than 10 m thick, where spoon-like geometries are predominant. Likewise, where the auriferous sedimentary cover is thin (< 10 m), mining works were laterally extended to benefit as much surface as possible. This is the case of Los Fuchacos, a fan-like structure in the Jamuz area. As observed in Figure 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 reservoir not seen from the oblique aerial image).

A prospection panning carried out over the raña deposits provided an ore grade upon 32 mg/m^3. This is a rather low gold grade compared to other similar deposits in the Duerna and upper Eria sector, where grades, ranging from 80 to 115 mg/m^3, have been reported (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 those shown in Figure 7A and B, Los Fuchacos, the total amount of gold obtained by the Romans reached less than 10 kg.

c. Geomorphological impacts on the landscape

LiDAR data provide a useful picture of the significant impact of mining activity on the landscape. The close proximity of water reservoirs to the main valleys and their connection through a complex irrigation system defines a systematic procedure for prospecting and mining based on the washing of the raña sediments. The distribution of a well-established fluvial network configuring a lineal and anastomosing geometry over the raña plateau is juxtaposed to the mining hydraulic system (Fig. 3).

It is worth noting 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 (Fig. 2 and

8). For instance, this stream is characterised by a more than 300 m-long flood plain, similar to the adjacent everlasting Eria River, which varies between 300 and 1.500 m in its widest part. Figure 8 shows the presence of farming lands in the central part of the flood plain, indicating that the Valtabuyo torrent is mostly inactive ever since. We interpret the presence of such a large flood plain in the Valtabuyo creek as the result of human-induced landscape modification caused by the nearby roman gold mines.

Other geomorphological elements configure a landscape of undulated river banks or anthropic structural benches that configure a staircase with each terrace (Fig. 2). Minor valleys are characterised by the presence of headward erosion that produces 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 (Figure 2). This is supported by the deep incision suffered by small valleys at the stream headwaters and the presence of tailing deposits, called *murias*, highlight the location of the mining sites (Fig. 6D, E and F)

Particularly interesting is the presence of anthropic funnel-like valleys attached to the hillsides of the raña. They were formed as a result of the washing of 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 an open surface upwards, narrowing towards the lower part of the hillside, where the fine material would be channelled for an eventual extraction of gold particles by the Romans.

d. The starting of mining operations and the army's role

Parallel documents for other mining sites in the northwest, the logic of mining resource extraction in the period and the strong military presence in the area, where there is evidence of a series of important changes around the late days of Augustus' rule and the beginning of Tiberius', frame the beginning of gold mining in the Jamuz area in the first twenty years of the first century AD. Roman troops played a decisive role throughout the entire process, affecting the most diverse fields. By contrast, it is far more difficult to accurately determine the presence of settlements in the area and their relationship with such sites. Nevertheless, the data available for other areas of the peninsular northwest suggest that the situation could not have been very different.

7. The role of raña deposits in Roman gold mining

The Roman gold mining is broadly represented in NW Spain, which holds some of the major gold deposits in Europe: Las Médulas (Pérez-García y Sánchez-Palencia, 2000), Omañas, Eria-Cabrera (Sanz-Ridruejo and Vélez-González, 1974; Fernández-Posse 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 Duerna Gold Districts (Domergue and Hérail, 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, of a precise system of irrigation represented by water reservoirs that connects supply canals to the main mining sites. The creation of this irrigation system —which is certainly different from other valleys where supply canals are more relevant—, lies in the large dimensions of the raña, together with the reduced amount of water available from nearby ephemeral rivers and streams, which forced the construction of an extensive water reservoirs network, widely distributed in the area. The identification of Roman´s infrastructure has been improved by the combination of airborne LiDAR technology and image enhancement techniques and tools. Both technologies 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 transformation of the landscape by anthropic activity reduce the 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 argue that Cenozoic auriferous deposits in the northwest are mostly confined to ancient river terraces, Miocene in age (Pérez-García, 1977; Hérail, 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 (Pérez-González, 1979) benefited for the extraction of gold. These sediments comprise strong similarities to 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 comprises a series of alluvial fans, sourced from the Teleno Mountains, with W to NE directed palaeocurrents building up a wide plateau that raises over the Duero Basin.

