Analysis Using LIDAR and Photointerpretation of Las Murias-Los Tallares (Castrocontrigo, León-Spain): One of the Biggest Roman Gold Mines to Use the “Peines” System

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Abstract

A comprehensive study of the Las Murias-Los Tallares Roman gold mine (Castrocontrigo, León-Spain) was conducted using Light Detection and Ranging (LIDAR) technology and photointerpretation. The analysis of the mine structure show two main phases of ascending mining works and that the gold recovered by the Romans was at least 510 kg. Although LIDAR technology proves to be very valuable and essential to analyzing Roman hydraulic mining structures, there are some aspects that are still hardly decisive given the interpretation difficulties.

Introduction

The Las Murias-Los Tallares Roman gold mine is situated near Castrocontrigo (León-Spain), on the edge of an extensive plain which raises 20–30 m above the current Eria River (Fig. 1). It is one of the largest Roman mines to have used the “*peines*” system, expressly used for the hydraulic processing of extensive yet shallow secondary auriferous deposits, which affects a narrow strip 4.6 km long and 3 km² of surface area where 60 mine units (*peines*) have been recorded.

This Roman hydraulic mining system, which can be seen in the aerial images as a series of grooves that converge in a single washing canal, was also used significantly in another two auriferous deposits situated in the province of León. One of them is located several kilometers to the north at Las Moraceras near the town of Priaranza de la Valduerna. It measures 5.25 km² in surface area (2.8 × 2 km) and features nearly 40 *peines*. The other one is located in the town of Las Omañas and measures 5 km² in surface area (3.25 × 1.3 km) with barely 20 *peines*.

The Roman mining area of Las Murias-Los Tallares was exposed as a result of a fire that occurred in August 2012, when more than 10,000 ha of valuable pine trees were burnt down. This is why the main mine structures can now be directly analyzed across the surface area.

Adequate field exploration, the reconstruction of the supply hydraulic system, and the use of digital terrain models (DTMs) obtained from Light Detection and Ranging (LIDAR) flights open up a wide range of possibilities when interpreting the various work phases and methods followed at the Las Murias-Los Tallares mine (Fig. 2).

Background

The Sierra del Teleno is one of the most important reference auriferous mining areas from the Roman Empire and has been studied by several authors (Lewis and Jones 1970; Bird 1972; Domergue 1973; Sáenz and Vélez 1974; Pérez García 1977; Domergue and Hérail 1978; Sánchez-Palencia 1980; Perea and Sánchez-Palencia 1995; Matías 2006; Dieulafait et al. 2008; Matías and González-Nistal 2014; Justel Cadierno et al. 2014; Fernández-Lozano et al. 2014; Fernández-Lozano and Gutiérrez-Alonso 2016; Matías and Llamas 2017).

The first modern approach to an analysis of the ensemble of Roman mines in the Eria River basin was by the engineers Sáenz and Vélez (1974, pp. 97–109), who evaluated the total

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Fig. 1 Location of the study area (image: LANDSAT, map: IGN 1:200,000)

mined volume of the Roman works in 20 Mm³ (10 Mm³ in a single mine: Las Murias-Los Tallares).

Contemporary of Sáenz y Vélez, the mine research work was done by geologist Luis Carlos Pérez for the company Río Tinto Patiño, S.A., in order to evaluate the possibility of reopening the secondary gold ore deposits in this area (Pérez García 1977, pp. 186–254). Pérez evaluated the materials mined at Las Murias-Los Tallares in 8 Mm³. His main contributions to the knowledge of this area have been the following:

- To establish a system of alluvial fans from the denudation of the Sierra del Teleno mountains as the main source of the secondary ore deposits.
- The geological exploration of the inner structures of the Miocene alluviums and quaternary terraces.
- To determine the gold content of the alluvial materials and their mining potential.

At the start of the 1980s, archeologist Javier Sánchez-Palencia outlined up to 26 Roman mine work areas in alluvial lands on the banks of the Eria River, questioning the validity of some of those suggested by Sáenz and Vélez (Sánchez-Palencia 1980).

