Roman gold exploitation at the archeological site of Las Médulas (NW-Spain) by means of *Ruina Montium*: a rock and fluid mechanics perspective

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ABSTRACT: Las Médulas is an area located in NW-Spain featuring a landscape environment formed by an old Roman gold mining operation. It is thought to be the largest open-pit gold mine in the Roman Empire and it was exploited during I and II centuries AD. The archaeological site and its environment were declared UNESCO World Heritage in 1997, based on its value as a cultural landscape. The most spectacular mining system used there was the one that Pliny the Elder called "*Ruina Montium*", that is, "the collapse of the mountains". This technique was applied to reach in one go the conglomerate levels richer in gold (Santalla formation), removing a thick cover of conglomerate block-in-matrix (bimrock) type waste. Unfortunately, there are no obvious remains of this procedure. In this multidisciplinary study in progress, archaeologists and engineers work together to better understand the detailed process used by the Romans to cave the mountains.

Keywords: Roman mining, archaeology, fluid mechanics, rock mechanics, collapse, bimrock.

1 INTRODUCTION

Las Médulas was included in 1997 in the List of the UNESCO World Heritage Sites for being one of the best examples of the mark that History has left on the Landscape. It occupies an extension of about 20 km^2. We are not just referring to leftovers, materials, more or less spectacular, of a past activity, but to the possibility to understand in-situ the permanent relationship between society and the territory it occupies, between communities and the natural resources they exploit, and ultimately, the social relations in which that occupation and exploitation develop. The remains of Roman mining in Las Médulas make it an outstanding example of ancient technology. But the meaning of the gold production thus obtained can only be understood within the complex process history of which it was a part (Sánchez-Palencia et al. 1998 & 2000; Pérez-García et al. 2000).

The area started to be mined some decades after the pacification of the area in the Cantabrian wars (29-19 BC). The value of gold in the Roman Empire cannot be understood, as nowadays, in profitability terms. It had though a strategic importance due to its use for minting the gold coin, the *aureus*, which, with silver too, constituted the basis of the Roman monetary system since the time of Augustus. This allowed economic stability of the Empire precisely in the time slot when the area was mined. Mining proceeded until the transition from the II and III centuries AD. The main reason of mine closure must be sought in the crisis that the Roman monetary system experienced at that time.

Estimates based on geomorphology and geophysical works suggest the material removed at Las Médulas was in the order of 80-90 Mm^3 and the production of 4-5 tons of gold all along exploitation process (Sánchez-Palencia et al. 1998). The geomorphology of the area was vastly affected during the two centuries of extractive activities (Figure 1.a). The mining works carried out involved the alteration of the environment but resulted in a landscape of reddish conglomerates, currently partially covered with chestnut and oak trees. This, more than ever human, landscape is undoubtedly today one among other reason, which attracts a good number of tourists to the area (Figure 1.b).

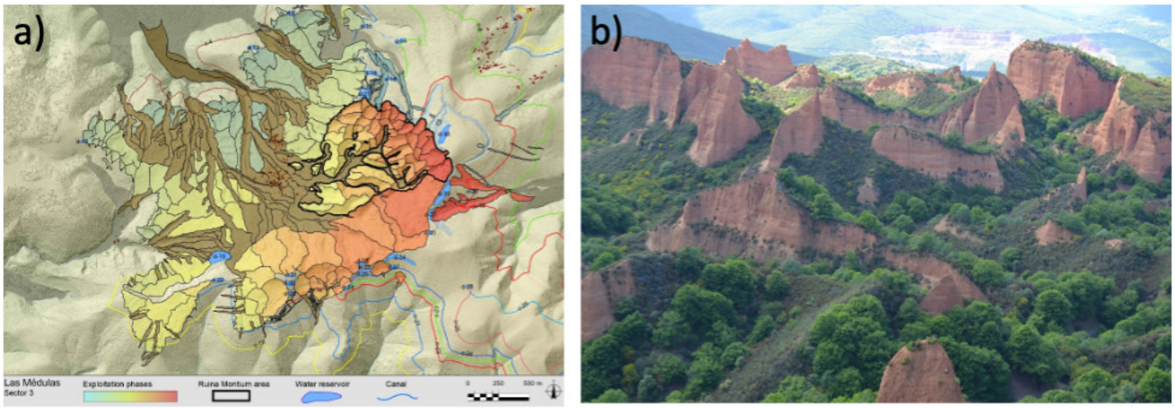


Figure 1. a) Plan of the mined area with main identified features and indicative sequence b) General view of Las Médulas from the South-East showing its characteristic landscape.

