Journal of Archaeological Science: Reports 49 (2023) 103962

Contents lists available at ScienceDirect

Journal of Archaeological Science: Reports

journal homepage: www.elsevier.com/locate/jasrep

Transport and distribution of heavy loads in ancient times: Estremoz Marbles in the Roman province of Lusitania

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ARTICLE INFO

Keywords:
Estremoz marbles
Roman times
Lusitania
Transport and distribution
GIS

ABSTRACT

This article analyses the distribution of Estremoz marble from the production centers to the redistribution ports and consumption areas. The marble of the Estremoz Anticline is the most important of the Roman province of Lusitania, and one most of the Hispania, located over150 km from the coast. This product was exploited and distributed to several cities in Roman Hispania and North Africa. This article examines how this transport was carried out by land and river, calculating the economic costs involved. To do this, it is used several Geographic Information Systems (GIS) tools in order to find the optimal routes and discuss the transport for heavy loads, relating the mobility to the cumulative economic cost of displacement.

1. Introduction

Geographic Information Systems (GIS) tools have been widely adopted by researchers in various fields for the historical study of landscapes and territories. While many studies focus on aspects of mobility and trade (Carreras & de Soto, 2013; Brughmans, 2013; Verhagen et al., 2019), others employ quantitative techniques to support and understand economic models (Trapero Fernández, 2021). This article combines these approaches by examining the transport and mobility of heavy products, specifically marble archaeological pieces, from a historical perspective that takes into account the entire trade process. While some studies have already been conducted on this subject (Jiménez Madroñal et al., 2020), this paper aims to go further by highlighting the existing limitations of the GIS tools currently used. In order to do so, it is necessary to adapt the criteria to the historical reality of this complex product, and discuss: (1) the type of vehicle and associated problems; (2) adaptation to Roman legislation; (3) the accumulated economic costs of transport; (4) the organization and management of extractive activity and the territory; and (5) differences according to chronology and historical periods.

For these reasons, a particularly paradigmatic key study has been selected, namely the marble from the Estremoz Anticline (hereafter referred to as Estremoz Marble; Lopes, 2007; Lopes & Martins, 2015; Moreira & Lopes, 2019; Moreira, 2022). The historical importance of this key study can be summarized in the following points:

It is a production not reflected in written sources, but with a wide chronological and spatial Roman diffusion, confirmed by recent studies (e.g. Moreira et al., 2020; Moreira, 2022).
It is a significant industrial region, with diachronic production over time (e.g. Mourinha & Moreira, 2019), and one of the socio-economic drivers of the region (Quintas, 2019). Its study and knowledge may improve its national and international market.
It is a high-quality product within the Roman production circuits (Gutiérrez García-Moreno, 2012), but also in present times.
Despite this, there is an important transport problem, once the production center is located more than 150 km away from the main redistributing port, *Olisipo*, currently Lisbon, Portugal.
It is possible to relate the transport estimation to the Lusitania road network in Roman times, allowing to identify possible optimal routes for the transport of the Estremoz Marble loads.

Under these conditions, the trade cost of this raw material to a redistributing port would be remarkable. The analyzed data are based on the mapping of the exploitation and use of the Estremoz Marble, this is tracing the evidence of exploitation on-site and the evidence of use in

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https://doi.org/10.1016/j.jasrep.2023.103962
Received 30 July 2022; Received in revised form 6 March 2023; Accepted 13 March 2023
Available online 23 March 2023

the consumption areas.

This article applies the modelling methodology of terrestrial mobility using GIS tools to a paradigmatic case study, discussing the criteria and problems of the mobility of raw materials and heavy products. On the other hand, this study discusses the transport of Estremoz Marble as a historical problem, proposing alternative land routes to those traditionally expressed in the bibliography. Although three Roman routes are considered as main connections between *Augusta Emerita* and the main Atlantic port of *Olisipo* (Carneiro, 2008: 47–76), and all of them pass very close to the Estremoz Anticline, route XII seems to be the most logical (Almeida, 2017). This paper proposes a workflow for modelling the mobility of heavy loads. Firstly, several internal transport conditions were constrained, such as the weight of the load and the capacity of the oxen to move it. Considering this, the usual method for performing the Least Cost Path (LCP) is modified through the use of a mobility algorithm (Tobler, 1993). For heavy loads, there will be limitations on the maximum slope change that can be crossed, a speed difference, and stronger limiters in areas of difficult passage such as streams. With this information, two complementary models were created. On one hand, the classical LCP was used with the new function to connect with a city for water distribution. On the other hand, river and sea transportation were modelled, not in terms of time spent, but in a new way - by measuring the increase in economic cost per tonne per kilometre.

2. Background and theoretical framework

2.1. The study area in Roman times

During the Roman period, the region of Estremoz Anticline was remarkably central, despite no known urban settlements existing in its regions or immediate surroundings. The Estremoz Anticline is located approximately halfway between the provincial capital, Augusta Emerita (current Mérida, Spanish Extremadura), and the provincial Atlantic seaport, Felicitas Iulia Olisipo (present-day Portuguese capital Lisbon). For this reason, one of the main itineraries connecting the two urban poles cuts precisely through the Anticline: the so-called Via XII of Antonino's itinerary, whose route was the subject of a recent study (Almeida, 2017). The recent attribution of a milestone identified in the 18th century to a local toponymy - "Horta do Agaixa" - Horta do Agacha (located a few kilometers south of Estremoz; Carneiro, 2014: 173) allowed confirmation that the area would be directly served by this strategic route. As marble exploitation began with the Roman presence in the region, and route XII was built to serve Augusta Emerita, an urbs ex novo, it is recognized that the Roman landscape in construction is entirely new, leaving no pre-existing evidence.

It is important to note that despite recent synthesis works (e.g., Carneiro, 2014; 2022), the regional settlement framework in Roman times is far from being known. The Estremoz Anticline does not have a reference framework sustained in recent intensive fieldwork (current ongoing projects are in a preliminary stage), so the existing information is scattered and sporadically collected in different historical periods. Despite the strategic importance of the resource, there does not appear to have been any urban settlements in the region, and only recently has a route been identified, using GIS analyses, that may have served as an alternative to Via XII – the "Estrada das Tesas" (Carneiro, 2022) to the river Sorraia, which will be referred to in the following chapters.

2.2. The marble of the Estremoz Anticline: Historical and landscape context

In the southernmost domains of *Hispania* (current Iberian Peninsula), there are marble production centers that focus on two different geological zones: the Ossa-Morena Zone and the Baetic System (e.g. Moreira & Lopes, 2019). Among them, the Estremoz Anticline, located in the Ossa-Morena Zone, is one of the most outstanding marble production centres (Lopes and Martins, 2015). In the south-western limb of the Estremoz Anticline, there are hundreds of quarries, some of them are still in use today, although there is evidence of exploration dating back to Roman times (e.g. Justino Maciel, 1998; Taelman et al., 2013). The spatial distribution of archaeological marble pieces coming from the anticline has already been studied based on the analysis of marbles used in consumption centers (e.g. Encarnação, 1984; Cisneros Cunchillos, 1988; Moreira et al., 2020; Moreira, 2022). The production from the Roman period has only been confirmed in a few *in situ* testimonies (e.g. Justino Maciel, 1998; Taelman et al., 2013; Carneiro, 2014, 2019; Calado & Mataloto, 2020), together with delocalized ones (Alarcão, 1997; Alarcão and Jorge, 1989; Fusco & Mañas, 2006). Although it is known that marble quarrying took place, no epigraphic marks have been located, which are one of the main Roman production features (Vinci & Ottati, 2020). A summary of this issue can be found in recent publications (Carneiro, 2000).