The first detailed map of the hydraulic system of the Roman mines at Teleno situated above an elevation of 1400 (Matías 2005) was published barely 10 years ago which would be complemented shortly thereafter with new data on the mine structures and a proposal regarding the evolution of the development of the mines (Matías 2006). The existence of

a new and extensive primary gold ore deposit was recently defined on the southern slope of the Sierra del Teleno mountains, well known by the Romans (Matías and González-Nistal 2014), which offered a new outlook on the source of the gold in the secondary ore deposits in the area.

Material and Methods

The operational method for analyzing the Roman mine structures is mainly based on exhaustive exploration of the ground for an initial reconstruction of the mine morphology, supported at all times by existing maps and the possibilities offered by aerial photographs (orthoimages) both for the precise location of important elements as well as to obtain an adequate view of the ensemble. Added to all of this is the use of LIDAR data to obtain a local and detailed DTM to highlight, differentiate, and analyze the evidence of anthropic activity on the ground. This all-new technique opens up an important range of possibilities as it enables very reliable observation of the ground below the vegetation layer.

As concerns, the particular use of LIDAR technology in Roman gold mining, specific and multi-disciplinary work has already been done (Fonte et al. 2014) very briefly outlining the advantages and limitations with everything in the end passing through exhaustive field exploration with adequate criteria and parameters due to the difficulties of interpretation as a result of the deterioration of the evidence and the overlapping

Fig. 2 Orthoimages (PNOA 2006-0.5 m and PNOA 2014-0.25 m) of the Roman mine before the forest fire of 2012 (a) and after (b). DTM-LIDAR showing the roman mining structures (c)

of structures over the nearly 2000 years of anthropic use of the land.

The source of all of the images and the digital maps (historical aerial photographs, orthophotographs, LIDAR, etc.) is the IGN (Spanish National Geography Institute), promoter of the project PNOA (National Plan of Aerial Orthophotography) as well as the Institute for Agricultural Technology of Castilla y León (ITACyL), which are freely disseminated for non-commercial use. They were processed and the DTM was generated based on LIDAR files using the commercial programs Arcgis10.3 and Global Mapper 16.0, respectively.

The metadata (ISO 19115:2003) of the LIDAR 2010 flight used are the following:

Nominal density, 0.5 p/m²
 Nominal distance, 1.4 m
 Altimetric precision points, RMSEz ≤ 0.20 m
 Altimetric precision DTM, RMSEz ≤ 0.5 m
 Grid, 5 × 5 m

Multiple returns, 4
 Classification, automatic
 Geodesic reference system, ETRS89

Analysis of the Las Murias-Los Tallares Roman Gold Mine

The detailed study of the different aspects (geology, hydraulic system, mining areas, tailings, and work methods) comprising this great mine will make it possible to better understand the approaches used by Roman engineers to make use of the auriferous alluviums and their evolution, both in space and over time.

In general, this Roman mine is known for the great longitudinal extension (4.6 km) with barely 400 m of maximum width. The mining works is located between elevations of 985 and 920 m and was done on the edge of a fluvial terrace. The

tailings from the washing process were accumulated by hydraulic drag at the exit of the mines on the current Eria River floodplain.

Geology

The area studied is located on the eastern edge of the Sierra del Teleno Mountains, a well-known mountain chain characterized by the abundance and types of auriferous ore deposits and Roman mines. The highest altitude is reached by the Teleno Peak at 2188 m., the maximum elevation of a range which extends uninterruptedly in a N 120 E direction for more than 60 km. The primary geological materials comprising the Sierra del Teleno are Paleozoic sandstone, slate and quartzite (IGME, 1981), the ages of which are between the Cambrian (570 million years) and Silurian (400 million years) periods.

The great geological structures reflect a dominant NW-SE direction corresponding to Hercynian folding. The Ordovician quartzite stands out due to its influence on the relief of the current landscape. The differential erosion of this quartzite has given rise to steep headlands.

The ensemble was elevated during the Alpine orogeny (45–15 Ma) with a succession of several geology phases of intense meteorization. The tropical climate conditions of this area during the Miocene (37–15 Ma) led to major accumulations of alluvial deposits of a characteristic red color. There are great discordant beds of Miocene materials (clay and round pebbles) from the current Eria River banks to an elevation of 1200 (in the towns of Pozos and Corporales) which were later eroded with the remains filling the foot of the forest in gentle layers. The most modern materials (Quaternary) are comprised of fluvial terraces as a result of the remobilization of the prior levels (Fig. 3).