In the first stages of mining gold panning extraction in alluvial deposits and sluicing in artificial channels were the main gold exploitation methods in the area. In thicker deposits, the richest levels of gold were selectively mined, making successive “converging furrows” through which the water was thrown to drag the entire conglomerate, leaving only the boulders on the ground.

But, the most spectacular mining system used in Las Médulas was the “*Ruina Montium*”. This technique was applied to reach in one go the conglomerate levels richer in gold, removing a cover of waste often more than 50 meter thick. Unfortunately, there are no obvious remains of this procedure. The vertical cuts left and the use of water kept in large deposits (18 000 m^3) in the upper part of the mine suggest that Romans made collapse or caved large masses of conglomerate. It is though not clear how they exactly proceeded.

The main goal of our study is to advance towards a better understanding on how the Romans caved the mountain. The authors have critically reviewed existing hypotheses such as the use of the water hammer effect and simple saturation of the conglomerate formations. New hypotheses are now under scrutiny, including one suggesting the undercutting of slopes while directing naturally induced tensile cracks to produce the slope secondary toppling. To do that, authors are reviewing these hypotheses in the light of rock mechanics characterization and modelling, fluid mechanics, archaeological evidences and comparison to classic sources.

2 CLASSIC SOURCES

Pliny the Elder was the basic classic source explaining the so-called “*Ruina Montium”* method that we want to understand, in the Book XXXIII of his Natural History. We present the section of his text dealing with this topic, by reproducing the English translation by Bayle (1929):

“(72.) For the Earth in places is of a certain kind of c1ay mixed with gravel - they call it *gangadia* - which can hardly be overcome. They attack it with iron wedges and the hammers mentioned above, and they consider that there is nothing more stubborn save the most stubborn thing of all, the hunger for gold. When the operation is completed, they cut the supports close to the roof, beginning with the one which is farthest from the mouth; the subsidence of the earth gives a signal, seen only by a watcher stationed on a peak of the same mountain. (73.) By shouts and signals he bids them call out the miners, while he too rushes down. Its own weight brings the shattered mountain down in widespread destruction, with a roar that can scarce be imagined by the mind of man, and causing a rush of air powerful beyond belief. Nature lies in ruins before the eyes of the conquerors. But even yet they have obtained no gold, nor had they any certainty when they began to dig mere hope of satisfying their desires was sufficient incentive to incur such peril and expense."

The main objective of our study is understanding how exactly this was undertaken. In the past, it was suggested that water hammer effect could be used to generate the caving, something we will study. However, in Pliny's text, water is not explicitly mentioned in this regard. It is though mentioned the cutting of support, even if this process is still not clearly understood.

3 GEOLOGY AND ROCK MECHANICS

3.1 Sedimentary sequence

Las Médulas is an alluvial or secondary gold deposit composed of alternate layers of conglomerates showing boulders with clayey matrix, gravel, sand and silt. All of them are Miocene-age red deposits produced due to the erosion of rock materials from mountains located at the East, where gold associated with veins of quartz can still be found. The strong erosion rising from the Sil river basin subsequently dismantled almost completely those primary gold deposits. Accordingly, we can found now alluvial fans in which there are three main conglomerate-type formations, overlying discordantly a Paleozoic basement (Pérez-García et al. 2002).

From the base upwards, we identify first lying on the Paleozoic basement, the Orellán formation with a relatively soft matrix and many slate slender boulders that would be waste (it would hardly have gold). Overlying this, the Santalla formation would rest, made up of conglomerates with a matrix of medium to hard strength boulders (sandstone, quartzite) and partially clayey up to about 25-m thick (variable) and that would be the main gold source (it contains the gold that the Romans were looking for). On top of this, the Médulas formation would rest, up to a 100-m thick, formed by an alternation of conglomerates with thick boulders and others with much finer materials depending on the degree of energy of the alluvial fans. This formation contains very small amounts of gold, presenting in any case less interest than the Santalla formation. The stratigraphic sequence and the formations at stake are illustrated on Figure 2.