The landscape does not present major natural barriers to the transport of goods, as the territory's morphology is fairly flat (Fig. 1), with river plains between the Sado, Guadiana and Tejo rivers and some tributaries of the latter, such as the Sorraia river (Fig. 1). This implies that there are no significant constraints to mobility along rivers but rather that they are the preferred location to move loads. Using a current elevation model, it can be estimated that the topography is very flat, varying by only 200 m in elevation over 150 km. The topography of the Estremoz Anticline range between 300 and 500 m above sea level. The only significant morphotectonic relief in the region between *Augusta Emerita* and *Olisipo* worth mentioning is the Serra d'Ossa (with the highest vertex at 652 m). This mountain range has a WNW-ESE general trend and is located to the west of the Estremoz Anticline (Feio, 1983; Martins et al., 2022), representing a major natural barrier separating the marble resource from western territories of consumption, such as *Ebora* and *Olisipo*. To the north, mention should be made of the Serra de São Memede (with the highest vertex at 1025 m) is the main morphologic obstacle separating the marble resource from some cities like *Ammaia*.

Although GIS tools have been applied to the study of the mobility of raw materials in other regions such as Baetica (Jiménez Madroñal et al., 2020) or Greece (Rivas, 2019), they have never been applied to the study of this raw material's mobility in Portugal. Although there have been important recent studies that combine modern ways of approaching these problems (de Soto, 2019), the state of the art is still precarious. The main issues are predominantly two, one technical and the other historical.

2.3. Least costh path applications in history and archaeology

The use of LCP analysis in archaeology and history is nowadays a very common practice (Llobera, 2000; Howey, 2007; Brughmans, 2013). In general, these tools require the initial construction of a friction raster, which determines the constraints of the territory. There are several available algorithms that allow the translation of this stress relationship into parameters such as time or energy invested (Tobler, 1993; Llobera and Sluckin, 2007; Baek and Choi, 2017). Generally, the basis of any friction map will mainly be the difference in slope, although other parameters or constraints such as hydrography, soil type, vegetation, communication routes, etc. (Herzog, 2010) can also be included. At a minimum, navigable routes must be included, as the tool does not recognize riverbeds as areas where one can run without geographic features.

To generate the LCP, the first step is to create a distance cost map (DCP) and a backtracking map. The DCP expresses the increase in cost value as it is preset, while the backtracking map indicates the direction of movement. By combining these two maps, the best corridors can be identified. There is literature available on this topic (Llobera et al., 2011; White, 2015; Verhagen et al., 2019), as well as several innovative applications (Fábrega Álvarez and Parcero Oubiña, 2007) based on other tools such as the combination of mobility packages with hydrography.

In addition to traditional land studies, there are also applications in

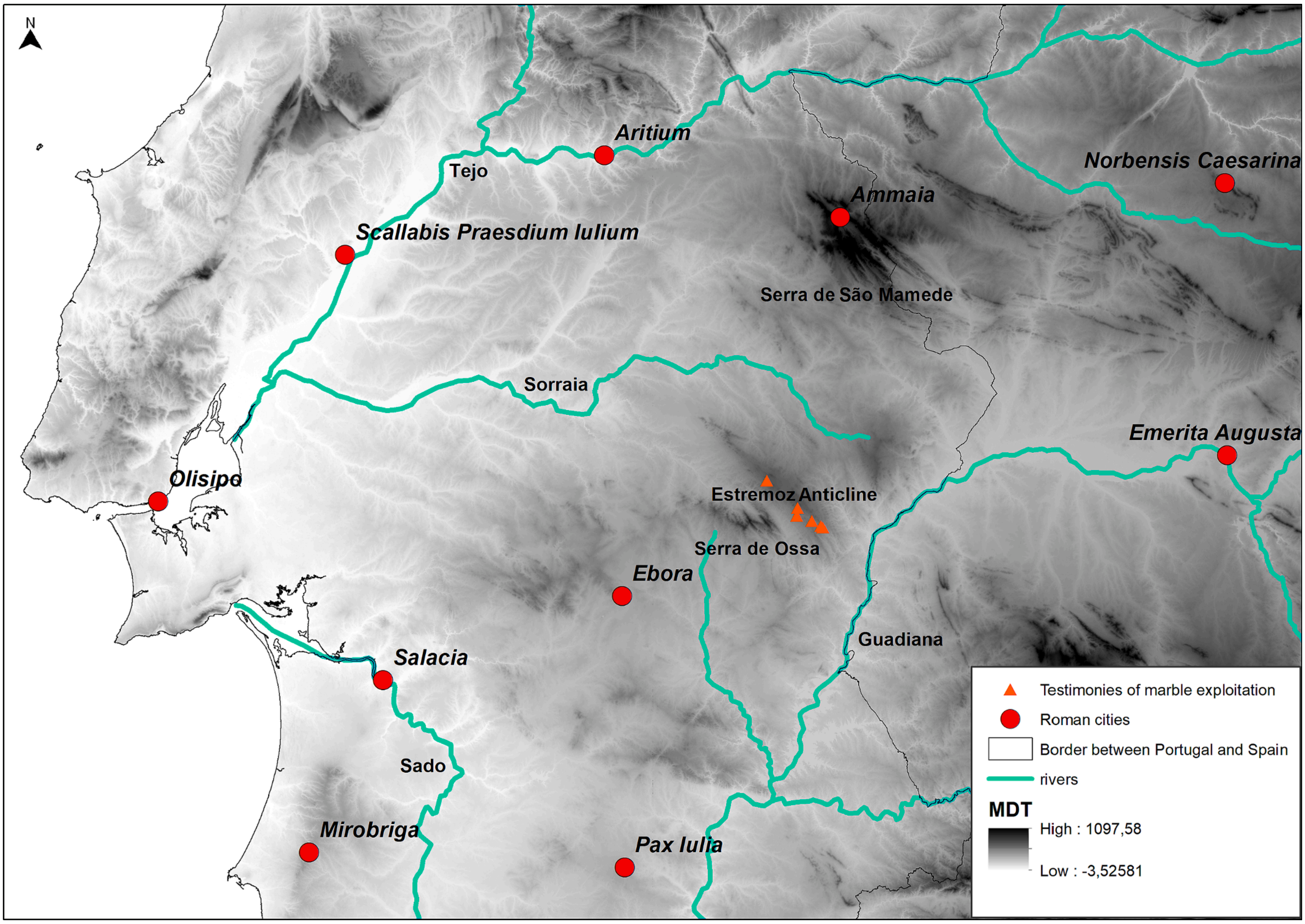

Fig. 1. Location of the study area with indication of towns, recognized roman marble production centers in Estremoz Anticline (Justino Maciel, 1998; Taelman et al., 2013; Carneiro, 2022), current boundaries, hydrographic network and main toponyms indicated in the text.

other environments such as rivers or the sea. The process is quite similar, but the friction map must be constructed with other conditioning factors, such as waves and currents (Gambash, 2017; Gustas and Kisha, 2017; Alberti, 2018; Jarriel, 2018; Milheira et al., 2019; Trapero Fernández and Aragón Núñez, 2022).

However, there are few examples of the combined application of terrestrial, fluvial, and maritime constraints (Trapero Fernández, 2021). Most studies focus on human mobility on foot, with few cases, such as the study of mobility by car (Parcero Oubiña et al., 2019) and even fewer on the transportation of heavy loads such as marble (Haisman and Goldman, 1974; Rivas, 2019).

3. Materials and methodology

The complexity of transport is evident in several epigraphs such as the *corpus traiectum marmorarius* (CIL X, 542) for Rome and in the reference by Vitruvius (Vit. X. 2,11), where the inconsistency of the roads and the hardship of transporting heavy loads are mentioned. It is important to consider favorable travel conditions (Raepsaet, 2022). The typical transport vehicles would be the equivalent of the *tetrakukloi* known for the Epidaurus blocks, which were vehicles with longer wheels and greater stability (Burford, 1960). Therefore, for the transport of large goods in Roman times a set of conditions or parameters had to be considered, including the load, the type of vehicle, the speed, and the economic cost involved. To address some of these issues, two main problems must be examined in the case study::

(1) A function that makes it possible to calculate mobility for the vehicle, as exists for people (Dijkstra, 1959). It is possible to analyze mobility in terms of time (Tobler, 1993) or energy (Llobera & Sluckin, 2007; Herzog, 2010), but these analyses have primarily focused on human land mobility. Although, the latter is ofen used as a general model, it is not appropriate for the Estremoz Marbles case. Therefore, further research is necessary in this domain.
(2) The marble (or other geological raw material) transport are quite particular. There are constraints to its specific extraction sites, its trade circuit that can be managed and its heavy load, meaning that it cannot be considered within a traditional mobility analysis. This is even stronger in the study case, where there is an important network of land routes in the ancient itineraries (Alarcão, 2006; Carneiro, 2008, 2014). The existence of this network suggests an eminently terrestrial trade, with the redistributing ports located at a great distance, which makes its mobility difficult, generating an extra challenge to be modelled.

