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Absent Voices and Unwarranted Presences: A Combined Multi-Approach to Mapping the Roman Hydraulic System Supplying Las Médulas Gold Mine (NW, Iberia)

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Abstract: This study analyses the Roman hydraulic system linked to Las Médulas gold mining complex in Northwest Iberia. The research includes a detailed mapping and assessment of the hydraulic network, which extends over 1110 km, using advanced geomatic techniques and an innovative script for tracing canals implemented in Matlab. The study reveals previously unidentified canals, improves existing cartographic representations, and addresses water sourcing and canal distribution uncertainties. It identifies 41 canals distributed between La Cabrera and El Bierzo regions, (33 and 8, respectively), with 14 canals supplying water to Las Médulas. Our study also provides evidence that this canal system had a wider purpose than simply supplying the mining works at Las Médulas. Furthermore, the findings presented here challenge established assumptions about the system's water sources and offer new insights into how this outstanding canal system was built. Thus, this work not only provides a detailed map of the Las Médulas hydraulic system but also constitutes a model for an effective methodological approach for studying similar ancient hydraulic systems worldwide.

Keywords: Matlab; Roman hydraulic system; gold mining; Las Médulas; GIS

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1. Introduction

Water is an essential component of our planet, playing a vital role in the development and growth of civilizations. Since the dawn of humanity, mankind has utilised water as an energy source, including but not limited to fulling mills, watermills, and irrigation wheels. Hydraulic force is ubiquitous across civilizations in different fields, such as agriculture, transport, and mining [1]. Its application in mining has been crucial for supply, mineral washing, and ultimately removing waste materials from mines [2,3].

Driving the necessary resources to initiate mining operations required a well-defined hydraulic system, allowing water collection and supply to the main mining centres. This technology is often based on canals comprising a large-extent drainage system and water reservoirs. Some of them are locally known for being part of ancient cart tracks, the *carriles—corrugus*, referred to by Pliny the Elder [4]—as they are locally known [5], constitute a network through which water flowed by gravity to the main mining areas during Roman times [6]. The first works on Roman gold mining in the Northwest Iberia that managed to decipher the magnitude of this extraordinary hydraulic work were undertaken by Lewis and Jones [7] and Jones and Bird [8]. These authors identified some remains of this intricate mining complex, such as the coined Montefurados (i.e., Montefurado tunnel) and other unique hydraulic elements of Roman mining, such as the kilometre-long network of canals directed to Las Médulas mine, which they detailed in its final section, as well as a set of water reservoirs associated with mining activities.

The first systematic works were carried out to understand the Roman's mining context, in which the gold mining operations were developed in Northwest Iberia (Figure 1A). Scientific research was mainly focused on the archaeological and mining study of one of the largest Roman mining complexes of international relevance, the gold mine of Las Médulas [9,10]. Internationally recognised for its archaeological importance, this mine was designated a UNESCO World Heritage Site in 1997 [11–13]. However, the hydraulic network was excluded from this declaration, despite its relevance for the development of mining activities and probably, given the enormous spatial extent of the network, exceeding 700 km, which comprises the regions of La Cabrera and Montes Aquilianos-Teleno [14].

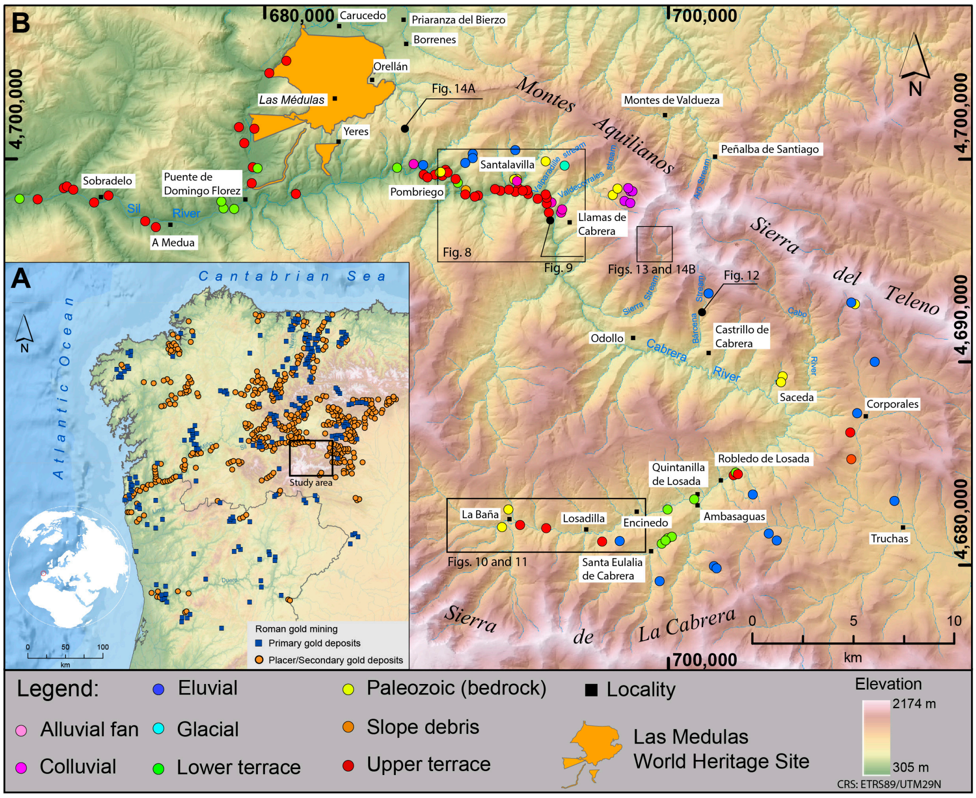

Figure 1. (**A**) The study area is delineated by the square on the small-scale map (mining data based on [3]). This area has been enlarged in (**B**) to show the locations of Roman gold mining sites in the León Mountains (Spain). The coloured circles indicate types of exploited deposits (see legend below).

Although not included in the Las Médulas World Heritage site, the mine's canal system is the subject of considerable ongoing scholarly attention. Early in the new millennium, Sánchez-Palencia and Sastre-Prats [5] summarised the existing state of knowledge about the Las Médulas hydraulic system identifying seven canals from La Cabrera and two more from Valdueza, with these authors acknowledging that their exact number "is little less than impossible to know, given the poor state of conservation of their layout" (p. 241). The maximum length of this hydraulic network would exceed 147.2 km (ca. 100 miles according to Pliny the Elder's testimony), constituting at least a system between 80 and more than 100 km between its northern and southern slopes of the Montes Aquilianos-Teleno, respectively [15].

The first modern attempts to map the hydraulic network were made in 2004, revealing around 600 km of canals. New research has since uncovered up to 700 km of canals [14,16]. These maps were generated using known sections of the canal as control points and Geographic Information Systems to extrapolate a possible trajectory from point to point [17]. However, due to the assumptions of the model, specifically that the slope of a canal remains constant along its entire length, this method can lead to non-physical results, such as the prediction that the water would have been running uphill in some sections of the canals. Variations in canal slope are, in fact, present (from 0.15 to as much as 0.40%; [16]) across the hydraulic network. The canal slope depends on the local orography and lithology; of the presence of available water resources in the area; and which section is being supplied (i.e., upper, middle, and lower) within the mining complex framework [18].

Initially, the mapping of the hydraulic system relies on historical aerial photography from the "Vuelo Americano (Serie B, 1956)" [13,19–21]. The scale of these images and the sparse vegetation due to the intense livestock farming activity in the area at the beginning of the last century allowed for the identification of many of the canal traces. However, the sparse contrast of the black-and-white images and the presence of the wooded regions made it difficult to study many sections of the hydraulic network, due to its large extent.

The development of airborne LiDAR and other geomatic aids such as Unmanned Aerial Vehicles (UAVs) to carry a variety of sensors has greatly improved our ability to investigate archaeological sites. In particular, they enable remarkably accurate mapping of archaeological features even where thick vegetation would prevent visual identification. Thus, such techniques have been employed successfully at several mining sites in Northwest Iberia to examine their hydraulic networks [18,22,23]. Even more detailed mapping of this kind of site has been enabled by the introduction of Geographic Information Systems (GIS), which use digital terrain models (often generated from LiDAR data) to visualise geographic information [17]. The large amounts and complexity of the data involved in GIS do limit its usefulness due to the risks of generalisation and difficulties of interpretation. However, this may be overcome with recent advances in artificial intelligence as described by Fernández-Alonso et al., who taught a neural network to identify mining remains from UAV-derived images [24].

Additionally, the hydraulic infrastructure was essential to Roman gold mining operations and its construction has had a lasting impact on the surrounding landscapes, crucial for our understanding of the evolution of mining landscapes [3]. Until now, there has not existed any detailed and complete open access digital cartography of the Roman hydraulic network.

This work provides a new and precise cartography of the Las Médulas hydraulic network. To achieve this goal, we implemented a novel methodology that enables a precise modelling of canal trajectories employing advanced geomatic techniques to pinpoint existing remains in combination with a Matlab trajectory-mapping script to fill in missing sections using digital terrain models.

The map provides answers to some questions that were still unanswered, such as the reason for the construction of an extensive hydraulic system, the variations in canal slope, and the interruptions observed in some canals across their length. In addition, the generated 3D map will serve as a tool to help in decision-making in managing the Las Médulas UNESCO World Heritage Site, as a basis for future research works, and to enhance the open access public diffusion of such an impressive piece of cultural heritage in Europe.

2. Geographic and Geological Framework

2.1. General Framework

The Las Médulas hydraulic network lies in the León Mountains, a mountain system that extends across the modern Spanish municipalities of La Cabrera and El Bierzo in the province of León. With a principal NW-SE orientation, the León Mountain system comprises two parallel mountain ranges known as the Sierras de La Cabrera and Montes Aquilianos-Teleno. The SE slopes of these ranges descend into the Duero Basin and with an average elevation of above 950 m a.s.l., with maximum altitudes of 2122 m a.s.l., and 2188 m a.s.l., respectively.