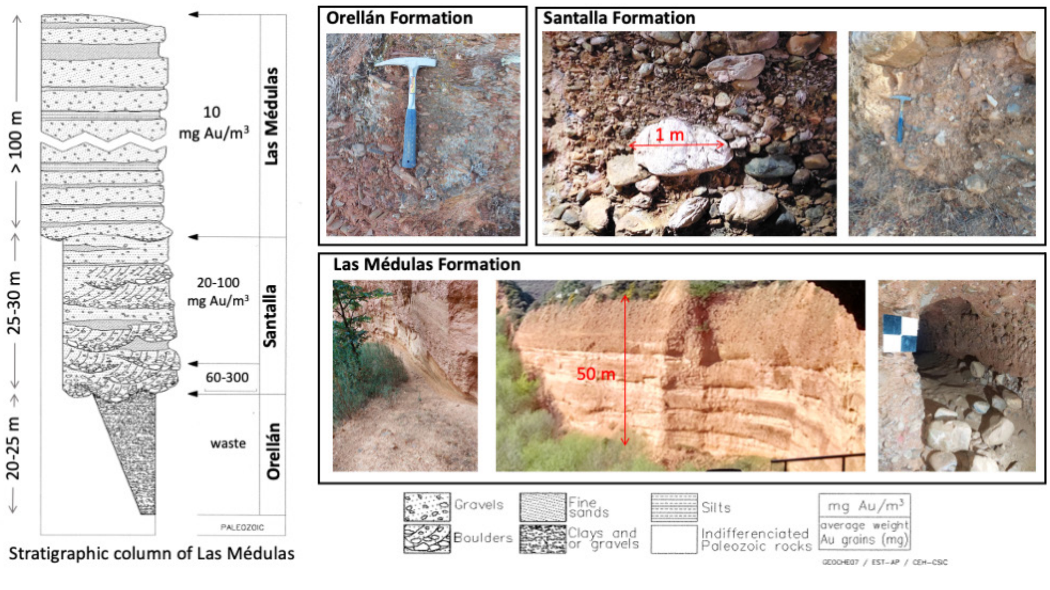


Figure 2. Sketch of the stratigraphic sequence at Las Médulas, with pictures of the different formations.

Based on the observed consistence and potential erosive processes, it seems that when the Romans first arrived to Las Médulas they applied the so-called "converging furrows" method in the mild slopes. As they advance towards the higher part (up-slope), a relevant layer of Las Médulas formation and steep slopes would be generated, making the waste removal difficult and time consuming. So a new approach was necessary. "*Ruina Montium*" was the procedure apparently developed to remove the increasingly thick cover of the gold-bearing Santalla formation.

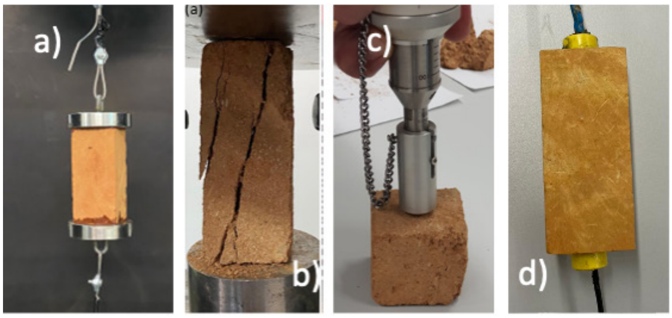
3.2 *Rock Mechanics*

Already in a first field visit, it was observed that the conglomerates of these formations could be classified as "BIM (Block in Matrix) rocks", materials formed by more or less hard blocks embedded in a matrix, with complex behavior. The materials of the matrix do not seem not very consistent or highly cemented, so the properties of the set will depend mainly on the properties of the matrix, but also on the percentage of clasts in the rocks and their grain size distribution (Figure 2).

The terms "bimrocks" and "bimsoils" (Medley, 1994) refer to different types of formations with a geological structure of blocks embedded in a matrix. These complex materials are characterized by internal heterogeneity and spatial variability of the mechanical parameters and lithological compositions. Moreover, it is often difficult to obtain representative samples of these materials for lab testing. Due to all this, understanding their behavior is still a challenging task. The Santalla and Las Médulas formations can be classified according to Napoli et al. (2020) as "Soft BIM rocks M5H", that is soft matrix materials with high percentages of clasts.

For this reason, and after a dedicated visit to the area, it was only possible to recover samples that could be cut and tested from the finest materials (silt bands as shown in Figure 2, associated with the Las Médulas formation), in those areas in which wind induced rockfall phenomena. There exist some geotechnical techniques allowing rough estimates of these materials' properties. To characterize these materials properly, it is though convenient to have as detailed as possible knowledge of the materials that make up these rocks, especially the matrix.