These challenges make it extremely difficult to approach these problems, especially considering the historical dilemmas and technical issues involved. Thus, this section will provide a detailed description of the parameters to be considered for mobility analyses conducted for Estremoz Marbles.

3.1. Vehicle and load

The load itself is the most crucial factor to consider in this study. Transport would preferably be carried out by ox vehicles (Raepsaet, 2022). It is known from Roman legislation that they could not carry more than 450 kg on average: 1,500 *librae* – 482.75 kg *Codex Theodosianus* (8.5.30), and 1,200 *librae* – 396 kg *Edictum De Pretiis* (Carreras, 1994). However, this estimate is based on the law, and the actual capacity could be much higher, up to more than 1 ton (Burford, 1960; Raepsaet, 2010; Pegoretti, 1863). The law was probably applied, especially in semi-urban contexts, to limit or avoid damage to public roads (Adams, 2012). The marble case may have been special, an exception to the rule, although the problem of transporting a large load over a very long distance must be considered (Rodríguez Ennes, 2018; Verhagen et al., 2019). In the Estremoz Marble case, the route to the main port of the area, *Olisipo*, is almost 150 km in a straight line, taking about 30 h on foot. The time to move the marble pieces with an ox-drawn vehicle would be considerably longer, especially if the time to rest or to the animals feeding is taken into consideration (Sippel, 1987).

In the study case, approximate examples of the loads that were transported are known, which can be significantly higher than the limits set by legislation (Tables 1 and 2). The analysis of both tables emphasizes that from the Estremoz Anticline region came a set of imposing funeral, sculptural and architectural pieces in marble, most of them with a mass varying between 0.5 and 1.5 tons, but which could reach higher values (2 to 3 tons). Among the pieces is a set of sarcophagi of chronology varying from the second to the fifth century (Table 1; Moreira, 2022 and included references), as well as a set of statues and other architectural pieces (e.g. capitals or bases of columns) scattered throughout several cities of *Lusitania* (e.g. *Olisipo*, *Emerita*) and *Baetica* (e.g. *Baelo Claudia*, *Cordoba*), between the first and fifth century. To estimate the volume of the pieces, simple geometric shapes applied to the dimensions of the pieces were used (see Tables 1 and 2), applying the value of volumetric mass density (2.71 g/cm^3 for Estremoz Marble; Casal Moura et al., 2007) to estimate the mass of pieces to be transported. In statues and other architectural pieces, the presented values will surely be slightly lower, since the pieces would be transported already in their semi-finished state, as evidenced by *in situ* findings in the region (e.g. Fusco & Mañas, 2006; Mañas & Fusco, 2008).

The loads themselves involve other issues such as the economic cost of transport, which will be discussed below. Indeed, it is perhaps necessary to consider whether there are other vehicles or routes for the marble and other heavy load transport (Weller, 2021). In Vitruvius (Fig. 2), there is a clear example of this: the author emphasizes the problems involved in moving some shafts from the quarry to the temple, referring to the inventions of Ctesiphon and Metagenes. It is possible to adapt a wheel to this piece, excluding the vehicle, but allowing the oxen to pull it directly, giving it the stability required to be transported over more unstable terrain (Vitr. *De arch.* 10.2.11–12.) In the reported case, the aim was to transport these heavy loads over short distances (around 8 Roman miles, which is just over 10 km). In the case study, this type of transport may not be ideal, but should be considered as viable. It should be emphasized that Roman roads usually used natural paths and, with some exceptions due to the difficulty of the terrain (marshes, mountains, etc.), large investments were not usually made (Moreno Gallo, 2006).

3.2. Land speed

The transport speed is a crucial variable for calculating the route, and an ox-drawn vehicle can travel on average 25–30 Roman miles in a day, approximately 1.14 miles per hour (pprox.. 1.5 km/h). According to Elius Aristides (*Theod*, 27, 1–8), a journey of 42 miles in a day without rest can be achieved, but if rest, is taken it would be approximately 1.16 miles/hour. Horace (*Sat.* 1.5) describes a journey of an average of 1 mile/hour. Apart from the time, it can also be related to the energy expended (Llobera and Sluckin, 2007; Llobera, 2000). With these data,

Table 1
Sarcophagus made by Estremoz Marble (*considering 37% of the total volume; ** obtained using a volumetric mass density of 2,71 g/cm^3 for Estremoz Marble - Casal Moura et al, 2007; *** new data for internal dimensions; see references on table II).

Sarcophagus	Location	Sec.	External dimentions				Internal dimentions				Transported volume			Weight** (Kg)	References
			height (cm)	width (cm)	length (cm)	volume (cm^3)	depth (cm)	width (cm)	length (cm)	volume (cm^3)	int /extl ratio (%)	ext – int volume (cm^3)	calculated* (cm^3)		
Sarcófago de caixa retangular	S. Manços - Pardais	?	60	66	218	863,280	53	52	205	564,980	35	298,300	–	808	[1] [2]
Sarcófago de cabeceiras arredondadas	S. Manços - Pardais	?	60	62	208	773,760	53	49	205	532,385	31	241,375	–	654	[1] [2]
Sarcófago Monte D'El Rei***	Monte D'El Rei, Bencatel	?	75	62	210	976,500	60	48	198	570,240	42	406,260	–	1101	[3]
Sarcófago dos Leões	Évora	II d. C.	56	90	245	1,234,800	–	–	–	–	–	–	456,876	1238	[4]
Sarcófago da Vindima	Castanheira do Ribatejo	III d. C.	35	45	118	185,850	–	–	–	–	–	–	68,765	186	[4]
Sarcófago Monte do Regoto (2 specimes)	Monte do Regoto - Estremoz	III-IV?	59	64	206	777,856	49	49	191	458,591	41	319,265	–	865	[2]
Sarcófago das Musas	Alfazeirão, Alcobaça	III-IV	54	80	202	872,640	44	62	190	518,320	41	354,320	–	960	[5]
Sarcófago romano de Tui	Pontevedra	IV-V d.C.	58	60	195	678,600	53	50	185	490,250	28	188,350	–	510	[6]
Sarcófago de los Apóstoles de Pueblanueva (catalogue # 50311)	Toledo	IV-V d.C.	70	85	220	1,309,000	60	60	200	720,000	45	589,000	–	1596	[7]

Table 2
Estatues and other architectural pieces made by Estremoz Marble (* obtained using volumetric mass density of 2,71 g/cm^3 for Estremoz Marble - Casal Moura et al, 2007; ** considering cylindrical form). Dimension of archeological pieces from: [1] Oleiro (1996–97) [2] Justino Maciel (1998) [3] http://www.monumentos.gov.pt/ [4] Justino Maciel et al (2002) [5] Justino Maciel et al (2003) [6] Soutelo et al (2018) [7] http://ceres.mcu.es/ [8] Lapuente et al (2014) [9] https://arachne.uni-koeln.de/ [10] Hauschild (1991) [11] Carvalho (2018) [12] http://www.museudelisboa.pt/pecas/detalhe/news/estatua-de-sileno.html [13] http://www.museosdeandalucia.es/ [14] Beltrán Fortes et al., (2018) [15] Justino Maciel et al. (2006) [16] Marquez (2014) [17] Gonçalves (2007).