The principal river in the region is the Cabrera. It forms a dendritic drainage network, but lithologic variations mean its course is characterised by numerous capture elbows [25]. The processes of river capture are responsible for the Cabrera's significant height variations: more than 500 m between its headwaters and its mouth, located at an altitude of just over 350 m a.s.l. The particular local tectonic and geological conditions mean that from its source near La Baña to where it joins the Sil River, the Cabrera River describes a horseshoe shape initially running W-E on the north of the Sierra de La Cabrera before turning to run E-W to the south of the Montes Aquilianos-Teleno (see Figure 1).

The geological structuring creates a horseshoe-shaped relief on which a dendritic drainage network is arranged, configured by lithological variations and large tectonic structures. Additionally, cirques and moraine remnants located at the valley heads condition the drainage network, giving rise to distinctly glacial valleys, such as those located in the Sierra de La Cabrera and Teleno, extensively exploited by Roman mining activities [26].

From a geological perspective, the area is in the western part of the Variscan Massif, at the boundary between the Asturian-Leonese Zone (ZAOL) and the Central Iberian Zone (ZCI), the so-called NW Iberian Gold Belt [18,27]. The study area broadly covers the Truchas Syncline [28–30]. This structure consists of a polyphase deformation with interference from overturned structures (D1) and subsequently verticalised (D3) with successive episodes of hydrothermal activity leading to the formation of mesozonal-type gold mineralisations [31].

The Truchas Syncline comprises a substantial series of low-grade metamorphic rocks ranging from Cambrian to Silurian. The presence of gold has been reported in the Cambro-Ordovician rocks of Serie Los Cabos and the volcanic intercalations within the overlaying Luarca slates [32–35].

The elevation of the León Mountains is relatively recent. It is associated with the reactivation of Variscan structures during the Oligocene-Miocene, in two phases of shortening that led to the reactivation of the Sierra del Teleno fronts [36,37]. As a result, the western edge of the Duero Basin was compartmentalised, leading to the formation of intramontane basins during the Cenozoic [38]. These Miocene sediments comprising red conglomerates constitute part of important present-day gold deposits like Las Médulas [36]. The final stages of basin infill are associated with reactivations of thrust fronts, leading to the deposition of gold-bearing Raña-type alluvial fans [39–41].

Finally, during the Quaternary, glacial and especially fluvial dynamics shaped the area's relief, resulting in moraine deposits in headwater areas [42–44] and a network of hanging fluvial terraces along the entire Cabrera River basin, which contains variable amounts of gold [45].

2.2. What Do Roman's Exploit?

Until now, little attention has been given to characterising the types of geological deposits exploited by the Romans [46]. However, knowing which deposits the Romans were most interested in is vital to understanding their methods of mining and prospection [47].

A total of 102 mining sites have been identified in the La Cabrera area (Figure 1B). These are associated with primary deposits (in bedrock), but predominantly placer deposits (secondary or sedimentary) (Figure 2). Of the known sites, 45% exploited sedimentary beds located on the hanging upper terraces along the banks of the Sil and Cabrera Rivers (Figure 3A). At many of these sites, the deposits have been exhausted of exploitable minerals, leaving only waste materials composed of large, rounded quartzite blocks, known as *murias* [48]. Furthermore, 17% of the exploited deposits correspond to eluvial materials associated with the transformation and alteration of minerals in slate-like formations. These are predominantly clayey deposits containing slate pebbles and, in some cases, sandstones, which are strongly reddened due to the secondary transformation of chlorite into goethite [49].

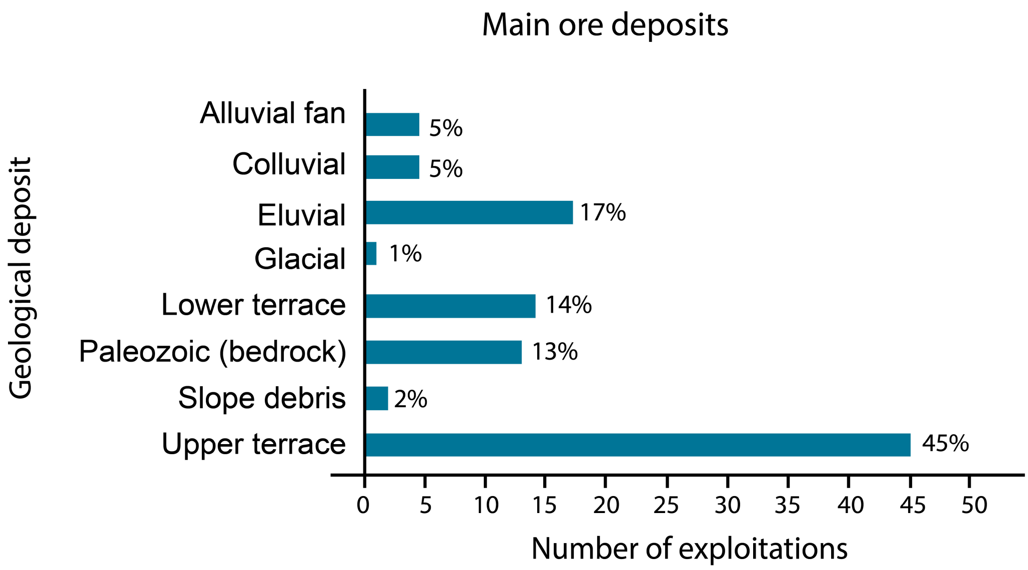

Figure 2. Types of geological deposits (as a % of all deposits) exploited by the Romans in the La Cabrera region.

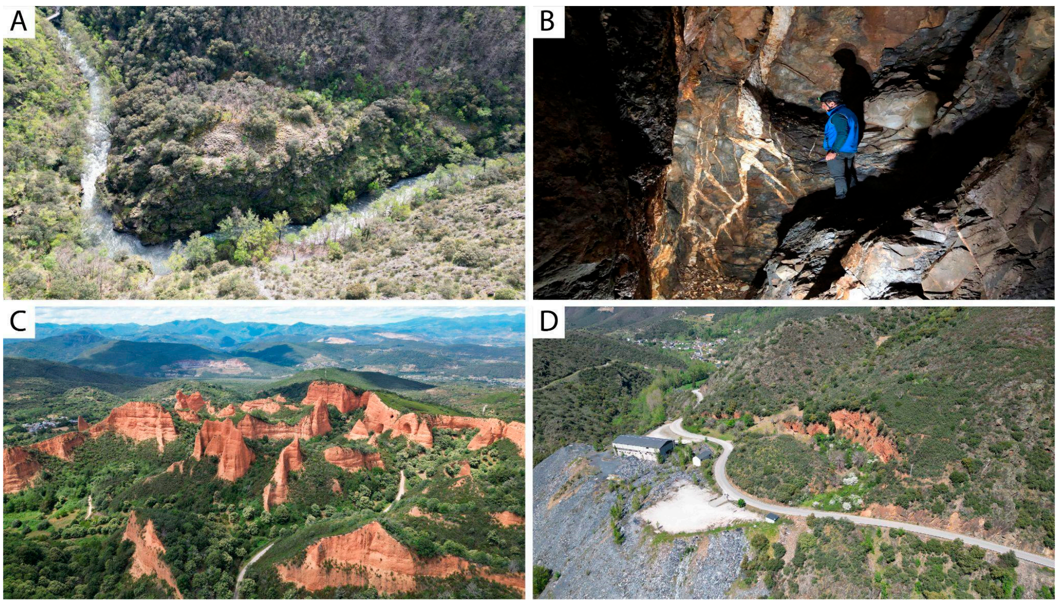

Figure 3. (**A**) Mine located on a Quaternary terrace on the Cabrera River. (**B**) Auriferous quartz vein in the Llamas de Cabrera adits. (**C**) Cenozoic alluvial fan deposits at Las Médulas. (**D**) Quaternary slope debris deposit filling an ancient meander of the Cabrera River near Pombriego.

The lower terrace levels located near the current river courses or just a few metres away have also been significant, comprising 14% of the deposits worked by the Romans. These are the most recent materials, associated with current fluvial dynamics. Notably, there was significant interest in exploiting quartz veins and dikes within the Paleozoic formations, primarily of Ordovician age, which consist of slates, sandstones, and quartzites. Exploitation of these materials accounts for 13%, sometimes conducted through underground mining or by trenches and ditches. The best examples are found in the sectors of La Baña, Saceda, Llamas de Cabrera, and Pombriego (Figure 3B).

The remaining geological formations that constitute the gold placers include materials associated with alluvial fans, such as those found in the Las Médulas deposits (5%) (Figure 3C), and colluvium associated with periglacial processes, especially significant in the more mountainous areas where sandstones and quartzites outcrop (5%) (Figure 3D). To a lesser extent, the exploitation may also occur in slope debris and glacial remnants (2% and 1%, respectively), but these are considered to be of minor importance.

3. Roman Hydraulic System of Las Médulas

The hydraulic network supplying the Las Médulas mining complex is a unique example of Roman engineering which merits detailed study. Its canals were used to supply water for a range of different mining processes and extend throughout the La Cabrera and El Bierzo regions, taking full advantage of the abundant supply of meltwater. The canals show significant technical prowess, for instance, their construction would have required the use of levelling instruments such as the "chorobate" [50–52]. Similarly, the superiority of Roman engineering skill is evident in the way that canal geometry is tailored to the functions of different sections of the system varying significantly between the intake channels at the headwaters through intermediate or lower sections to those nearest the mining operations. Throughout the hydraulic network, an average gradient is maintained of between 0.15 and 0.40% and canal width ranges between 1.20 and 1.50 m. Some of the highest canals collecting water from peat bogs in the Sierra del Teleno are 0.5 m while the greatest widths are seen in sections of maximum curvature to reduce hydraulic force.