Mettalogeny

The mettalogenetic profile of the primary gold mineralization distributed within the Sierra del Teleno and surrounding areas correspond to stratoid and hydrothermal quartz and sulfide (arsenopyrite), characterized as epigenetic and discordant, relating to polyphase tectonic structures embedded in detritical rocks in greenschist facies (Tomos 1992; Tomos and Ribera 1993). These authors observed a spatial disconnection with the shear zones yet related, however, to extensional structures associated with fold lines. The recent study of various primary gold ore deposits in the Teleno region have made it possible to definitively consolidated this mettalogenetic model (Gómez Fernández et al. 2005, 2010, 2012).

The specific type of this gold mineralization, which is structurally connected to rocks of low metamorphism with barely or no direct relationship to magmatic sources, fits within what was recently defined as *orogenic gold* (Ridley 2013).

The elevation and later degradation of the Sierra del Teleno by atmospheric agents generated major accumulations of alluvial deposits in the Neogene (Miocene) of a characteristic red color where there are particles of gold (nuggets) mechanically carried from their places of origin following a system of alluvial fans towards the east. The remobilization of these materials gave rise to the formation of a system of thin fluvial terraces (T-1, T-2, T-3, and T-4) with higher gold content than that of the original Neogene materials due to natural reconcentration (Pérez García 1977; Hérail 1984).

The Romans mined all the thickness of the T-2 terrace until the Miocene period, between 5 and 8 m, at Las Murias-Los Tallares (Fig. 4a), which exceptionally reached 15–20 m only on the NW end where a drag cut was created near the Paleozoic substrate.

The multinational mining company Río Tinto Patiño, S.A., conducted a preliminary washing pan sampling of terrace T-2 with 13 185-kg samples, one of which reached a grade of 204.6 mg/m³. The primary sampling was conducted through 11 shafts using a 3.5 t clamshell bucket with a diameter of 1.40 m hanging by a cable from a crane. It reached 40 m deep (Fig. 4b). The shafts were created following the N edge of the Roman mine after their work areas (Pérez García 1977, pp. 186–254).

The size of the gold particles from terrace T-2 is submillimetric. Only as an exception are some of them 3.5 mm long. They exclusively pertain to the terrace T-2 area where nonlaminar particles (grains and distorted shapes) have also been found which clearly indicate possible Paleozoic origin (Fig. 5).

Grain size analyses revealed the existence of a significant portion of fine gold (<0.08 mm), practically impossible to recover in an economic manner. The percentage of this fine gold out of the total grade is around 20%, and even 50% in some cases. Thus, the following results were found at terrace T-2 considering only the recoverable gold:

- Volume of alluviums researched, 16 Mm³
- Mean Au grade, 58 mg/m³ (maximum value, 81.5 mg Au/m³)
- Total Au, 0.928 t

Hydraulic System

The Las Murias-Los Tallares supply (Matías and Llamas 2017) was comprised of two main canals (CEr-01 and CEr-02), which got water from the Eria river and a third supporting one (CEr-03), situated quite well above the maximum mine elevation which was sourced by the Formosina brook near the town of Morla (Fig. 5). To a greater or lesser extent, all of these canals could have been involved later in the exploitation

Fig. 3 Geologic map of study area (source: authors, adapted from SIEMCALSA)

of the other auriferous ore deposits situated upstream, especially canal CER-02, due to the longer route (Table 1).

The maximum supply elevation for the Las Murias-Los Tallares Roman mine is 985 m, meaning both canals could have been operative from the very beginning which would have allowed simultaneous use of the entire hydraulic system during the initial mining work phase, sourcing both the E as well as the W ends of the mine without producing any type of interference between the various gullies, the pace of which would have been marked by the availability of water and labor. Nonetheless, and with some exceptions, a clear progression towards the W of the mine work sites can be observed in the mine canal intersections. Canal CER-01 was no longer available for the final phase of the work.