Statues and other architectural pieces	*Location*	*Century*	*height (cm)*	*width (cm)*	*length or thickness (cm)*	*volume (cm^3)*	*Weight* (Kg)*	*References*
Agrippa Statue (Inv. n° 93)	Coloniae Forum, Mérida	I d.C	200	87	50	870,000	2358	[8] [9]
Female Statue (Inv. n° 18.958)	Templo de Diana, Mérida	I d.C	157	75	45	529,875	1436	[8] [9]
Thoracata Emperor Statue (Inv. n° 645)	Roman theater, Mérida	I d.C	160	65	45	468,000	1268	[8]
Clipeum Jupiter relief (Inv. n° 33.002)	*Cononiae Forum*, Mérida	I d.C	60	164	164	1,613,760 1267444**	4373 3435**	[8] [9]
Caryatid relief (Inv. n° 33.003)	*Coloniae Forum*, Mérida	I d.C	164	62	60	610,080	1653	[8] [9]
Dama anciana de cuerpo entero statue (CE27804)	Necrópolis near of Casa del Anfiteatro, Mérida	I d.C	157	50	28	219,800	596	[7]
Corinthian capital	Roman temple, Évora	I d.C	59	136	136	1,091,264	2957	[10] [11]
Corinthian capital	Roman temple, Évora	I d.C	48	105	105	529,200	1434	[10] [11]
Base of column	Roman temple, Évora	I d.C	48	136	136	887,808 697283**	2406 1890**	[3] [10] [11]
Capital (CE27501)	Calle Juan Dávalos Altamirano, Mérida	I d.C	94	70	70	460,600	1248	[7]
Silenos	Roman theater, Lisboa	I d.C (middle)	123	50	53	325,950	883	[13]
Silenos	Roman theater, Baelo Claudia	I d.C (final)	190	55	44	459,800	1246	[13] [14]
Alamo statue	Villa Alamo, Alcoutim	II d.C.	163	77	45	564,795	1531	[15]
Aion-Chronos Statue (Inv. n° 86)	Mithraeum House, Mérida	II d.C	170	60	44	448,800	1216	[8] [9]
Chronos Leontochaline Statue (Inv. n° 87)	Mithraeum House, Mérida	II d.C	128	55	45	316,800	859	[8]
Fluvial divinity Statue (Inv. n° 85)	Mithraeum House, Mérida	II d.C	68	198	50	673,200	1824	[8]
Mercurio Statue (CE00089)	Plaza de toros, Cerro de San Albín, Mérida	II. d.C	150	84	66	831,600	2254	[7]
Iconic female statue	Foro de Torreparedones, Córdoba	III-IV d.C	192	66	50	633,600	1717	[16]
Togaed statue with head (n° 27 in the catalog)	S. Sebastião do Freixo, Leiria (*Collipo*)	?	200	70	55	770,000	2087	[17]

average, minimum and maximum values can be hypothesized:

Maximum speed – based on Elio Aristides quote and assuming 12-hour journey without stopping (and not 24 h), the maximum value can be considered as 3.5 km/h;
Average speed – according to previous presented values, an average speed of 1.6 km/h can be considered for the ox-drawn vehicle;
Minimum speed – assuming the minimum value is half the average speed, it can be considered that the minimum speed is 0.8 km/h.

This would be an ideal case, but it is necessary to consider some potential variables of these speed parameters:

Animal strength: This could be a variable to be considered, especially in the case of large loads. However, it is not relevant for the present study, as it would be solved with more oxen heads in any case. It could be considered that adding more animals would not substantially change the speed.
Friction: Mainly related to terrain slope. In general, a fully loaded vehicle would not be able to overcome gradients greater than 7 to 9 % (Efkleidou, 2019).
Direction of movement: As the vehicle tends to move sideways on the descent route, the oxen have to be slowed down. Thus, the progression would be similar to going uphill, although the speed could be slightly higher during the downhill run, as the driver would be able to intervene by braking the vehicle (Commonwealth Agricultural Bureaux, 1980).

The type of animal used is also significant as certain animals, such as oxen, may have greater strength than others like donkeys or horses. This limitation of maximum slopes is related to the ability of the animals to maintain momentum and pull the load (Rivas, 2019). Therefore, this study will start from the maximum ideal conditions.

3.3. Fluvial and maritime speed

While Least cost path (LCP) analyses typically focus on the land routes, it is important not to forget that in the ancient world, rivers and the sea were the preferred modes of transportation (Casson, 1971). A combined analysis of costs on land and inland waterways is difficult. Why would they not ship marble when it was possible to do? The constraints and problems are more easily solved, given the greater loading capacity of transport, something achievable with ships. Cargo can be carried in three main types of vehicles when it reaches a water area: a simple one, keeping the cargo in a wagon, a river draught ship or a large cargo ship (Villalba Babiloni, 2018). Depending on the other vehicle, the cost analysis could vary substantially (Gambash, 2017):

Trolley-loading boat: This boat could carry one or more trolleys and could operate in most of the peninsular rivers with very small draughts (Bonino, 1988). The speed of movement is usually constant, influenced by going with or against the current. If it goes against the current, it will be pulled by animals from the land and thus the speed of transport would be similar to that of land transport.. If going with the current, the velocity will depend on the current speed, although it can also be helped by animals when the current is lower.
Riverboat: This type of vessel can carry a maximum of5.5 tonnes (de Soto, 2019). In this case, the cargo would be transferred to the ship, which could make its journey directly to the redistributing port. The speeds are typically similar to those of trolley-loading boats, as the current and direction of the river are the main factors.
Large cargo vessel: These vessels, known as *Caudicariae*, can carry more than 50 tons, with draught being the main limiting factor. Their speed of movement will depend on a multitude of conditioning factors, such as waves, wind direction and strength, as well as currents. They may enter rivers with sufficient draught (Alberti, 2018), as in the case of the Tejo or Sado estuaries.

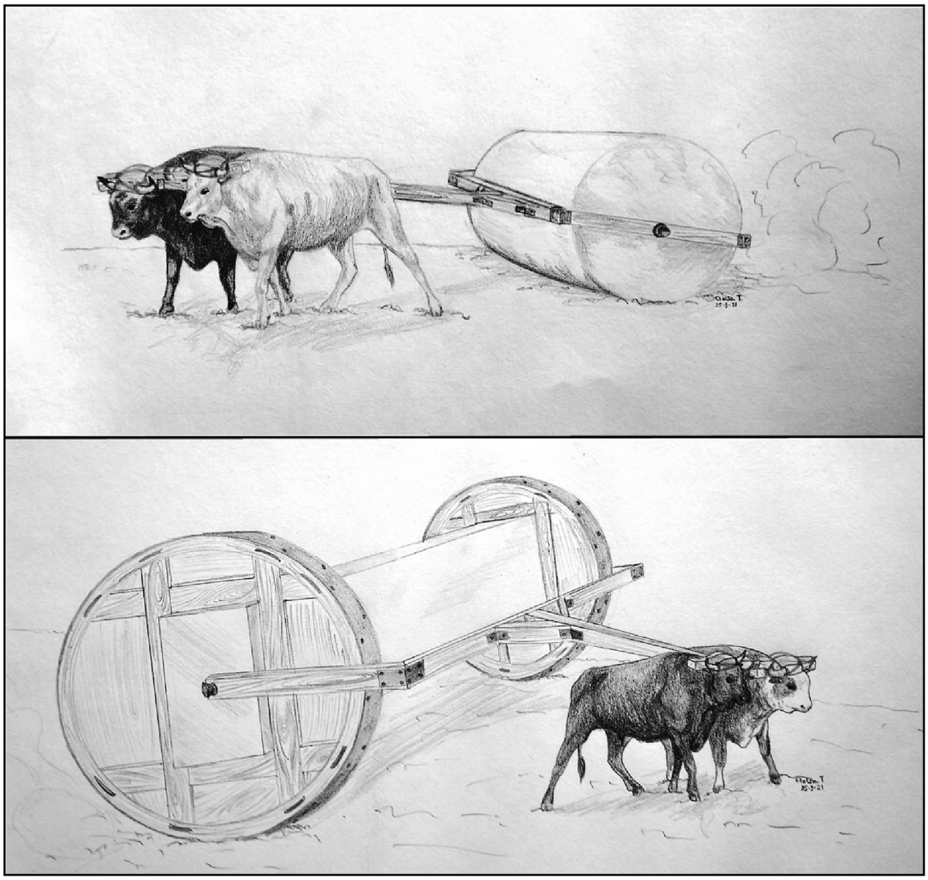

Fig. 2. Possible interpretation of the inventions of Ctesiphon and Metagenes. Drawing by Eloísa Toscano Gracia.