Canals were cut, as needed, into all rock-types which, in this region, includes slates, sandstones, and quartzites. These rock-types are extremely diverse in terms of hardness and bed thickness varies across the region; thus, canal geometry is highly variable depending on local geological and geographical conditions [18] (Figure 4). In regions dominated by slate, for example, open canals with retaining or slope-stabilisation walls were built using dry stone blocks. In contrast, in sandstone or quartzite regions, tunnelling through the rock was the most effective means of canal building (Figure 5A).

Several engineering solutions were used to collect and divert water for the hydraulic system, for instance, stone dams and weirs or aqueducts constructed of either wood or stone. Alternatively, in some cases, water was captured directly in conduits [53].

Canals were necessary to divert water from rivers, enabling the extraction of the auriferous sands, as seen in Montefurado, Lugo (Figure 5B) [7,8]. There are also examples of canals being used to transfer water between two valleys, straight through the hard quartzite rocks [54]. This is seen at Pozos de Cabrera, where, in addition, a dry-stone wall is necessary to maintain the canal slope on its way into the mining area (Figure 5C).

To ensure sufficient water supply, large reservoirs were built above or beside the mining areas. Reservoirs located at especially high altitude would take advantage of the abundant meltwater; examples of these so-called snow reservoirs can be found in the Sierra del Teleno (Figure 5D) among other places in the region.

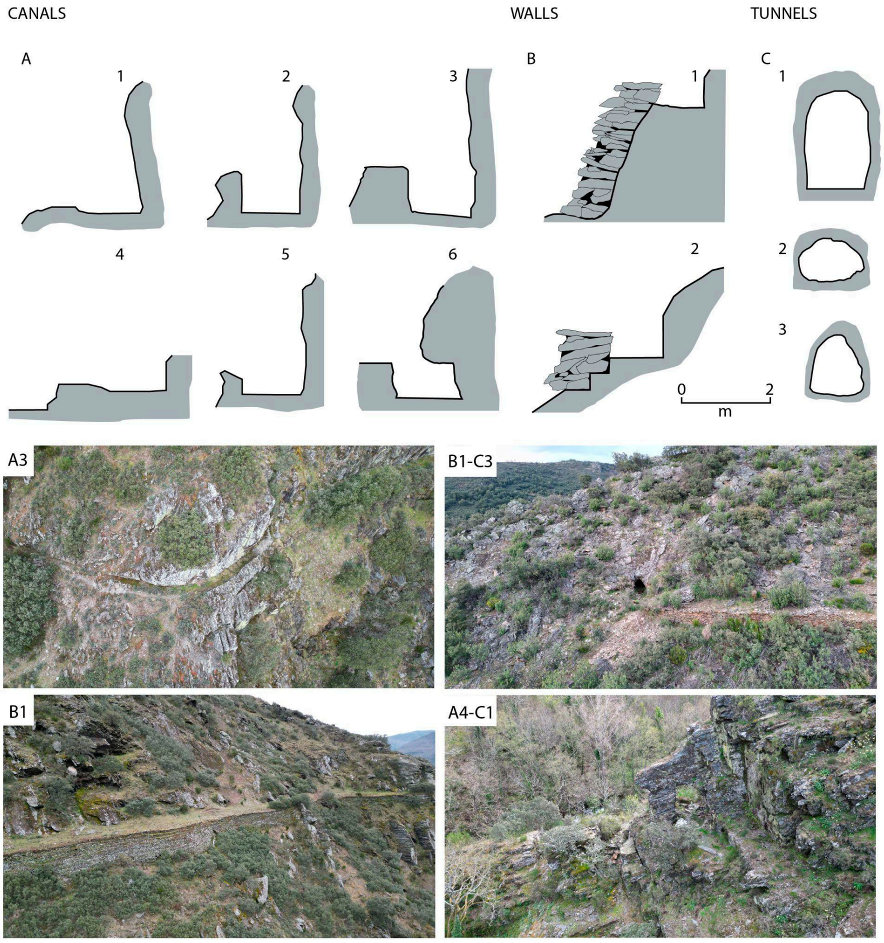

Figure 4. A diversity of preserved geometries and elements that comprise the mining hydraulic system in the study area (based on Sánchez-Palencia [13]). Above: (**A**) canal box; (**B**) canal walls and (**C**) tunnels. Below: photographs of the best-preserved field examples showing combinations of these geometry types: Top left (**A3**) Castrillo de Cabrera: canal box on slate; Top right (**B1-C3**) Llamas de Cabrera: canal wall and tunnel; Botton left (**B1**) Llamas de Cabrera: canal wall; and bottom right (**A4-C1**) Llamas de Cabrera: canal arch, known locally as "La Campana".

Figure 5. (**A**) Tunnel-canal near Pombriego. (**B**) Montefurado Tunnel, used for mining auriferous deposits. (**C**) Inter-basin transfer canal comprising an elevated tunnel, Pozos de Cabrera. (**D**) Snow reservoir at Sierra del Teleno.

4. Material and Methods

To complete the new map of the Roman hydraulic network at the Las Médulas mining complex, a combination of techniques was necessary. Initially, a field campaign was undertaken to locate existing archaeological remains using GPS-RTK. Additionally, an extensive visual analysis was conducted based on aerial orthophotography from various flights, ranging from the "Vuelo Americano (Serie B, 1956)" to the most recent PNOA2020 (Plan Nacional de Ortofotografía Aérea), to detect possible traces. Then, a Matlab script was used to interpolate the possible routes of canals by a 2 m digital elevation model from Download Center of National Center for Geographic Information (https://centrodedescargas.cnig.es/CentroDescargas/modelo-digital-terreno-mdt02-segunda-cobertura, accessed on 4 January 2024).

Canal remains were located using a GNSS receiver (GG04 plus Professional: Leica Geosystems, Leica Geosystems A.G., Heerbrugg, Switzerland) combined with the Leica GNSS network. The mountainous nature of the terrain in the study area means that 4G connectivity is not always stable, thus, to obtain RTK data, the Leica SMARTLINK system was used (Figure 6). This satellite-based system enables extremely precise positioning (RMSxyz~8–10 cm).

Figure 6. Data acquisition in the field using accurate positioning of canal reaches using a GNSS receiver.

The Matlab script is a straightforward script that automatically traces a constant-slope trajectory from a starting point defined by geographic coordinates. The slope can be positive or negative, depending on whether the trajectory follows an upstream or downstream path. This trajectory is plotted on a Digital Terrain Model (DTM), where a series of calculated points outline the determined path. A MDT02 was downloaded from the cartography download centre of the National Geographic Institute of Spain (available at: https://centrodedescargas.cnig.es/CentroDescargas/index.jsp. Accessed on 26 August 2024). This digital model has a resolution of 2 × 2 m, and it was generated from LiDAR flights as part of the second coverage stage of Spain's National Aerial Orthophotography Plan (PNOA). The coordinate reference system is EPSG25829, and orthometric altitudes are used.

The script requires three input parameters: the desired slope, a search radius for identifying the next point, and an approximate initial azimuth of direction. Once these parameters are set, the algorithm evaluates all elevations within the search radius across a wide arc (270°) in the direction of advance. By fitting a continuous function to the absolute elevations retrieved from the DEM, the script determines the theoretical direction that meets the specified slope condition. A new point along the trajectory is then established in this direction at the corresponding distance and theoretical elevation. Although the DEM's actual elevation at that point may not precisely match the theoretical elevation, the algorithm consistently relies on accurate DEM altitudes for slope calculations, ensuring that the theoretical trajectory closely follows the DEM.

In addition to the DEM, the script utilises a slope and aspect digital models to prevent unexpected changes in direction. This issue arises because, for any given slope, there are always two possible uphill directions with the same positive gradient and two downhill directions with the same negative gradient. For slopes as gentle as those required for tracing Roman canal trajectories (typically around 0.15–0.40%), the angle between these opposing directions can approach 180°. To address this, the script selects the correct direction by identifying the path of minimum slope in the slope and aspect digital models closest to the azimuth of the previous segment.

Another challenge the script tackles is when a calculated point lands in a local minimum (such as a depression or sinkhole) or a local maximum (like the peak of a small hill) in the DEM. For example, if the downstream trajectory encounters a pool, all surrounding points will be higher, making it impossible to find a direction that satisfies the slope condition. In such cases, the script incrementally increases the search radius until it identifies a lower point that continues the descent. Similarly, for upstream paths, if a local maximum is reached, the search radius will be expanded until a higher point is found that meets the required slope.

After calculating the trajectory, the series of points can be exported as a polyline in Shapefile or DXF format using the MapTool Boox Matlab libraries. The resulting polyline typically spans 5 to 20 km. Users can overlay this polyline on aerial images to monitor and recognise traces or other indicators of the canal's presence. This also allows for fine-tuning the slope through successive iterations.

5. Results

In this study, 41 canals were identified, mapped and distributed between La Cabrera (southwest) and El Bierzo (northeast) sectors, leading to a total length of 1110 km, including the observed and the interpolated traces (Figure 7). All data were published opensource in Zenodo open repository [55]. The canals were named according to the nearest town, including two letters that identify them, along with the elevation of the canal catchment area. If the canal reached Las Médulas, the letter "M" was included in the name. Additionally, the interpolated sections of the canals and the sections of the canals within Las Médulas are shown with a dashed line and include "_disc" in its name. Table 1 summarises some key details of all 41 canals (identified according to their alphanumeric code) including their initial and final altitudes, their total lengths and average slopes.

The LB_M_1241 canal is the lengthiest complete observed canal, reaching 136.5 km to Las Médulas, but LB_M_1170 could be the longest with 145 km with our interpolated trace.