Due to the broad extension that configure these sedimentary deposits and its reduced thickness, mining works are confined to the upper part of the raña. Prospection works based on gold panning indicate a low gold grade (≈32 mg/m^3). This confirms 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 major 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 Figure 7). However, due to the nature of the raña deposits, which comprises 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 highly dispersion of open-casts and the differences in mining style (i.e. from ground-sluicing to fan-like structures). This supports the idea suggested in previous studies that the widespread mining and their reduced dimensions mostly correspond to prospection works carried out before an intensive exploitation started (Pérez-González 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 water reservoirs 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. In El Cabaco (Salamanca), Sánchez-Palencia (2012) and Ruiz Del Árbol et al. (2014) suggest that, although these reservoirs could have been lately transformed for farming, they played also 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 torrent, have also present-day farming activity on the flood plain, indicating the lack of drainage. The presence of tailings consisting in *murias* deposits —characteristics of Roman activity— within the valleys, confirms the large-scale impact of gold extraction over the raña. This method of exploitation cause a backward erosion at the river headwaters, provoking the subsequent aggradation of the valley flood plains.

Notwithstanding, the little amount of open-cast mining compared with other nearby areas like the Duerna 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 Sánchez-Palencia and Pérez García (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 use of the hydraulic resources.

Given the strong transformation occurred in 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 highlight that this activity caused a dramatic transformation in the northwest, which led to a profound economic change. According to López-Merino et al. (2010), the transformation did not affect not only the lifestyles, but the entire landscape as a result of the control of resources forced by the Roman policy (Sánchez-Palencia, 2000). The construction of the hydraulic network and the recovery plants had a deep impact in the reorganization of the territory (Ruiz del Árbol et al. 2000). In fact, the mining activity was developed thanks to the military control of the northwest after the consolidation of the *Pax Romana* by Augusto (27 B.C.-14 A.D.) and the transformation of the monetary system, which was based on the gold-silver pattern, a crucial element for the Roman economy (Greene, 1990; Howegego, 1992).

In order to achieve this target, the Roman Empire deployed an important military contingent throughout the Spanish northwest, 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 the early exploitation of systematic 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, Curras et al., 2012).

This military infrastructure suggests the importance that had for the Roman Empire the control of the mining resources. Within this context, our findings suggest that the Jamuz and lower sector of the Eria River Valleys could represent and 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, 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 been started in the Jamuz area and were rapidly extended towards the nearby headwaters of the Eria and Duerna 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 set by the Roman miners, aimed at the development of a complex mining system involved in the benefit of similar geological materials and systematically developed in other adjacent gold districts. These results confirm that the dense and complex mining infrastructure, established by the Roman Empire, is much broader than 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 northwest Spain.

8. Conclusions

The raña deposits of the western Duero Basin maintained a discreet role within the Roman "gold-rush" context of the Spanish northwest, going unnoticed by 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 complexity of the hydraulic systems. However, the combination of image enhancement techniques and new technologies, such as airborne LiDAR, together with the geological and geomorphological 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 canals and water reservoirs 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 characterise the ephemeral streams, suggest their correlation with an important mining activity carried out in the area. Overall, the new findings recorded 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 plateaus towards the adjacent valleys, reinforces the idea of an upstream erosion due to gold mining activity, which would have extended from the Jamuz to the head of the adjacent Duerna and Eria valleys.

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Figure Captions

Figure 1. General map of the study area and location of the gold samples shown in Figure 5. A) Distribution of auriferous roman works in northwest Spain both primary and secondary deposits based on Pérez-González 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.

Figure 2. A) Geomorphological map of the study area (modified after Geode). 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.

Figure 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.

Figure 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 Figure 1 for sample location.

Figure 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.

Figure 6. Roman mining infrastructure comprising water reservoirs and supply canals in the Jamuz area (A and B); C) water reservoir, canal (D) and murias deposits (E, F) in the lower sector of the Eria River Valley.

Figure 7. Strong size variations observed among the upper sector of the Eria District at Las Murias-Tallares and Los Fuchacos in the Jamuz area. A) 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). B) Small-scale open-cast at Los Fuchacos site (≈200 m) and C) multihillshading digital terrain model obtained from LiDAR data showing the main mining infrastructure. See Figure 1 for location.

Figure 8. Oblique aerial image of the Valtabuyo stream, showing the large alluvial plain 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 turned into a farmland, indicating the absence of seasonal streams. See the text for further explanation.

Table caption

Table 1. Size and volumes of the study water reservoirs. See Figure 1 for location.