3.4. Economic cost increase

When consideringdifferent road types, it is necessary to take into account not only the possible time improvement but also the economic cost of transport. This is usually represented as the "cumulative incremental cost value over a given journey", usually presented in tonne per kilometre (t/km). Although it is not a historical concept, it makes logical sense to consider the various types of vehicles that may increase the final product cost (Carreras et al., 2019). This value is directly related to the cost of the product, the time taken to transport it, and the transportation mode used. The incremental cost can be estimated based on various parameters presented in Table 3.

The cost parameter is extremely important in route analysis. It is generally felt that the economic cost is not a value to be considered, as in the Roman mentality it did not have the relevance that it has today (Baena Sierra, 2016). However, it could be considered in the case of a land or navigable route, since the land cost is higher when compared with the cost of using river or sea transport (Table 3).

In this section, two complementary GIS models are developed from the parameters described above:

Table 3
Transport values in Roman times (adapted based on de Soto, 2010).

Transport type	Speed(km/h)	Capacity (t)	Cost (t/km)
Maritime	4,25	92	0,097
Fluvial (downstream)	2,5	5,5	0,33
Fluvial (upstream)	0,6	5,5	0,66
Terrestrial (Cart)	1,6	0,090	4,21

a classical land-only mobility analysis, which calculates the cost of distance in time and adjusting the algorithm to a car carrying a heavy load, approximately at the limit of what is allowed by law at 400 kg; starting from the former to include the possibility of combining river and sea transport and calculating the cumulative economic cost.

3.5. Method and constraints

Firstly, it is necessary to identify the departure and arrival points for the products. The departure point is constant across all the models used in this study, which is the Estremoz Anticline. On the other hand, there are multiple possible destination areas for the transported products, as previously discussed in works such as Moreira et al. (2020) and Moreira (2022). The current study considers the following destinations: (1) cities with ports, especially those that could function as a *portorium*, such as *Olisipo*, *Myrtilis* and *Salacia*; (2) the main civitates near the Estremoz Anticline such as *Emerita*, *Scallabis* and *Pax Iulia* (as convent capitals); and also (3) other cities such as *Aritium* (as an important city with a proximal fluvial port in the Tejo river) and nearby cities such as *Ebora*, *Ammaia* (conditioned by the Serra de São Mamede), *Mirobriga* and *Norbensis Caesarina*.

To construct the model, Arcgis software and its distance cost analysis tools (Path Distance and Cost Path) were used, modifying the methodology applied by Trapero (2021). Firstly, a friction raster was created, which will condition the mobility, depending on the following parameters:

Maximum gradients. Vehicles cannot go for terrain slopes higher than 7 to 9°, the vehicles cannot go either for or against the slope. This value is currently applied to analysis of transport efficiency, and although it is not a historical concept, its application is logical, as such gradients will difficult the transport, increasing the cost of the final product in different ways.

Mobility constraints. Rivers and watercourses make overland passage difficult. In the performed analysis, it is believed that some rivers may have navigable potential, making them communication ways. Near the Estremoz Anticline, no watercourse would have the capacity to serve as a potential export route to transport the product to supra-provincial spheres, thus not competing (or serving as an alternative) with land roads. Only the Guadiana river (*Anas* in Roman times) has sufficient flow to be an alternative. Although this river would not be navigable to the Atlantic due to the existence of the Pulo do Lobo knickpoint (e.g. Ortega-Becerril et al., 2018), it could be an alternative in the region from *Pax Iulia* and *Emerita* and to the south of Mértola (*Myrtilis*), where it has become newly navigable and a Roman port having been identified there (Lopes, 2017). In this sense, the watercourses were divided into two groups: those that can limit and those that would serve as a communication way. In this sense, there are approaches that use potential bridges as crossing points (Parcero Oubiña et al., 2019), but since they are not fully known, rivers were considered as barriers for land mobility and communication routes for river mobility.

Topography and human constraints. In this case, these were not considered, on the assumption that the environmental conditions would be very similar to the current ones. Most of the study region is fairly flat and has not undergone significant changes in geomorphology, being characterized by a flattened topography (e.g. Pereira et al., 2014). With respect to human constraints, Roman roads are known, but this was not considered either, as the paper intends to perform a complete analysis of all the possible places of arrival, whether or not they are connected to the roads. In addition, by limiting mobility due to the slope of the terrain, the optimal places for vehicle movement are calculated, many of them coinciding with the Roman roads that were identified. For this study, the calculated optimal routes were considered, without the roman roads, because if it is considered the roads in this analysis, there was priority to the routes which have archaeological evidences. In other cases, it doesn't have archaeological evidence for roads that could have served as potential connections to other cities.

For the remaining steps, two complementary models were used. The first one consists of a cost analysis and optimal routes between the extraction sites on the Estremoz Anticline and the previously mentioned sites, only using terrestrial roads. Any terrain with a gradient change of more than 7 degrees has been add as a restraning. To do this, the hydrographic network generated with Arcgis Hydrology tools has been used, in order to discard rivers or streams whose areas have been modified by human action. As an example, the Guadiana reservoirs to the southeast of the study area have had to be corrected, namely the Alqueva and Pedrogão reservoirs, as these large reservoirs will be considered by the model as optimal areas for mobility, and the tool will tend to run "over the water" as if it were a natural path. Therefore, there are several ways to add a mobility limiter in these areas, generally eliminating these areas or adding a high slope gradient. It has been tried with 5° and 15°, with the latter value being more optimal. Technically, what was done with this methodology was to create a "barrier" that makes it difficult for mobility to cross a river or stream, since this is also a difficult area of natural transposition.

The main problem with the analysis was that there was not a specific distance costing algorithm for ox-drawn vehicles. For this purpose, we generate a second model with the function of Tobler (1993), as it is more intuitive and simpler to use. The function was adapted taking into consideration the aforementioned maximum and minimum speed, respectively 3.5 km/h and 0.8 km/h, making an ascending progression from average values (Fig. 3). In this way, the speed curve decreases less with a moderate slope, being maximum when approaching 7° or −7°, at which point movement would no longer be possible. Finally, it was believed that the optimum speed would be at −1°, rather than at 0 degrees, given the impulse that certain inertia can give (Otavio Rodríguez, 1984). Fig. 3 presents a graph that shows the used function limited in degrees between 7 and −7 and that oscillates in values from 0.0002 h/m to 0.0013 h/m (the unit represents the portion of time in hours that would be needed to travel 1 m). The Path Distance tool, used in this study, will represent the number of hours it takes to get to a known site; this is the reception sites above mentioned.

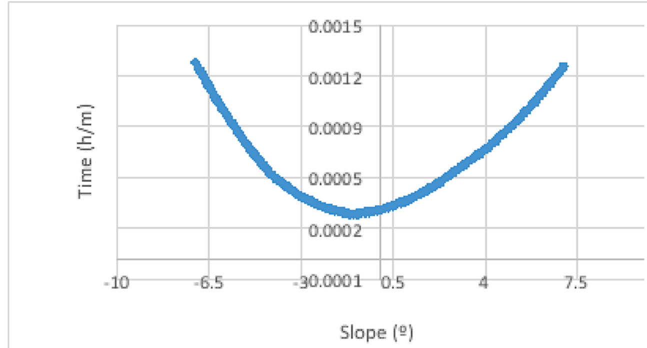

Fig. 3. Representation of the variation on the slope regarding the time consume for the ox cart by modification of Tobler (1993) function.