The supply capacity (Table 2) of these canals for annual continuous service for the entire supply system under ideal conditions was 20.2 Mm^3 ($55,296 \text{ m}^3$ per day).

Mining Tanks and Canals

Up to six regulation-distribution tanks have been located (Table 3 and Fig. 6). Two of them are still in an acceptable

state (DER-01 and DER-03). They are systematically found near the mine faces (Figs. 7 and 8a).

There are a number of mine canals between tanks DER-03, DER-04 and the adjacent tanks responsible for taking the water to the faces with several derivations between them and the mine work sites, reflecting a maze that is complex and difficult to explain as there are also modern roads overlapping the old watercourses. In the case of the area around deposit DER-03, one can see how some of these derivations were laid out at different times with a predominant, deeper one towards the east. In summary, it could be said that it is an apparently labyrinth-like structure which proves different periods of work in the western third of the mine, supplying different sectors.

After the western third of the mine, the water was taken through a single canal situated near the edge of the mine work sites and then would derive as necessary to supply the various faces (Fig. 9b).

Peines System as a Roman Mining Exploitation

Jones and Bird (1972, p. 61–62, sectors I and II) classify the method followed at Moraceras as the result of “giant plowing”

Fig. 4 a Schematic section showing geology and Roman mining works (from Pérez García 1977). b Inside a Río Tinto Patiño prospecting shaft (1.4 m Ø)

making reference to the use of the technique known as *ground sluicing*. They also suggest that water was also used to first remove the tailings cover (*hushing*).

Domergue analyzed this specific type of Roman hydraulic mining in-depth for the first time ever, making reference to the three main Roman mine sites of this kind located in the province of León, although he mainly focused on those found at

Las Moraceras (Priaranza de La Valduerna) and Las Omañas (Domergue 1973; Domergue et al. 1988). He used the term “chantier-peigne” to establish similarities between this method and *ground sluicing*, used in the nineteenth century California gold mines, yet clarified different aspects. He also defined a means of operation for each mine work unit largely consisting of the manual layout of rectilinear and parallel

Fig. 5 Submillimeter gold nuggets of the terrace T-2. Note the low degree of rolling

Table 1 Supply canals. Las Murias-Los Tallares Roman gold mine

Canal	Length (km)	Elevation intake	Supply elevation	Approx. average slope
CEr-01	7.75	1000	985	0.2%
CEr-02	16.9	1046	993	0.3%
CEr-03	1.3 + 3.3	1078	1014	

These elevations were obtained from the existing maps (IGN) without any topographic measurements

trenches separated 15 m from each other where water was released to deepen the trenches 1–2 m and drag the auriferous sediments towards the washing canals which were located outside the drag areas. Each mine unit features a single evacuation canal where all the parallel grooves lead. This process would have to be supported by plenty of labor to facilitate the sediment dragging as well as separate the largest pebbles. With a width of 3.5 m, the washing canals (sluices) would be defined by pebble walls on each side with the back covered in these materials as well. The deepening work to reach the bedrock would be done in successive 1–2 m cycles all along the length of the grooves or in different sectors until the end of the mine was reached (Domergue and Hérail 1978, pp. 263–268; Domergue 1990, pp. 465–466).

Sáenz and Vélez (1974, pp. 105 y 109) define the look of the Las Murias-Los Tallares Roman mine as a “plowed field,” calling the different mine units “mine shovels” (due to their similarity to this tool), using the term “valley mining” for this type of work without going into any details concerning the specific means of operation of this mine yet another section of their publication (Sáenz and Vélez 1974, pp. 56–60) defines the work method in a general manner. Their description also supports the combined use of water and labor to open and deepen the grooves with the simultaneous participation of 2000–3000 operators and the possibility of working at different heights over the same point in different phases clearing the land in several layers.

Sánchez-Palencia define this system as “plowed grooves” (Sánchez-Palencia 1977, pp. 66–71) and indicate a work procedure similar to the one described by Domergue with excavation of the main trench first where the water was released, thereby rejecting the suggestion by Sáenz and Vélez of work being done at the same point at different heights in several

phases. In their study on Roman auriferous mining in the Eria basin, no additional details in particular are added except that the mining was done in an ascendant manner (Sánchez-Palencia 1980, p.225).