The La Cabrera zone contains 33 known canals; however, only 6 of them were used by the Romans to exploit Las Médulas (i.e., Mirador de Orellán, La Frisga, and Yeres sectors). The remainder relates to the satellite mines of the surrounding area (e.g., terraces and alluvial deposits) or do not even reach the vicinity of Las Médulas, ending in other mining sectors. Eight (three long-distance, three short-distance and two connecting water deposits in the mining area) of these canals end at the Llamas de Cabrera mining sector (Valdecorrales/La Petadura valleys), two in La Baña, two in Robledo de Losada and six in the Corporales area, among others. All these canals are treated in detail in this section. Regarding the El Bierzo area, eight canals were mapped, all of them running to Las Médulas. They supplied water to the oldest sectors located in the lower parts of the mine (e.g., La

Frisga/Carucedo), while the more recent ones supplied water to the upper sectors of Las Médulas (e.g., Mirador de Orellán and surrounding areas).

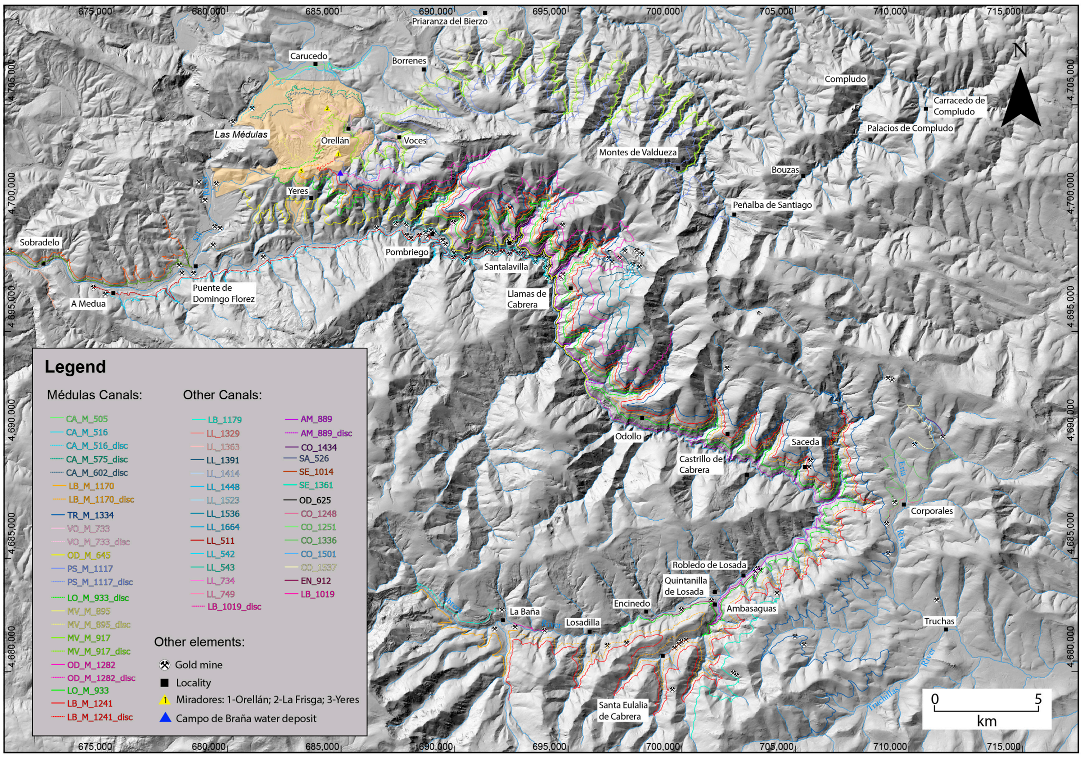

Figure 7. Map of the Roman mining hydraulic system.

In the La Cabrera area, six canals reach Las Médulas. In order from lowest to highest elevation, the first of them is the OD_M_645 canal. This canal captures water in the Cabrera River, near Odollo, at an altitude of approximately 645 m. This canal runs for 45 km with a mean slope of 0.160% and ends in the lower sectors of Las Médulas exploitation, between Salas de la Ribera and Yeres. Furthermore, this canal was used in other upstream exploitations, like the one in Santalavilla or near Llamas de Cabrera

The LO_M_933 canal is born near Losadilla, at 933 m of altitude, in the Cabrera River as the OD_M_645 canal, and enters the Médulas exploitations near the north of Yeres, with a total length of 97 km and an average slope of 0.150%.

The LB_M_1170 can be observed from the Valdecorrales Stream, in Llamas de Cabrera at 984 m a.s.l., reaching Las Médulas after 34 km. However, using the new Matlab tool, this canal could be extended to the Lake La Baña valley, where a canal was observed running in the direction of La Baña. In this case, this theoretical section of the canal could have been used in some exploitations, especially in the upper areas, like La Baña and Losadilla, but no remains were observed in the middle section between La Baña and Llamas de Cabrera. Considering all these sections as the same canal, the total length would ascend to 145 km, starting at 1170 m a.s.l. with an average slope of 0.216%, being, then, the longest canal of the Las Médulas hydraulic system. Likewise, our new tool provides extraordinary help during fieldwork and could be used in the future with the objective of finding any remains in this section that could confirm that this section really exists. Moreover, another of the big facilities that this tool provides is the interpolation of the trace when this is totally missed.

The LB_M_1241 canal is the longest complete canal and one of the best preserved that reaches Las Médulas. Born in the La Faeda Stream, in the locality of La Baña, runs for 136.5 km. The catchment area is located at 1241 m of elevation and reaches Las Médulas with an average slope of 0.222%. This canal was also used in other gold exploitations upstream at Pombriego and Santalavilla. The latter is located at Hortoloceños, La Guiana and Valparadille Stream valleys.

Table 1. Summary table with the principal characteristics of each mapped canal. Z0 refers to initial elevation (m a.s.l.) and Zf to final elevation (m a.s.l.).

Canal	Village	Zone	Length (km)	Z0	Zf	Ave. Slope (%)
AM_889	Ambasaguas	Cabrera	47.7	889.5	660.7	0.480
CA_M_505	Carucedo	Bierzo	5.5	505.2	489.5	0.285
CA_M_516	Carucedo	Bierzo	11.2	516.6	502.0	0.131
CA_M_575_disc	Carucedo	Bierzo	9.5	576.0	555.1	0.219
CA_M_602_disc	Carucedo	Bierzo	10.2	602.3	579.0	0.229
CO_1248	Corporales	Cabrera	3.5	1248.0	1244.6	0.094
CO_1251	Corporales	Cabrera	4.1	1251.6	1247.5	0.102
CO_1336	Corporales	Cabrera	9.1	1336.0	1298.5	0.410
CO_1434	Corporales	Cabrera	1.2	1434.0	1382.0	4.320
CO_1501	Corporales	Cabrera	4.4	1501.8	1492.7	0.208
CO_1537	Corporales	Cabrera	4.9	1537.9	1528.0	0.203
EN_912	Encinedo	Cabrera	10.5	912.8	893.2	0.186
LB_1019	La Baña	Cabrera	1.6	1019.6	1017.2	0.145
LB_1179	La Baña	Cabrera	6.4	1179.0	1166.5	0.196
LB_M_1170	La Baña	Cabrera	145.4	1170.8	857.2	0.211
LB_M_1241	La Baña	Cabrera	136.5	1241.9	938.4	0.222
LL_511	Llamas de Cabrera	Cabrera	30.3	511.8	398.0	0.375
LL_542	Llamas de Cabrera	Cabrera	36.1	542.2	421.0	0.336
LL_543	Llamas de Cabrera	Cabrera	13.1	542.8	516.7	0.199
LL_734	Llamas de Cabrera	Cabrera	15.9	734.2	705.5	0.180
LL_749	Llamas de Cabrera	Cabrera	2.0	749.6	744.1	0.273
LL_1329	Llamas de Cabrera	Cabrera	0.3	1329.4	1311.5	6.616
LL_1363	Llamas de Cabrera	Cabrera	0.4	1363.8	1331.8	7.986
LL_1391	Llamas de Cabrera	Cabrera	9.4	1391.3	1368.5	0.242
LL_1414	Llamas de Cabrera	Cabrera	0.5	1414.2	1414.1	0.011
LL_1448	Llamas de Cabrera	Cabrera	1.1	1448.2	1447.4	0.079
LL_1523	Llamas de Cabrera	Cabrera	1.0	1523.7	1522.7	0.098
LL_1536	Llamas de Cabrera	Cabrera	6.7	1536.0	1521.7	0.214
LL_1664	Llamas de Cabrera	Cabrera	5.1	1664.2	1647.0	0.334
LO_M_933	Losadilla	Cabrera	97.5	933.2	787.0	0.150
MV_M_895	Montes de Valdueza	Bierzo	76.1	895.7	761.9	0.176
MV_M_917	Montes de Valdueza	Bierzo	71.6	917.1	789.3	0.178
OD_625	Odollo	Cabrera	11.7	625.9	604.2	0.185
OD_M_645	Odollo	Cabrera	45.2	645.5	573.3	0.160
OD_M_1282	Odollo	Cabrera	43.4	1282.9	1094.3	0.435
PS_M_1117	Peñalba de Santiago	Bierzo	64.2	1117.2	951.5	0.258
SA_526	Santalavilla	Cabrera	8.7	526.3	508.2	0.207
SE_1014	Santa Eulalia de Cabrera	Cabrera	1.5	1014.9	969.3	3.070
SE_1361	Santa Eulalia de Cabrera	Cabrera	13.7	1360.9	1245.7	0.838
TR_M_1334	Truchillas	Cabrera	122.2	1334.6	976.9	0.293
VO_M_733	Voces	Bierzo	20.7	733.6	720.5	0.064

The TR_M_1334 canal is the second-largest complete canal of the Las Médulas hydraulic system, with 122 km and a mean slope of 0.293%. The catchment area is in the Truchillas River at 1334 m a.s.l. This river belongs to the Duero River basin, involving a transfer of water between hydrographic basins, as the Cabrera River belongs to the Miño-Sil basin, carrying out the basin transfer at the Puerto de Peña Aguda, in Corporales, and descending downstream to Las Médulas from here. This is one of the canals that supplied water to the Campo de Braña deposit, the highest reservoir used for the exploitation of the upper sectors of Las Médulas, at 976 m a.s.l. This canal could also be used in the same exploitations mentioned before for the LB_M_1241 canal, besides other minor exploitations that can be found near Iruela and Baillo, before the basin transfer. It is possible to observe two steps in the trace of this canal, one in the Valdecorrales Stream, at 1070 m a.s.l. approximately, and another in the Cabo River, at 1210 ma.s.l.