4. Results

4.1. Cost analysis in a terrestrial environment with ox-drawn vehicles algorithm

The first cost model uses time values and is developed in terrestrial conditions. Two variations, based on more or less friction for crossing river and stream areas of 5 and 15 degrees, have been considered in the first model, although their values are quite similar (Fig. 4). A priori, it was interesting to discuss if there is a preponderance of *Aritium* or *Salacia*, two cities (with fluvial ports) that allow two versions of northward or southward transport. However, there is not a significant preponderance of one or the other. If it is necessary to choose one way or the other, in practice they are similar. The closest sites are *Emerita* and *Ebora*. The isochrones show a more difficult mobility zone to the west than to the east (Fig. 4), which is directly related to the Serra d'Ossa located to the west of the Estremoz Anticline, becoming the mobility towards the Atlantic coast harder. In contrast, the Badajoz plain (related to the Guadiana river basin) allows a relatively easy way to move through *Augusta Emerita*. Mobility to *Emerita* in this model is only conditioned by the existence of the Guadiana river, which would be a potential natural barrier, except in places where there are built or boat bridges.

An important result of this analysis is the identification of potential problems associated with land mobility when determining the most cost-effective route for transporting Estremoz Marble or other products (see Fig. 4).. As mentioned, *Aritium Vetus* and *Salacia* have very close cost values and in fact, there is no fundamental time difference between communications to port cities such as *Aritium Vetus* and *Salacia* or *Olisipo*.

With the exception of Ebora (due to its geographical proximity) it would require more than one day journey. As already mentioned, the ox-drawn vehicle would have to rest and the animals would need to be fed, so the journey could not be more than half a day, even less if the journey lasted two or three days. In the case of *Salacia*, the values of the second model show a journey time of 34 h, which could be three days, while in the case of *Olisipo* it would be 39 h, which is quite similar, and *Aritium* would be around 34 h. So, in theory, there would not be a difference between transporting these products to one port or the other, especially taking into account that the last site could have a river-port on the Tejo

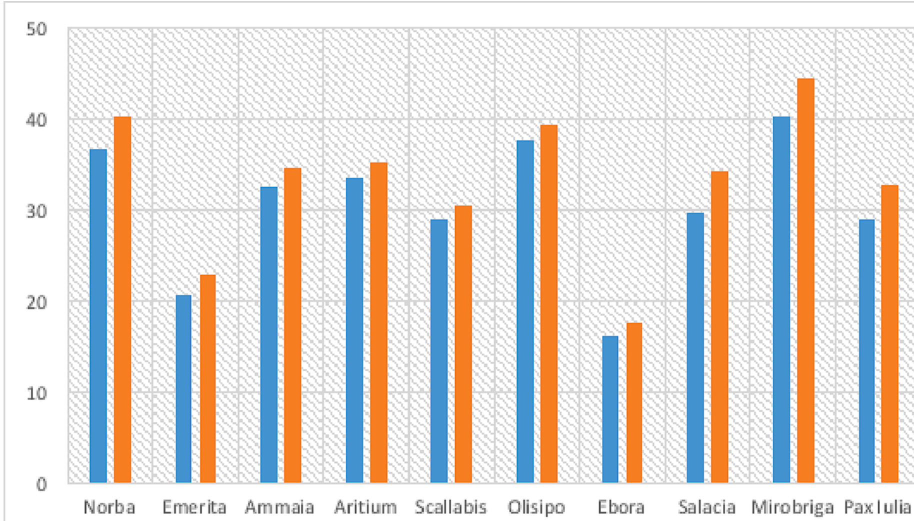

Fig. 4. Time isochrones in hours to go to each of the cities of the territory for first model: variation 1 (blue) and variation 2 (orange).

river (Gaspar, 1970; Filipe, 2019).

Regarding the other cities, *Scallabis Praesidium Iulium* should be emphasized, because the linear distance is shorter than *Salacia* and *Aritium*. This fact is explained by the flattened geomorphology of the north-west of the source area, which facilitates this type of mobility through the Sorraia river (a tributary of the Tejo River), where some authors also defend the existence of a Roman river-port, although without archaeological evidence (Filipe, 2019). The isochrones of the generated models show that this region is the most relevant route connecting to the Tejo River (Fig. 5). The second model will be used to specify the results, while the first one was mainly used to test the method.

4.2. Cumulative economic costs considering land, inland waterway and maritime transport

The second model is more complex and includes outcomes from the first model, adding several changes. The hydrographic network has been subdivided into areas that could potentially be navigable and areas that could be a barrier to mobility (Fig. 6). In both cases, a two-level friction raster has been constructed:

The first raster includes the same slope raster, to which fictitious slopes are added for both types of streams, i.e., by adding an artificial barrier in the areas where there are streams. It would be similar to

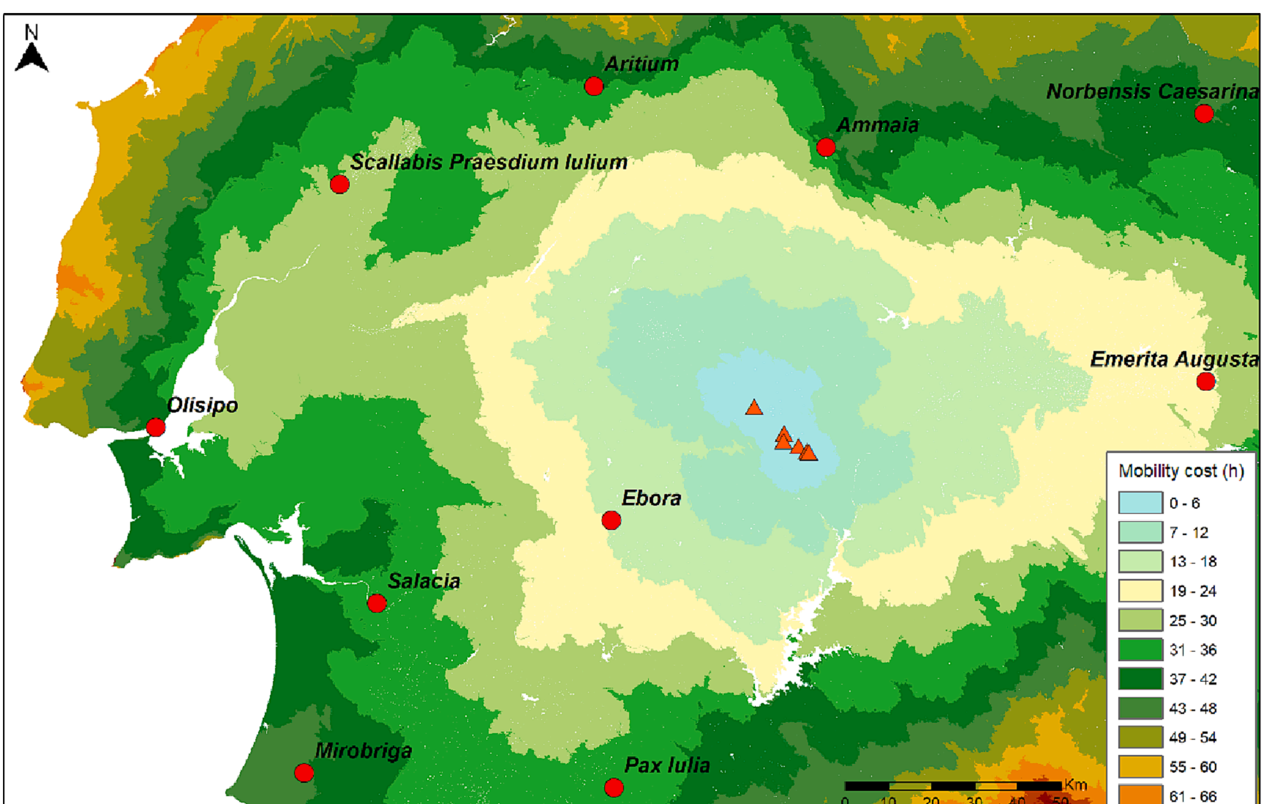

Fig. 5. Calculation of Isochrones in time from the extraction sites based on the second variation of first model.