Extraction Procedures

There are 60 mine units at the Las Murias-Los Tallares Roman mine with each one defined by groups of a specific number of trench canals (usually 6–8) which converge in a common evacuation corridor (Fig. 9a, b). This arrangement indicates that each group of canals was worked at a certain time either simultaneously, alternatively, or a combination of the two until the basement or bedrock was reached, determined in this case by the Miocene (Pérez García 1977, pp. 186–87, Fig. 36). The habitual width of the grooves is 13 m, with some values that may reach 16 m or even be as low as 8 m, such as in the areas of the most shallow sediments (*Vallico la Escoba*).

Pursuant to Domergue and other authors, the design of the Roman mine work areas as far as the planning and continuous supply of water largely correspond to the technique known in modern times as *ground sluicing*, which was widely practiced throughout the world during the mid-nineteenth century Gold Rush, the precursor of today’s hydraulic mining, which already used pressurized water: *hydraulic mining* (Phillips 1867, p.149; Waldeyer 1873, p. 390). As concerns this technique, some authors indicate the presence of tanks at the head of the mines as evidence of the *booming* technique deriving from *ground sluicing*, which consisted of releasing large quantities of water from these tanks in an isolated manner (Longridge 1910, p. 196).

Putting the observations made by other authors and specifically referring to the Las Murias-Los Tallares Roman mine, the following main characteristics can be readily seen:

- The existence of at least two different and overlapping work phases (Fig. 9a)
- The systematic presence of residual rock on the edge of terrace T-2 where the evacuation canals were opened.
- Significant accumulation of thick tailings at the exists of the evacuation canals, with the complete absence of any clay elements and their heterometric nature standing out (Figs. 10 a, b).

Table 2 Supply capacity (m³). Las Murias-Los Tallares Roman gold mine

	Length	Slope	Width	Depth	Flow	1 day (m ³)	1 month (m ³)	1 year (m ³)
CEr-01	7.75 km	0.2	0.90	0.45	0.22	19,008	570,240	6,937,920
CEr-02	16.9 km	0.3	0.90	0.45	0.27	23,328	699,840	8,514,720
CEr-03	1.3 km	0.2	–	–	0.15	12,960	388,800	4,730,400
Available flow rates				Total		55,296	1,658,880	20,183,040
				CEr-02 and 03		36,288	1,088,640	13,245,120

Table 3 Roman gold mine tanks.
Regulation tanks Las Murias-Los Tallares Roman gold mine

Tank	Location	Dimensions	Capacity (m ³)	Direct supply
DEr-01	La Pradera	210 × 15	4725	CEr-02
DEr-02	La Pradera	130 × --	--	CEr-01
DEr-03	La Pradera	(3200 m ²)	4000	--
DEr-04	La Pradera			--
(DEr-05)	Vallico la Escoba	(18.000 m ²)	8000	--
(DEr-06)	Cuesta del Pinar	(20.000 m ²)	10,000	--

- Very little slope at the bottom of the mine ($\approx 1.5\%$), which is practically even in all sectors (Fig. 11, Table 4).

In order to understand the specific supply process for this auriferous deposit, once must keep in mind that the lower level of the main mine is some 8–10 m deep with respect to the original ground of terrace T-2. However, the intermediate divisions between each groove where large pebbles sometimes accumulate barely rise 2–3 m above the bottom of the grooves. With an average separation of 13 m between the grooves, it is not possible to maintain the stability of the

ground for heights of 8–10 m. Under these conditions, it would not be very suitable to apply the concept generally accepted up to now of separating the large pebbles contained in the in situ alluvium but rather keep them there throughout the washing process. On the other hand and although there are many piles of pebbles inside the mine areas, obviously as a result of the final phase of the work, most of the tailings, which are already free of the clay fraction, are deposited at the exit of the various *peines* on the edge of the terrace. They all take on a characteristic and individual defection cone shape, clearly topped off by an evacuation canal responsible for taking these materials further and further away. A number

Fig. 6 Arrival of canals to the exploitation of Las Murias-Los Tallares

Fig. 7 Location of the main regulation-distribution tanks in the frame of the USAF Flight 1956 57

of large pebbles can be observed among the tailings which were not manually deposited.