Due to its relationship with the geotechnical behavior of the rock mass, it is necessary to determine in the lab the geomechanical properties of the material under study. The tested samples were cut starting from some blocks of material collected in the field corresponding to matrix material (no clasts). When clasts were present, it was impossible to prepare samples. Thus, some lab tests were performed in matrix samples of Las Médulas conglomerate. The tests performed included direct tensile strength (Figure 3.a), compressive strength (Figure 3.b), needle penetration (Figure 3 c), wave propagation tests to determine V_p (Figure 3.d), X-ray diffraction (results in Figure 3.e) among others (density, crumb and point load tests). For the sake of briefness, table on Figure 3.e show average and ranges of parameters of this matrix material. Based on these values and rock mechanics reasoning, an estimative set of parameters of the conglomerates was estimated for preliminary calculations.



e)

X-ray diffraction		Basic rock mechanics properties		
Mineral content (%)		Property	Average	Range
Quartz	57.9	V_p (m/s)	1320	1240-1380
Muscovite	33.0	ρ (kg/m3)	1.82	1.7-2.0
Kaolinite	6.88	UCS (MPa)	1	0.3-1.6
Goethite	1.92	E (GPa)	2.9	0.6-7
Rutile	1.28	UTS (MPa)	0.087	0.7-0.12

Figure 3. Testing: a) Direct tensile strength, b) Uniaxial compressive strength, c) Needle penetration d) Wave velocity propagation and e) Table with results of diffraction and rock mechanics parameters.

4 FLUID MECHANICS AND POSSIBLE USE OF WATER HAMMER EFFECT

The authors have carried out calculations by means of numerical simulations in order to assess the feasibility of using water hammer as a contributor to "*Ruina Montium*". The generation of water hammer has been studied assuming, as realistic, the following operation process: first, the construction of a system of internal galleries in the exploitation zone; second, the water load in the previously excavated conduits, and third, the subsequent sudden release of water stored in them. The water hammer phenomenon occurs in pipelines operating under load, that is, when the fluid fills the entire section of the pipeline. It generates high intensity overpressure and depression waves that travel and reflect inside the duct at high speeds, which can be of the order of 1000 m/s in some cases.

In order to evaluate the success of the different hypotheses considered in the collapse of the exploitation area, work scenarios are built that try, as far as possible, to support on the evidence found in the archaeological zone, as that presented in Figure 4.a, formed by a system of tunnels with two closed ends (A and S). Numerical models provide pressure wave results on any point of the system selected. See, for instance, in Figure 4.b the corresponding value at point A when a sudden opening at evacuation point S occurs. The results obtained for the presented (Figure 4 a) and other possible layouts analyzed indicated, for reasonable hypothesis, that the stronger waves generated could attain pressure oscillation amplitudes of the order of ±1.5 MPa in short characteristic times, of the order of the second. If the retention opening time is sudden, below tenths of a second (which could only be achieved with a "blowout" of the outlet), the water hammer phenomenon is more intense, being able to generate pressure oscillations even higher.

These values, for the compressive case, would not be able to damage significantly the stability of the tunnels. In the tensile case, these values could contribute to speed the eroding of the drifts by removing clasts of the rock walls in parallel with its washing with water.

Additionally, it does not seem that the Romans were aware of this hammer effect, and in case they were, it would have been still unclear if they were able to produce it, by an extremely rapid opening or closure of a large flow of water into a drift.

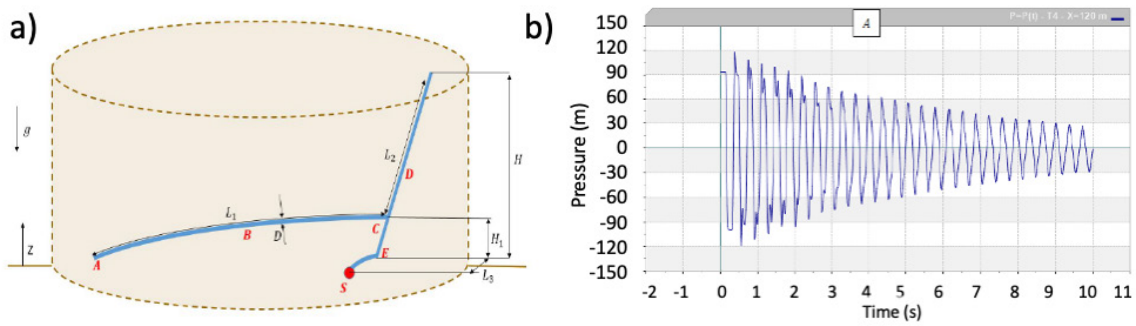


Figure 4. Fluid mechanics tunnels model as observed in Las Médulas. b) Pressure oscillation amplitude in water head pressure at outlet A, for a sudden evacuation of the flow throughout point S.