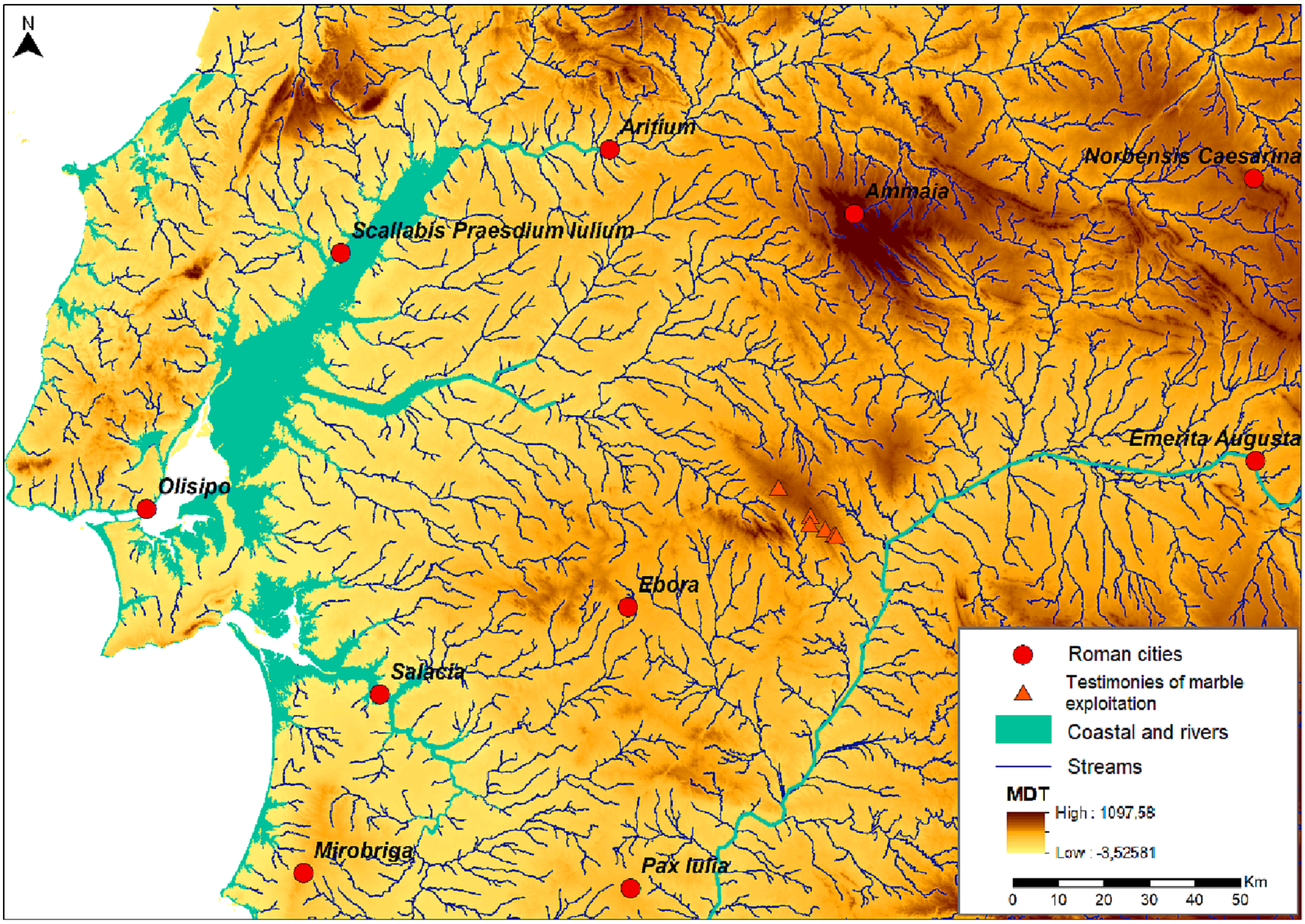

Fig. 6. Representation of classified rivers and streams and cost raster according with the described along the text.

converting the depressed areas of these streams into high and difficult-to-pass-through areas. This method makes it possible to assign specific cost values to them. Since the tool interprets the change in slope and not the absolute value, particularly high values, such as 70 degrees and 80 degrees, were used. The concept is as follows: when the algorithm finds a sloped area that is in a range, for example between 60 and 70 degrees difference, it will return a cost value that was considered as river navigation. This allows the two types of cost to be visualized in the same analysis.

A second raster is added to this, including the orientation of the rivers and streams. Mobility upstream, downstream and, above all, across rivers and streams is not the same. This was considered a limiting factor in both navigable and non-navigable areas. Because of this, it was necessary to isolate the lines that make up the hydrographic network, calculate their orientation and convert them to a raster layer to include them in the model (in accordance with the methodology of Trapero Fernández, 2021). In this case, the cost was not considered in terms of time, but in terms of the increase in economic cost (see Table 3). The analysis of the first model has been reproduced, but this time considering land transport, as well as river and sea transport, and especially considering the areas that would have navigable potential. This model is based on the hypothesis of prioritization of navigable routes in the case of very heavy loads, a feature of the Roman mentality. If large volumes and masses are considered - which is consistent to the studied raw material, this is the Estremoz Marble, and also to the studied territory, showing great distances between the production center and the reception sites -, this marble would have to be transported over long distances.

This analysis considers the costs of transport along the rivers that could be navigable, namely the Guadiana (which would be navigable only in the section of the study area), Sado and Tejo, and its tributary Sorraia (Fig. 5). Table 4 compares the two models, where the cost corresponds approximately to the distance, the quantitative difference between the two criteria not being pertinent. Since the transport time should have not been very relevant during the Roman period, the economic cost increase was considered instead. In practice, transporting something by river or sea is slower than by land. An analysis considering transport time will not give relevant results. However, it is the carrying capacity of ships versus ox-drawn vehicles that makes the difference, so the increase in cost was considered.

This is expressed in Figs. 7 and 8 resulting in the cost (T/km). In this analysis, the isochrones do not correspond to time, but to an accumulated cost of the number of tonnes of a product that could be transported

Table 4
Comparison between the time to go to the different locations and the distance considering topography.

Cities	Variation 1 (h) without water transport	Variation 2 (h) with water transport	Distance (km)
Norba	37	40	137
Emerita	21	23	102
Ammaia	32	35	73
Aritium	33	35	98
Scallabis	29	30	127
Olisipo	38	39	165
Ebora	16	18	48
Salacia	30	34	108
Mirobriga	40	44	142
Pax Iulia	29	33	87