Since the mine gets deeper and it is necessary to maintain the hydraulic slope for the alluvium to burst and the tailings to leave, the evacuation canal gets progressively longer over the debris. The big difference in height between terrace T-2 and the Eria River floodplain (20–30 m) allowed for a large accumulation of tailings in the initial stages over which the evacuation canals now observed on the ground would gradually extend. This fact can still be documented by the existence of some surface *peines* situated on the edge of the terrace and later abandoned as the adjacent work progressed, the tailings from which would directly accumulate on the edge of terrace T-2 without having developed the characteristic evacuation canal.

Thus, the mining system proposed by other authors must be reappraised and updated without invalidating some of their arguments yet adapting them to the reality of the ground which can now be better analyzed with the new technologies. Given the immense accumulation of heterometric tailings deposited in the Eria River floodplain, the piles of pebbles (*"urias"*) observed in mining areas pertaining to the final phase of the mining work are not at all representative of all of the tailings contained from the processed materials. These pebbles were manually separated for practical reasons during one of the many mining work cycles (the final one, in this case) given that the evacuation

of the debris had to be combined with the gold recovery in the washing canals.

Although it has been traditionally considered that the piles of pebbles are generally situated near the washing areas, Pérez García (1977), p. 187) also observed the circumstance on the ground that "the crests between the canals of one *peine* are already reduced in many places to the minimum expression and are even completely artificial with just piles of large blocks remaining, nothing more, indicating the methodic cleaning done on the neogenic bedrock." We can currently corroborate this fact in the section produced by illegal excavation at the base of a group of *peines* to extract materials used to repair roads following the 2012 fire (Fig. 12).

In view of the above, two facts must be taken into consideration which are habitual in *ground sluicing*:

- The entire auriferous level has been cleaned, even slightly deepening the bedrock (Miocene).
- The piles of thick pebbles would have been eliminated by means of a current of water if deepening had continued.

One must always remember that this hydraulic mining system was designed to handle large bodies of materials, meaning the objective is to place a significant quantity of alluvium into movement as a "sludge current" (debris flow) to get it through the washing canals.

a

b

- Once the desired depth is reached, the flow of water is interrupted to allow for the manual removal of the auriferous concentrate which is later washed out either in situ or elsewhere.
- All of the thick debris previously removed is evacuated, and the flow of water is reestablished to drag them to the grooves. This frees up the berms to lower them and continue digging deeper, separating the large pebbles.
- The washing canals are rebuilt.
- The extraction process begins again. The cycle is repeated until the sterile substrate is reached.

- On the other hand, there are also some *peines* which have not been depleted to the end of the supply canals (Figs. 13 and 14), which means the extraction could have been done up to the bedrock and maintaining the total height of the exploitable auriferous bank. This work process has the following advantages:

Fig. 9 a Structure of the Roman gold exploitation Las Murias-Los Tullares. b Detail of the Roman exploitation: exploitation canals (green lines), work phases (blue and red lines), and accumulations of sterils (brown)

- Increased water gradient in the extraction areas by working with 8-10 m level changes which reduces its consumption as the effectiveness increases, also affecting the amount of necessary labor.
- Less loss of auriferous materials as the cleaning is always done in the same position.
- The possibility of extending the washing canals lengthwise as the plain is filled, thereby reducing possible losses of fine gold.
- Ease of tailing evacuation without interrupting the process.

Without any in-depth studies of the other major examples of Roman auriferous *peines* mining (Las Omañas and Las Morceras), the possibility of using both procedures and even a combination of them must be accepted.

Mining Phases

It would be coherent to consider several work phases given the great longitudinal extension of the auriferous ore deposit. Pérez García (1977), pp. 186–187) already discussed three ascending mining phases completed by backwards on the terrace. In his exploration work, he located two already filled shafts on the upper plain which he attributes to Roman prospecting to establish the thickness and wealth of terrace T-2. Nonetheless, the singularity of these shafts which is not repeated in any other mining work for the area leads to the belief that they were completed in a more recent period related to the mining attempts in the 19th and 20th centuries (Fig. 15).