The preliminary conclusion of the research team is that the use of water hammer effect in "*Ruina Montium*" does not seem a very plausible assumption. However, it should be further studied whether or not this type of pressure oscillations can generate cracks in the formations in the area that could be somehow controlled and ultimately contribute to the collapse of the exploitation area.

5 A NEW HYPOTHESIS

The first author considers that a reasonably simple and feasible approach to generate the collapse of a vertical slope in the Las Médulas conglomerates will be as described below. This assumption relies on the limited observations in the area (since slope toes are covered with scree), on the description by Pliny the Elder and on possible mining approaches based on common sense. It would be first necessary to excavate drifts parallel to the slope strike at one or two positions along the height of the slope. These drifts will generate tensile cracks parallel to them upwards and downwards due to the tensile stresses generated by the stress distribution of the slope. This can be checked by means of simple stress distribution calculations according to Kirsch's equations and such cracks have been in-situ observed.

Then, it would be necessary to undercut the slope, either directly at its toe or by means of a drift parallel to its toe and a few meters inward. This could be generated with the help of the eroding potential of water, diverting a channel through this area. Moreover, this undercutting or drift could be timbered, so these timber will at least warn when this excavation would be about to become unstable (so the whole slope area caves). This can be related with Pliny's statement: "When the operation is completed, they cut the supports close to the roof". The control of this caving process would benefit from lateral separation surfaces. Some eroded slender drifts observed in the area could serve for this purpose.

Similar failure mechanisms of slopes provoking its instability due to secondary toppling have been described in the literature for the case of ignimbrite formations overlying tuffs prone to weathering (Figure5.a; Sari 2021) or observed in channels on a beach when water flowing erode and undercuts the channel bank toe ultimately producing toppling of the slope (Figure 5 b). A tentative simple numerical model with RS2 (Rocscience 2021) has been performed, compatible with the failure mechanism described (Figure 5.c). However, a more detailed characterization, more advanced models and further evidence in place are still needed before these initial assumptions can be considered plausible enough.

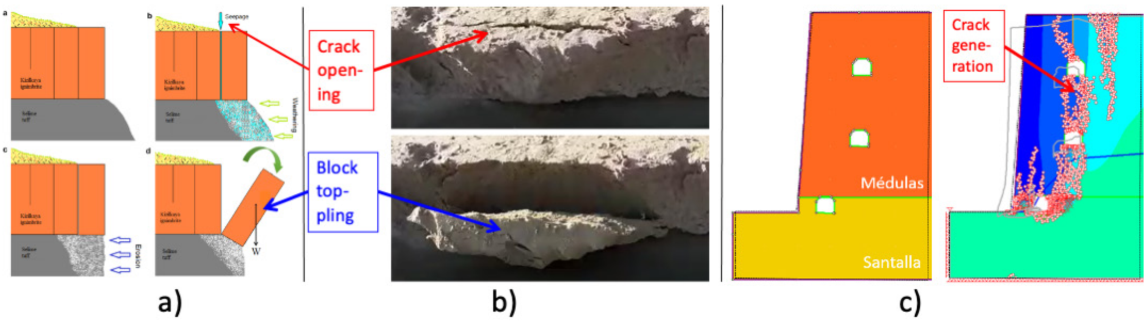


Figure 5. Secondary toppling failure mechanisms. a) Secondary toppling on ignimbrites in Cappadocia, Turkey, according to Sari (2021) b) secondary toppling in a beach natural channel and c) RS2 tentative model of crack generation and trend to collapse of a simplified slope at Las Médulas with RS2 (Rocscience, 2021).

6 CONCLUSIONS

In this multidisciplinary study in progress, archaeologists and engineers work together to better understand the detailed process used by the Romans to cave the mountains. A new hypothesis is proposed regarding the "*Ruina Montium*" mining approach that will need further work to be more rigorously tested.

ACKNOWLEDGEMENTS

The authors acknowledge financing of three projects, which have allowed the development the work-in-progress here presented: 1) "La Zona Arqueológica de Las Médulas y su red hidráulica (ZAM+RedH)" (Sub. dir. de la Junta de Castilla y León, CA 19708), IP: F.J. Sánchez-Palencia y A. Orejas; 2) "Paisajes culturales en el Norte y Noroeste de la península Ibérica: territorios urbanos, agrarios y mineros (NyNO)" (PIE CSIC 202010E147), IP: A. Orejas & 3) "AVRARIA: el oro de Hispania" (2019-T1/HUM-14288), IP: B. Currás.

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