The OD_M_1282 canal is the highest one that goes to Las Médulas from the La Cabrera area. Water catchment is found at 1282 m a.s.l. in the La Sierra River. This canal presents two steps in its trace, one in the Valdecorrares Stream (as TR_M_1334), and the other in the next valley downstream. This canal was also used in Valparadille Stream valley exploitation and in the lowest areas of the Llamas de Cabrera exploitations. With an average slope of 0.435%, it ends up in the Rozana hill, at 1094 m a.s.l., after 43 km, although more research and fieldwork are needed to determine how the Romans guided this canal to Las Médulas. In this last valley, this canal runs over 40 m above what was proposed until now, verifying this fact with field points taken with high precision in obvious remains of the canal.

From El Bierzo sector, eight canals provide water to Las Médulas, the three highest and longest of them being especially important. Of these three canals, the lowest is the MV_M_895. This canal catchment is in Montes de Valdueza, in the Montes Stream, at 895 m a.s.l. It finds Las Médulas area near Orellán, at 762 m a.s.l. and presents an average slope of 0.176%. MV_M_917 also captures water in the Montes Stream, at 917 m a.s.l. This canal runs parallel with MV_M_895 until the end in Las Médulas, with practically the same slope of 0.178%. The main difference between these two canals is the area of Las Médulas they exploit. PS_M_1117 is the highest of these three canals. It collects water in Peñalba de Santiago, in del Aro Stream, at 1117 m a.s.l. This canal ends at Mirador de Orellán, at 942 m a.s.l., with an average slope of 0.258%. From El Bierzo sector, there are also five more canals supplying water to Las Médulas exploitation, but much smaller and water transportation capacity, collecting water in the streams near the area, and mainly used for working the lower sectors of the exploitation. These canals are CA_M_505, CA_M_516, CA_M_575_disc, CA_M_602_disc and VO_M_733.

Despite Las Médulas being the most significant exploitation in the area, there are other noteworthy exploitations in the Cabrera River basin that must also be considered, each with its own specific canals. One of them is in the Valdecorrales Stream valley in Llamas de Cabrera. In this region, there exists an extraordinary network of underground galleries in primary deposits, as well as hydraulic mining works, with a total of eight canals dedicated exclusively to this exploitation. The three main canals that supply water for the mining labours in this area are LL_1391, LL_1536 and LL_1664. Based on field observations, the high altitude of these canals and the terrain's morphology suggests the presence of numerous snowfields that could have provided water for them, rather than being supplied from nearby streams. Additionally, we found evidence of a new, higher water deposit used in this area, situated at an altitude of 1645 m and supplied by the LL_1664 canal. Several minor canals were also mapped in this area, including LL_1329, LL_1363, LL_1448, LL_1414 and LL_1523. The OD_M_1282 canal was also employed in the lower areas of these exploitations.

The Santalavilla mine, another important site in the La Cabrera zone, was served by at least three canals: the OD_M_645, OD_625 and AM_889 canals. The OD_M_645 canal was explained before as one of the main canals of Las Médulas, reinforcing that Santalavilla mines are younger than the exploited sector of Las Médulas, suggesting the advancing mining works upstream; otherwise, canals would be destroyed. The OD_625 canal could have taken water from either the Cabrera River or the nearby Villarino Stream at 625 m a.s.l. Its main purpose was to exploit the lower areas of Santalavilla and was also used in surrounding exploitations at El Miédalo. It is 11.7 km long with an average slope of 0.185%. Something similar occurs with the AM_889 canal as with the LB_M_1170 canal. The main idea is that it starts in the Villarino Stream, at 705 m a.s.l. and with a total length of 16.8 km and an average slope of 0.252%; it was also used for the upper areas of the Santalavilla and nearby exploitations, like OD_625. However, another canal was found upstream of the Cabrera River, near Ambasaguas. This canal catches water at 889 m a.s.l. in the Santa Eulalia River and exploits some Cabrera River terraces northeast near Robledo de Losada. This canal can be found near Saceda, where any trace is lost, but, interpolating the trace from this point downstream, this can match the Santalavilla upper canal, existing the possibility that they are the same. In this case, this canal would be 47.7 km long with an average slope of 0.480%. Another canal that may have been used is the LL_734, which features a small pass carved into the rock near its catchment area in the Valdecorrales Stream valley. It has an average slope of 0.180% and extends northeast to Pombriego, covering 16 km.

In the Robledo de Losada exploitations, another canal was found. This canal, the EN_912, originates in Encinedo, along the Cabrera River, at an elevation of 912 m, and extends for 10.5 km to reach Robledo de Losada with an average slope of 0.186%. It exploits a small ditch near the terraces exploited by AM_889.

The Moyabarba site (LL_542) represents a lower canal that takes water from the Cabrera River, near Llamas de Cabrera, 542 m a.s.l. Along its length, it was used to work the higher terraces of the Cabrera River and the exploitations located in an ancient meander of the Sil River at A Medua. This canal spans 36 km with an average slope of 0.336%. Further downstream, at 511 m a.s.l., another canal, the LL_511, was constructed to exploit the lower terraces. The LL_551 canal closely follows the layout of LL_542, ending in the lower area of the same Sil River terrace, with a total length of 30 km and an average slope of 0.375%. These two canals exploited almost every terrace along the left margin of the Cabrera River. Two additional canals were constructed on the right margin of the Cabrera River to serve a similar purpose, while also exploiting areas near Pombriego. Like in the opposite margin, one canal was dedicated to the lower terraces (SA_526), and the other to the higher ones (LL_543). Both canals catch water from the Cabrera River. The SA_526 begins at an elevation of 526 m and ends in Pombriego, serving an exploitation located within the village itself, after covering 8.7 km with an average slope of 0.207%. The LL_543 canal starts at 543 m a.s.l. and extends for 13 km with an average slope of 0.2%, ending downstream from Pombriego and supplying water to two smaller exploitations. Therefore, it is also very likely that these canals reaching Las Médulas from the La Cabrera area, except for the OD_M_1282, were utilised in Pombriego's exploitations, along with the LL_734 canal.

Two canals were mapped in Santa Eulalia de Cabrera. The SE_1014 canal starts in the village of Santa Eulalia itself, in del Pedracal Stream. This short canal, measuring only 1.5 km in length, exploits some terraces of the right margin of the Ricasa Stream. Due to its short run and the terrain's morphology, this canal has an average slope of 3%. The other canal, the SE_1361, is located much higher, beginning at an elevation of 1361 m in del Argañal Stream. The main purpose of this canal was to supply water to an exploitation located in the Manzanedo Stream valley. This canal has a length of 14 km and an average slope of 0.838%.

The LL_749 is a small canal that catches water from the Valdecorrales Stream at an elevation of 749 m. The unique aspect of this canal is that, unlike the other canals that progress downstream along the right margin of the Cabrera River, it flows upstream towards minor exploitations located Northwest of Llamas de Cabrera. A rock-cut step is visible near the beginning of the canal.

Most of the canals and exploitations on the La Cabrera side are situated along the appropriate margin of the Cabrera River. However, two canals can be found on the left margin in La Baña. Between La Baña and Losadilla, there is a minor terrace exploitation served by the LB_1019, a small canal that diverts water from the Cabrera River. This canal is only 1.64 km long and has an average slope of 0.2%. The other canal, the LB_1179, originates at an altitude of 1179 m in the Lake Stream, very close to the LB_M_1170. This canal was used in an exploitation located just north of La Baña. It has a length of 6.4 km and an average slope of 0.196%.

Finally, five other minor canals are in Corporales, all of which draw water from the Eria River. The two upper canals, CO_1537 and CO_1501, originate at the river's source, beginning at elevations of 1537 m and 1501 m, respectively. These canals have total lengths of 4.9 km and 4.3 km, with average slopes of 0.203% and 0.208%. They were directed towards a nearby, smaller exploitation. The CO_1434 canal also begins at the source of the Eria River, at an elevation of 1434 m, but follows a different path along the left margin of the Eria River. This canal has a length of 1.2 km, resulting in a steep slope of 4.320%. It was used for a minor exploitation located in the catchment area of the Mascariel Stream. The CO_1336 canal captures water at 1336 m a.s.l., passing north of the Castro de la Corona and supplying water to an exploitation located to the west of Corporales. This canal has a total length of 9 km and an average slope of 0.410%. The remaining two canals, CO_1251 and CO_1248, start at elevations of 1252 m and 1248 m, respectively. Their purpose was to supply water to an exploitation located a few kilometres downstream, corresponding to an old terrace of the Eria River, southwest of the current cemetery in Corporales. CO_1251 has a length of 4 km and an average slope of 0.102%, while CO_1248 measures 3.5 km in length with an average slope of 0.094%.

6. Discussion

The initial efforts to study the hydraulic network provided a comprehensive overview of the system, identifying a network spanning 600 km [16]. The active participation of local municipalities, well-versed in the area's heritage, facilitated further advancements in recent studies. This led to the discovery of additional segments that extended the network length to 700 km [14,16,54]. However, the detailed mapping of the hydraulic network presented in this work has revealed the lack of a systematic approach to studying the Las Médulas hydraulic complex and the presence of interpretative errors in some sections. These errors primarily result from the extrapolation performed in the absence of fully preserved remains across the entire network and the presence of vegetation obscuring numerous sections, complicating their traceability over long distances. It has taken almost 20 years for this to be the first 3D map of the hydraulic infrastructure to provide a Google Earth map for diffusion purposes (the map can be downloaded from the Supplementary Materials Section).