In the case of Las Murias-Los Tallares, the existence of two supply levels (CEr-01 and CEr-02) does not correspond to two work phases given that both canals are above the maximum

Fig. 10 a Accumulations of tailing materials ("Murias") within the areas of exploitation (peines) after the fire of 2012. b Accumulations of tailings in an area unaffected by the fire of 2012

Fig. 11 Schematic profile of the mining works showing the slopes

Fig. 12 Miocene bedrock

ore deposit elevation (Fig. 8a). Rather, it seems to be related to the need to simultaneously feed different sectors.

Nevertheless and after observing the structure and arrangement of the *peines*, the existence of at least two overlapping phases using different procedures can be easily observed. The first phase seems to have worked the first 120–150 m of the edge width of the T-2 terrace slope towards the plain while the second overlaps the first, reaching 450 m. The presence of the first phase is detected almost all along the mine but it is particularly obvious on the eastern end.

The technology used in the two phases is the same, although greater regularity and surface area is noticeable in the *peines* in the second phase as well as a greater depth which sometimes distinguishes the two phases as part of the initial work was halted at a higher level than the final phase which hollows them out with the progression.

Gold Recovery

Simply remobilizing the auriferous alluvium with a current of water and circulating it through a narrow canal causes the gold particles, which are 8.5 times heavier than the materials among which they are found, to quickly move to the bottom of the

sludge where any natural or artificial obstacle easily retains them. This natural phenomenon is the basic principle behind *ground sluicing*, widely represented in *The Agricola* (1556, Book VIII), which demonstrates the continuity over time of this mining technique even though it did not receive any specific name until the nineteenth century. Nearly 2000 years before, Pliny described the gold recovery process in this way:

Plin.Nat.33.76: There is also yet another task to perform on the level ground. Trenches are excavated for the water to flow through—the Greek name for them means 'leads'; and these, which descend by steps, are floored with gorse—this is a plant resembling rosemary, which is rough and holds back the gold. The sides are closed in with planks, and the channels are carried on arches over steep pitches. Thus the earth carried along in the stream slides down into the sea and the shattered mountain is washed away. (Translation by H. Rackham, W.H.S. Jones and D.E. Eichholz. Also Pérez and Matías 2008).

Based on Pliny's text, Domergue initially situates the washing canals in the evacuation canals, where was common to each mining unit with a great length due to the scarce slope (3.35%). He bases this argument on the presence of large pebbles throughout the evacuation canal of the unit studied at Las Moraceras and the observations to this end from the existing bibliography on modern auriferous mining (Domergue 1973; Domergue et al. 1988). Afterwards, the same author corrects the site of the washing canal, situating it towards the entrance to the evacuation canal (Domergue and Hérail 1978, p. 267).

As the size of the gold particles increase, the area the current must run for them to reach the bottom becomes less. This

Table 4 Roman auriferous mining. Peines system. Average slopes of the different elements

Mine	Extraction zone	Drainage canal	Evacuation canal
Omañas	3–4%	3.5–5.75%	6–6.5%
Moraceras	2–3.8%	3.80%	3.3–7.5%
Murias-Tallares	1.2–1.7% ^a	2.3–4.3%	2.9–4.2%

^aThe slope in the western zone increases to 3.33%

Fig. 13 Rest of exploitation canals that show the possibility of simultaneous works on all the thickness of the gold layer (eastern sector). Orthoimage PNOA 2014-0.5 m

aspect is what defines the length of the washing canals, which may range from a few meters to hundreds of meters combining the slope with the flow of water and volume of materials to be processed. Nevertheless, the most basic idea of *ground sluicing* uses the very evacuation canal bottom to retain heavy materials. For improved efficacy, large pebbles or stones are placed in the current to foster sedimentation or a real washing canal is used equipped with retention systems for all the material to pass through after first removing the largest elements that could compromise the integrity thereof. Later, the debris that remains at the bottom containing the heavy materials must be manually processed either by tamping or by using other more complex systems (Levat 1905, 85–96; Longridge 1910,

pp.195–196; Wilson 1912, p.43; Thorne and Hooke 1929, pp. 51–56; Griffith 1960, pp. 120–121).