This methodology has facilitated a precise mapping of the hydraulic network, completing the lower exploitation sectors that had not been previously mapped [14], which constitute the initial phases of upstream prospecting in the search for large deposits like Las Médulas. Fluvial terraces had a key role in the development of mining activity in the area. In fact, some terraces have been covered by slope debris deposits (Figure 3D), forcing the removal of cover deposits down to the terraces. While the highest concentrations of secondary gold are in these fluvial terraces, owing to the continuous recycling process of geological materials during each river flood, extensive deposits like Las Médulas must have provided sufficient material (up to 90 Mm^3 of red conglomerates were exploited) to yield an appreciable amount of gold [56].

Exploiting the Sil and Cabrera River terraces, particularly the latter, involved the construction of an astonishing hydraulic complex designed to exploit the system of unpaired stream terraces on both sides of the river, resulting from unequal downcutting through bedrock (Figure 8).

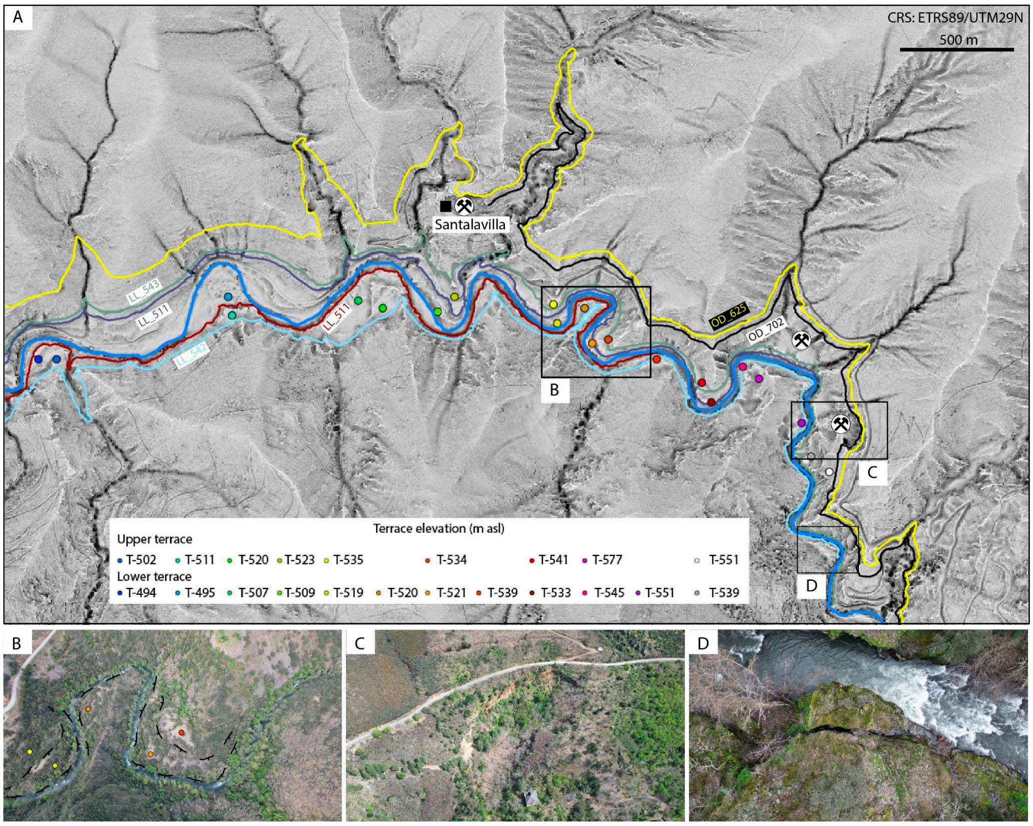

Figure 8. (**A**) Map of the lower sector of the Cabrera River showing the main canals used to work the left- and right-hand bank. Terrace elevations are indicated using colour coded circles (see legend below (**A**)). (**B**) Detail of upper and lower terraces in a river meander. (**C**) Evidence of Roman gold mining in alluvial fan deposits. (**D**) Detail of a canal in the Moyabarba site. See also Figure 1 for location of sites and Table 1 for general information about canals.

The so-called Moyabarba site is an example of a preserved section of these lower canals driven towards terrace exploitation (Figures 1B and 9), which had been erroneously associated with a specific structure for draining gold-bearing sands from the Cabrera River in this sector [46].

The destruction of certain canals supplying Las Médulas suggests that mining activity moved upstream over time. This enables us to give relative ages to the mining operations in the area, with upstream works at Losadilla and La Baña likely to be newer than those found in the lowest sectors of Las Médulas.

Other recent maps of the Las Médulas hydraulic network show a single canal collecting water from the La Baña lake at the source of the Cabrera River [16,56]. However, the suggested arrangement requires an unnatural, uphill water flow. There are, in fact, two distinct canals at different elevations: a lower canal (LB_M_1170) collecting water from the Lake Stream

(Figure 10A) and an upper canal (LB _M_1241), several kilometres downstream, gathering water from the Faeda Stream, one of the Cabrera River's many tributaries (Figure 10B).

Figure 9. (**A**) The Moyabarba cut, a canal used by Romans to exploit hanging terraces of the left bank of the Cabrera River. (**B**) Waste deposit left by Roman mining activity in the lower river terraces using canals like shown in (**A**). See also Figure 1 for location of sites.

Before continuing to Las Médulas, both these canals were used to work terraces at various elevations in the headwater region of the Cabrera River (Figure 11). The lower canal supplied water to the Cadabal mine, while the upper canal was used to exploit the gold deposits at the Reflejanos site. Sections of these canals appear to have been destroyed—leaving very few visible traces—once mining activities at these sites ceased, suggesting that these operations are more recent than those at Las Médulas.

Another contentious aspect of current maps concerns the water intake for canal TR_M_1334. Existing maps [16,57] propose that its intake was in the Lago valley. However, no evidence has been found to support this claim. Conversely, a large-block intake dam was observed in the Truchillas River, which, given its substantial year-round flow, could correspond to the intake point for this canal.

An important feature observed in the La Cabrera region is the modifications to adjust the gradient along the canals' entire course. These gradient adjustments are designed to maintain a consistent slope of approximately 0.200% throughout the canal's trajectory. In most cases, the canal slope tends to decrease close to the mining areas. Although this phenomenon is more widespread and shared throughout the hydraulic network than might initially be apparent, it is most clearly observed in the Bárcena Stream valley near the village of Castrillo de Cabrera (see Figure 12). Such adjustments were likely corrections made to the canal's alignment as the construction of the canals typically progressed from the mining areas toward the catchment zones [13]. Therefore, observed steps suggest that it may be the result of the subsequent hydraulic system expansion to exploit far away satellite mines located in the river headwater areas.

These canals are characterised by a relatively constant gradient, with less than 0.5% variations in the headwater and midsections. Additionally, the canal width remains relatively uniform, averaging between 1.2 and 1.5 m, with minor variations observed in curved sections. Minor widths (<1 m) are often associated with secondary canals or those with short distances and minor importance from the mining viewpoint. This feature has previously been noted by Fernández-Lozano and Sanz-Ablanedo [18] in another mining sector of Northwest Iberia, and it is also corroborated for the hydraulic system of Las Médulas. The design aimed to reduce water velocity at the canal's maximum curvature by increasing its cross-sectional area, thereby preventing structural damage. Notably, the water depth in the canal never exceeds 0.15–0.20 cm, as confirmed by observations of specific sections where automatic regulation systems have been identified (see Figure 13).

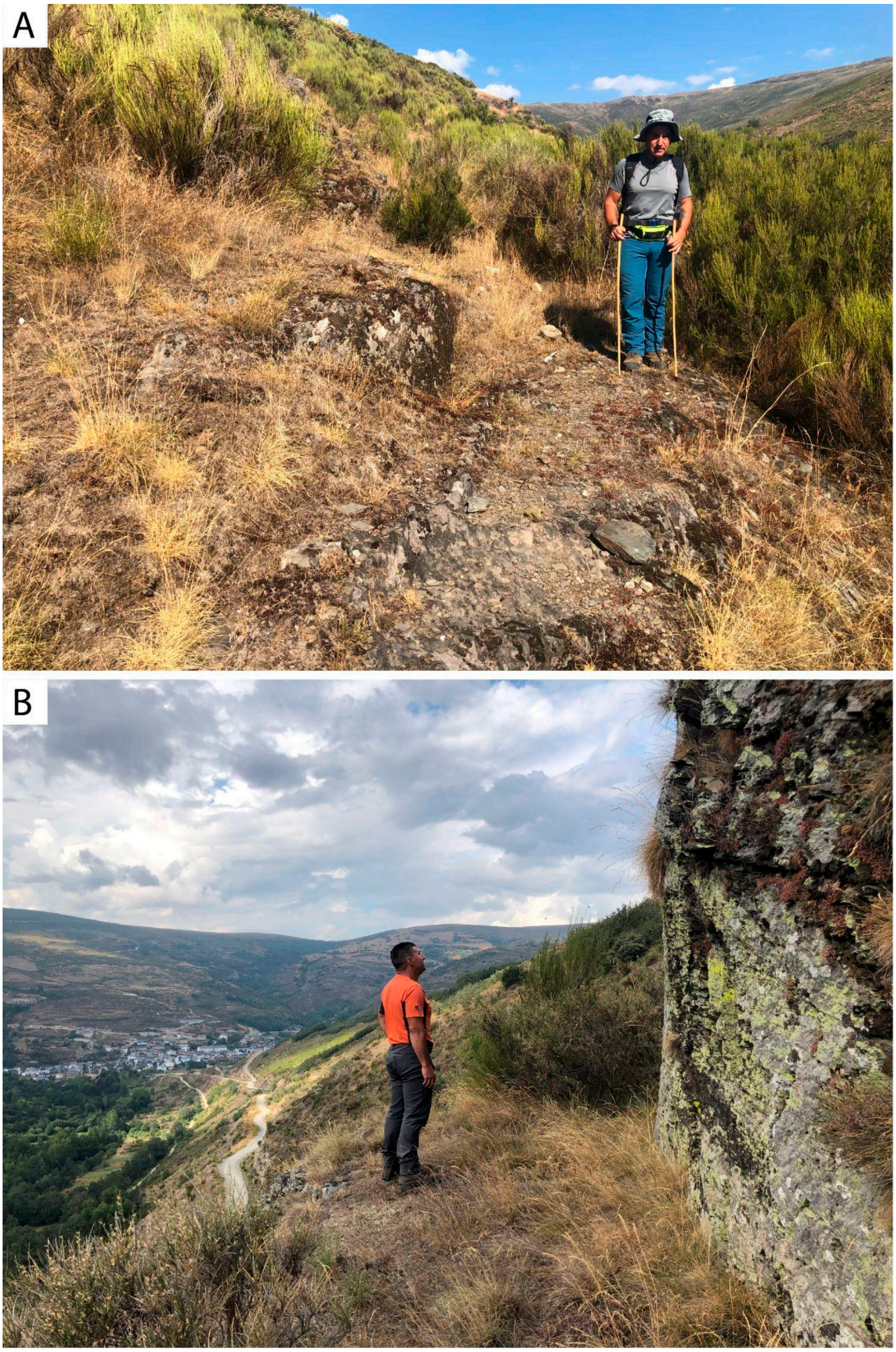

Figure 10. The two canals located on the right-hand bank of the Cabrera River at La Baña: (**A**) Lower canal LB_M_1170 collecting water from the La Baña River Valley and (**B**) Upper canal LB_M_1241 collecting water from the Faeda Stream. See also Figure 1 for location of sites and Table 1 for general information about canals.

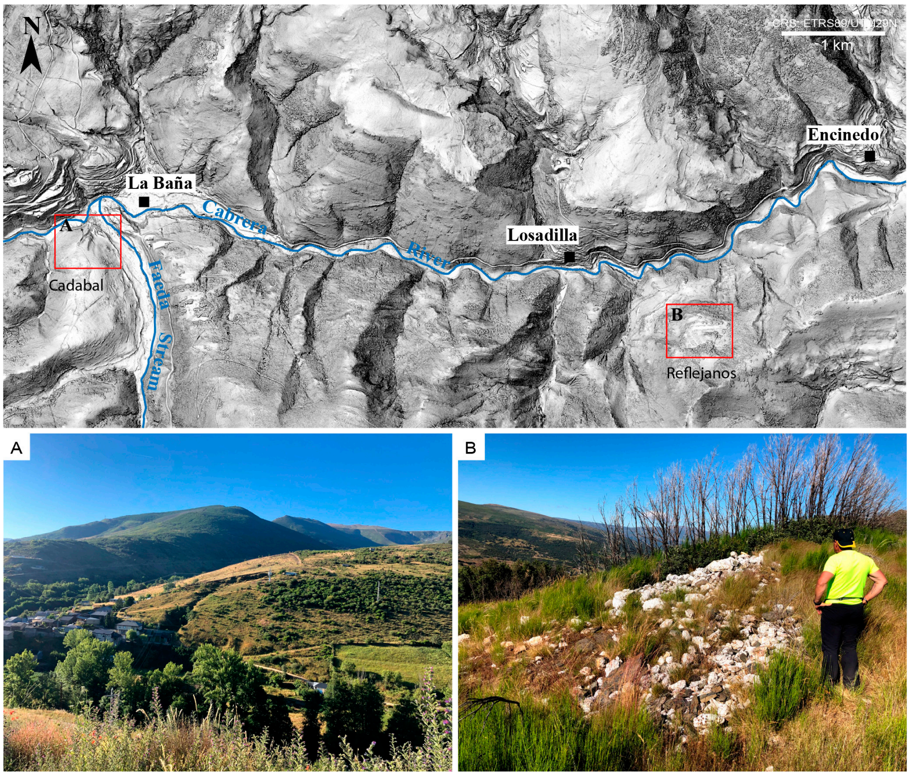

Figure 11. Remains of Roman gold mining activity shown by a slope gradient map of the La Cabrera zone obtained from visual enhancement of digital terrain model (2 m). The remains of Roman gold mining activity are indicated by the boxes labelled (**A**,**B**). These sites were exploited, respectively, using canals LB_M_1170 (Cadabal) and LB_M_1241 (Reflejanos). See also Figure 1 for location of sites and Table 1 for general information about canals.

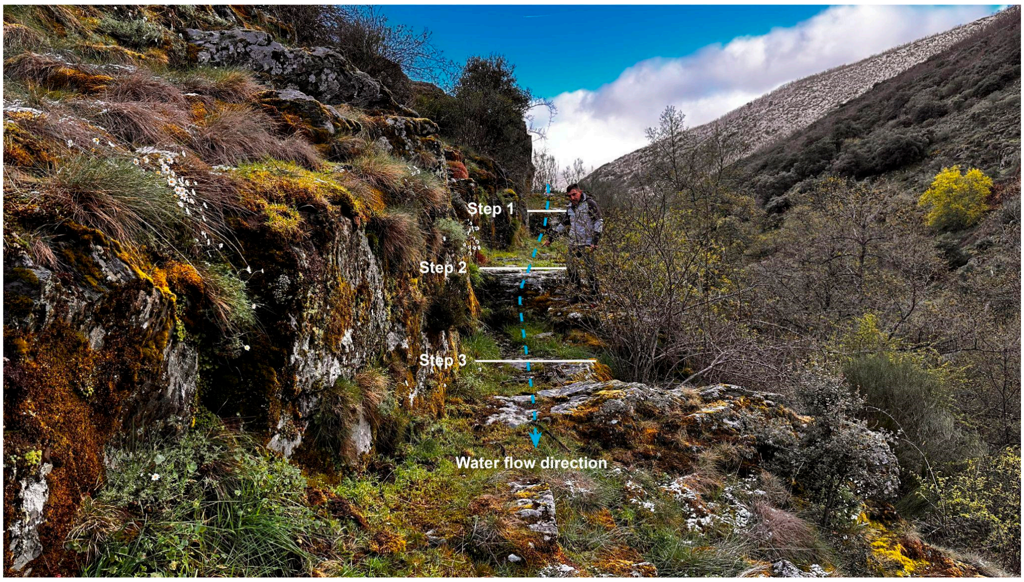

Figure 12. Reduction in slope in a section of 40 m by using a 10 m staircase slope restriction. See also Figure 1 for location of the site.

As previously mentioned, the three highest canals in the mapped sector of La Cabrera did not belong to the Las Médulas mining complex. Instead, these canals were used to exploit the Llamas de Cabrera mines. However, contrary to what has been suggested in previous studies [16,46], these canals collected water from nearby snowfields. This study has found no evidence of them collecting water from the Sierra River in the Montes Aquilianos region.

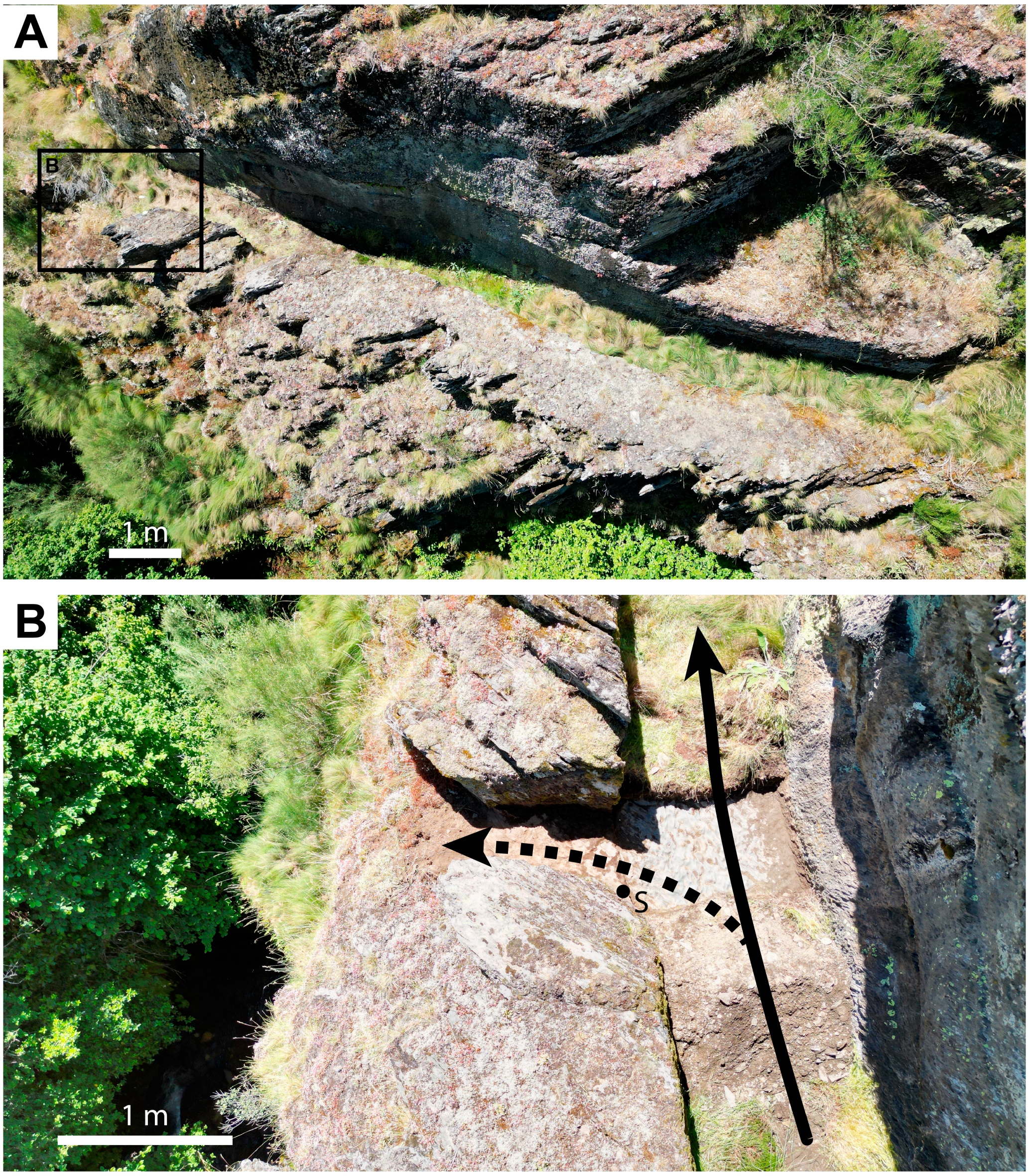

Figure 13. Canal OD_M_1282 (**A**) and location (**B**) of its spillway used for automatic water regulation: The step marked "S" is 0.13 m high and arrows indicate the direction of water flow. See also Figure 1 for location of the site and Table 1 for general information about canal.