The position of the manual piles of pebbles does not seem to be sufficient criteria to establish the situation of the washing areas in the case at hand, as they are preferentially inside the *peine* area to the start faces. However, without any related archeological excavations that could determine the exact position of the washing canals, we would also be inclined to believe that their position must have been in the evacuation canal which was the common point of passage for all extracted material. In fact, the very configuration of the ore deposit leads to the belief that if the washing canals had been in the same grooves, it would not have been necessary to use any common

Fig. 14 Rest of exploitation canals that show the possibility of simultaneous works on all the thickness of the gold layer (western sector). Photograph of the USAF 1956–57 American Flight

Fig. 15 Photograph of the USAF 1956-57 American Flight of the central sector of the exploitation, where the exploration shafts are appreciated

evacuation conduit and the tailings would have been directly dumped into the floodplain without leaving any residual rock.

The cubage of the tailings from the Las Murias-Los Tallares Roman gold mine reflects a figure of nearly 6 Mm^3 , for an extracted volume of materials of 11 Mm^3 . LIDAR makes it spectacularly clear that the tailings were carried and deposited by the force of the water (Fig. 16).

Discussion

LIDAR data processing is now an essential tool for analyzing Roman hydraulic mining structures in NW Hispania, the limitations of which may be as follows:

- The quality and precision of the data collected in the LIDAR scanner
- The state of mine structure conservation
- The overlap of modern structures
- Working scale (general or detailed)

Although the possibility of discovering new mining zones, most of which were already located in the 1970s and 1980s by means of extensive field explorations and meticulous photointerpretation work with stereoscopic images taken by archeologists Domergue (1987) and Perea and Sánchez-Palencia (1995) is quite low, there is still a good outlook for this technology in areas covered with vegetation with the aforementioned limitations. However, LIDAR is not proving to be effective in locating small mines over outcroppings of

Fig. 16 DTM-LIDAR showing in detail the accumulation of tailings material on the current terrace of the Eria River

primary ore deposits, more than a dozen of which have already been documented in the area (Matías and González-Nistal 2014).

The use of LIDAR in the study area made it possible to locate and analyze hydraulic mining structures hidden by trees (tanks and extraction areas), which has greatly facilitated field explorations.

There is still much unknown information as to the work procedures due to the complex nature of the Las Murias-Los Tallares Roman gold mine meaning this analysis needs to be done on the other two major headframe Roman mines (Las Moraceras and Las Omañas) in order to compare the findings.

Conclusions

LIDAR technology was used to study the Las Murias-Los Tallares Roman gold mine (Castrocontrigo, León-Spain). This technique had to be combined with an analysis of historical photographs and orthoimages all while doing meticulous field work to collect in situ data as well as to verify the nature of some of the evidence observed in the DTM and aerial photographs. The combined use of these technologies helped understand the evolution of the mining works.

The analysis of the structure and arrangement of the *peines* show two main phases of ascending mine work. The total material dug up by the Romans is 11 Mm³, which is 1 Mm³ more than the figures offered by other authors.

The maximum mine depth level is limited by a practically sterile Miocene bedrock although there is not enough evidence to define the reasons limiting the extension of the Roman work towards the north although Río Tinto Patiño, S.A. explorations show a very small gold content (average recoverable gold grade 58 mg Au/m³, with a maximum value of 81.5 mg Au/m³). By applying a recovery rate of 80% of the dug up materials (11 Mm³) to these data, the Romans would have obtained 510.4 kg of gold. This figure should be considered with reservations as the Romans paralyzed mining efforts voluntarily at specific points, gradually moving all work to the west until the ore deposit was depleted which clearly indicates a possible decrease in grades towards the north, pursuant to the geological model of the ore deposit where the T-2 terrace reflects a gradual transition towards until the Miocene period.

The tailings were evacuated using the same water as was used for the extraction work, and they are accumulated in large artificial dejection cones in the Eria River floodplains. The cubage for these materials is 5.75 Mm³.

The moderate slopes of this ore deposit required the use of large volumes of water for mining, combined with plenty of labor to facilitate the water work on the alluviums.

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