Current systematic studies have proposed the existence of two canals supplying water to the Campo de Braña reservoir from the El Bierzo and Cabrera areas [13,14]. This water reservoir exploited both the Medulillas de Yeres and Orellán sectors. However, the upper canal elevation from the Cabrera area (OD_M_1282) implies it runs from one valley to another to reach the Campo de Braña reservoir from the northern slope of the Montes Aquilianos. Unlike the suggested trajectories of this canal by Lewis and Jones [7] and Matías-Rodríguez [14], the latter forced its trace to coincide in elevation with the water reservoir; the identification of the accurate altitude of the canal (Figure 14) would necessitate a system akin to that proposed by Sánchez-Palencia [58] at Três Minas, likely involving siphons or other hydraulic regulation mechanisms such as a water deposit at the Rozana hill. Additionally, two potential scenarios are proposed. A first solution is that the canal could have supplied water to the Campo de Braña reservoir with a gradient of 1%, which contrasts with the primary observation of a slope reduction in the canal slope near Las Médulas. This increase in slope rate suggests that when it was necessary to avoid terrain obstacles, corrections in slope were common. Water from Campo de Braña could have been used for the mines east of Mirador de Orellán. Due to the dip slope to reach the mines, the Romans would have solved the problem by implementing a system of water structures (the Spanish term *valgones*) to control water flow [13]. If true, the highest canal collecting water in the Peñalba de Santiago area would have served to carry out the arrugia or Ruina Montium [6] system using the water reservoir of La Horta. This might indicate a compromise solution implemented during the final stages of mining, necessitated by the increased demand for water in the mining operations. And the second solution would consist of a transfer of water from the nearby La Rozada mountain pass redirected to feed the lower Peñalba canal (PS_M_1117).

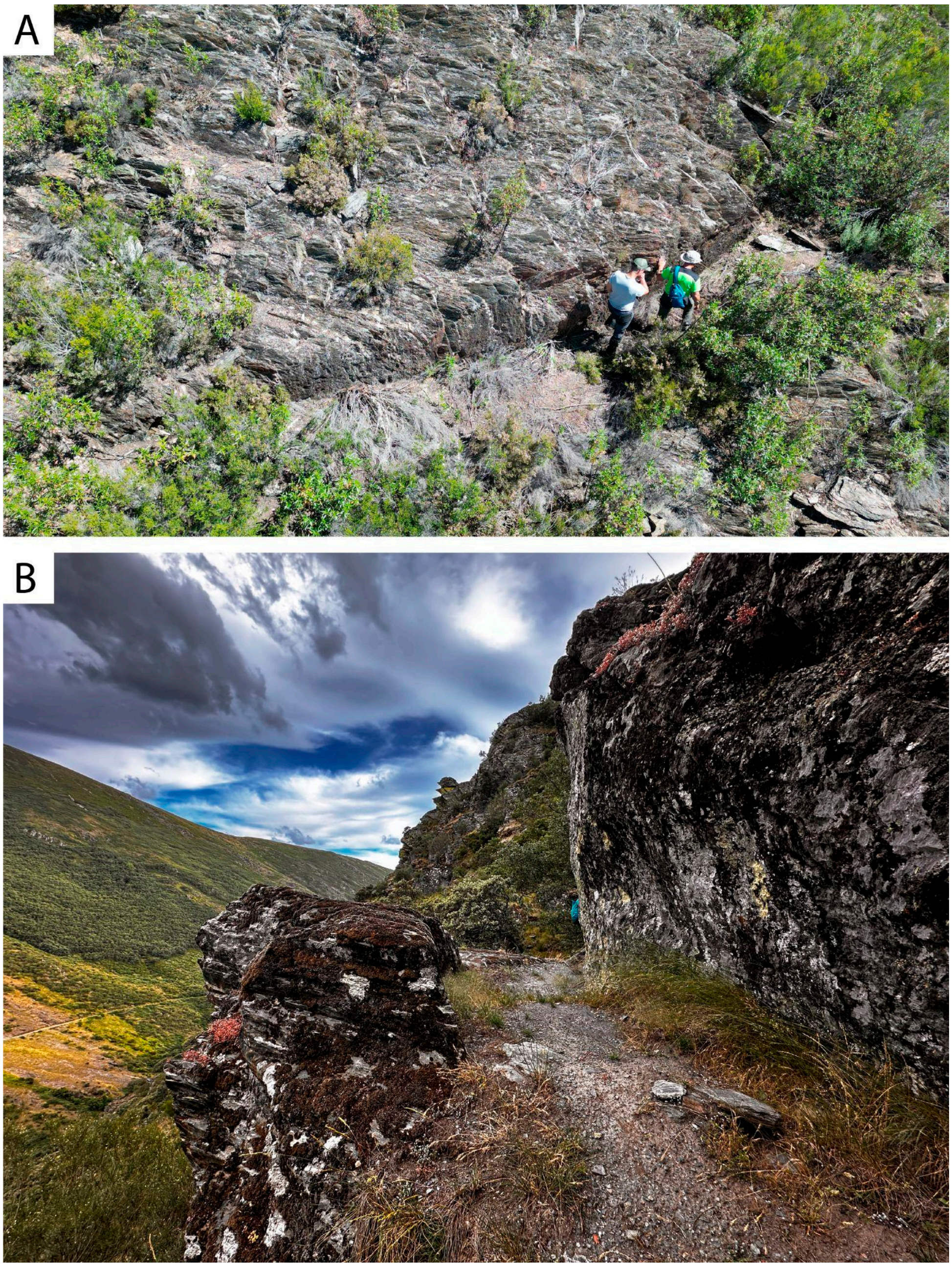

Figure 14. Canal OD_M_1282 near Las Médulas (**A**) and at where it collects water from the Sierra River (Odollo) (**B**). See also Figure 1 for location of sites and Table 1 for general information about canal.

The hydraulic system of Las Médulas comprises more canals in the northern sector of El Bierzo. The lower canals, which have not been identified in previous studies until now [13,16,56], were first used to exploit the terraces and lower sectors of Las Médulas (i.e., the La Frisga sector). As labour advanced towards the upper levels, the hydraulic system employed the three uppermost canals to bring water to the upper sectors of Las Médulas (i.e., Mirador de Orellán).

In the light of the above, we are ready to address the reasons for constructing such a large-scale, superb hydraulic system. One possible reason could be securing sufficient water, particularly during summer, to support mining activities. This hypothesis is one of the most widely accepted [13]. However, in this study, we propose a second possibility, considering the large number of mining sites identified near the canals' water intake points. The interest in exploiting mines in more distant areas could expand the hydraulic water collection network. Therefore, this could justify the construction of canals that exceed a hundred kilometres in length. If true, the Romans should have had a detailed organisation of mining activity before constructing the hydraulic system. This means that Romans led prospection works first to establish the area's mining potential, as suggested by Sánchez-Palencia et al. [59]. Mining works advanced using the natural drainage system from the lower terraces towards the more mountainous regions, from the mining area of Las Médulas, expanding towards satellite exploitations in the surroundings, which forced the development of a superb and vast hydraulic system.

7. Conclusions

The hydraulic system of Las Médulas and surrounding areas comprises over 1110 km of canals. Comparing the La Cabrera and El Bierzo hydraulic complex, the former is three times as large as the latter in terms of kilometres of canals destined for gold exploitation. Furthermore, the canals that supply water to Las Médulas were used in more minor exploitations throughout the Cabrera River basin, along with other smaller canals, destined for these exploitations, whereas on the El Bierzo side, Las Médulas canals were mainly constructed to supply water to Las Médulas, as no exploitations were observed. Moreover, it has been noted that there is a tendency for the slopes to soften as they approach Las Médulas, with slopes below 0.300%. This work presents a detailed mapping of the hydraulic system of Las Médulas based on a methodological approach supported by the combination of geomatic techniques and the implementation of Matlab script. This tool has facilitated a precise mapping of canal traces, eliminating errors in the current maps due to counter-slope variations and providing new insights into the entire hydraulic network. The work has allowed the identification of new canals and the establishment of those related to the mining complex of Las Médulas, improving current maps of the Roman hydraulic system. Moreover, a relationship with satellite mines in the area has been established, which may provide spatial–temporal relationships with the mining activity carried out at Las Médulas. Finally, this work delves into unresolved questions, such as why water was collected far from Las Médulas, despite the nearby presence of potential streams and rivers with enough flow rate. Our results help to strengthen the knowledge of the Roman gold mining activity at Las Médulas World Heritage Site and to configure the real size and extent of a cultural landscape by offering a new methodological approach based on a complete map of the mining hydraulic network.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/geosciences15010013/s1, Figure S1: Google Earth digital map of the Roman mining complex of Las Médulas hydraulic infrastructure and surrounding areas, Figure S2: Map of the Roman mining hydraulic system.

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