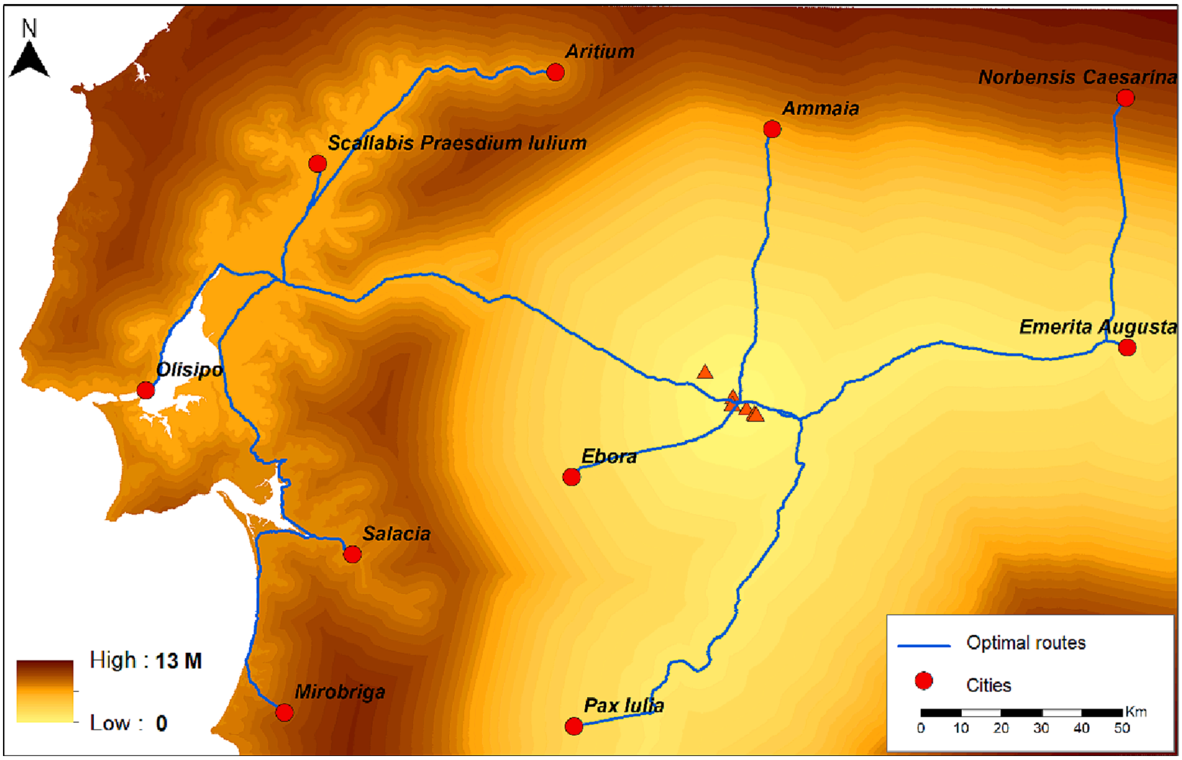

Fig. 7. Isochrones of the mobility analysis showing the highest or lowest suitability of each route, together with the optimal route lines between the production center and the main cities of analyzed territory.

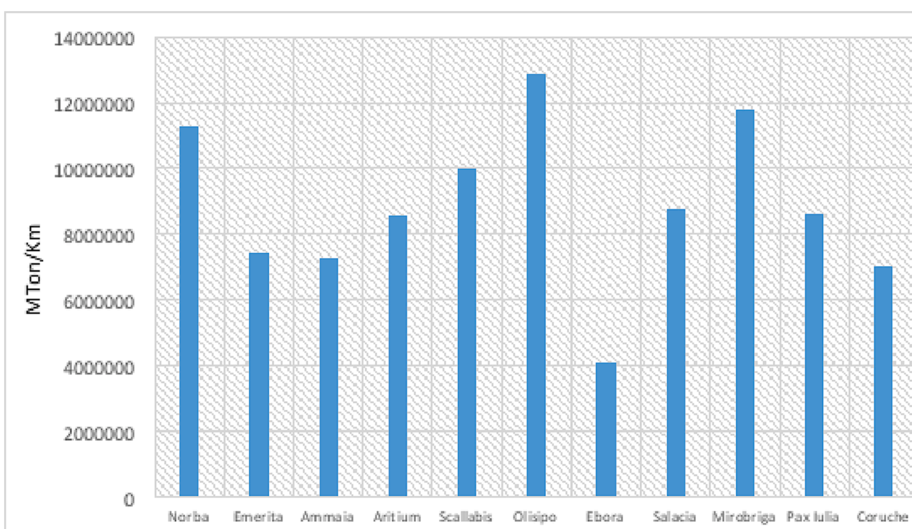

Fig. 8. Cost in terms of economic cost increase (to the main cities of the analyzed territory).

per kilometre. This parameter, used in modern transport logistics, makes it possible to measure the greater viability of a specific route for transport, as well as the value increase of the product.

The transport cost is significant in the case of large rivers that would allow lower costs (Fig. 8). The analysis of optimal routes with this model and the results are interesting because:

> The Guadiana waterway is optimal for transport, namely for *Emerita* and *Pax Iulia*, although the land option is not negligible in both cases. The Tejo and Sado river areas have relatively lower costs, combining both land and river costs.
>
> The route for *Salacia* and *Aritium* river-ports shows that the lowest economic cost is to use a navigable route on the Sorraia river and from there connect by land or use the Tejo river to other routes. Undoubtedly in the case of *Salacia* it would not make sense to unload the goods and then reload them as would be shown in the cost analysis, but the fact that this cost is lower is quite significant.

The analysis considers the terrestrial and fluvial environment for the calculation, but did not take the maritime area into account. This is why the coastal connections are made along the coast. This methodology allows include the maritime area, excluding other conditioning factors such as tides, currents, waves, bathymetry, among others (Trapero

Fernández and Aragón Núñez, 2022).

For the accumulated cost of transporting these products (Fig. 7), it iss curious that the most accessible place is *Augusta Emerita* due to the possibility of fluvial transport along the Guadiana river. The remaining cities are located in areas with similar accessibility, except for *Ebora* and *Pax Iulia*, the latter due to the same possibility of fluvial transport along the Guadiana river. The values entered in Fig. 8 show the cumulative cost in terms of tonnes per kilometre, i.e. the higher the value, the higher the cumulative cost. The numbers are indicative, as they are not in a measure that it can simply recognize, but helping to understand, for example, that the cost of transporting something to *Olisipo* range between a third to a fourth than to *Ebora*.

Thus, and considering the model, it is possible to take into account a river port in the Coruche region (in the Sorraia river), which would allow a lower transport cost for the Estremoz Marble.

5. Discussion and conclusion

The analysis carried out in the present study confirms what was originally proposed, this is that the economic costs of transporting marble from Estremoz Anticline would be quite large. The cumulative cost value is not relevant, but it can be used as a comparative parameter; as example, the cost of getting a heavy load to *Ebora* would be half the cost to *Augusta Emerita*, *Salacia* or *Pax Iulia*, and about a third of the cost to *Olisipo*. The used method innovates through the application of an algorithm for the calculation of the peculiarities and limitations of the mobility of a land vehicle with a very heavy load and the possibility of using different means of transport, not only by land, but also using fluvial and/or maritime vehicles. While there is significant potential for analysis in the field of Roman roads and bridges, we have not given them much attention in this study. We have not included bridges as a variable, as we only have limited knowledge about them and incorporating them could lead to a bias in favor of mobility in specific areas. However, an extensive and accurate archaeological study would allow for their inclusion. Nevertheless, we believe that there is still a scope for study in this area through the use of GIS. Firstly, by employing methods that enable us to predict the location of archaeological sites, such as bridges, or by analyzing areas with less traffic, through historical comparisons and hydrological modeling. Secondly, by using horizontal cost functions to accurately simulate passage over the bridge. While this approach has been proposed in a previous article (Trapero Fernández, 2021) and further research is required to validate its effectiveness.

From the historical point of view, the transport time would not be a determining factor, but rather the cost increase (in this paper measured in tonnes per kilometer). This parameter is currently used in transport logistics, but can also be applied to ancient times. It is necessary to consider whether the value of the cost that each route would have in value of t/km is indicative; indeed, the aim is the comparison between the cost of transport to distinct places, thus allowing to predicate the proportion of the cost. Furthermore, to the cumulative cost it should be include the monetary cost of the wagon, the driver, possible tolls along the way, etc. This methodological approach is novel, because although it is used for marble heavy loads and can be equally used in other contexts, with other raw materials and products, by interested researchers and projects. Of course, further research is required in this type of approach (Bongers, 2020), and the real cost of each type of transport, the amortizable costs of transport infrastructure, and loading and unloading should be considered.

Regarding the Estremoz Marble case, this article increases more debate than solutions to the transport problem of this raw material. It is not confirmed that the proposed route was the most "optimal", but it reopens some alternatives to the Roman road network from Lusitania, including possibly the "Estrada das Tesas" connecting Estremoz Anticline to Sorraia river. This road, i.e. Estrada das Tesas, was previously proposed as a Roman road (Carneiro, 2008, 2022), presenting a route outline quite similar to the lowest-cost path obtained through the present study, thus connecting the extraction center with a possible river-port in the Sorraia, enabling the outflow of this raw-material to the main port in Olisipo.

As regards the economic implications of the Estremoz Marble transport, its important distribution throughout Hispania and other western provinces is known (e.g. Moreira, 2022), however further research is still needed on the places of arrival.

Given the high economic cost of transporting this marble, it seems that it would not be very competitive in a supply/demand dynamic compared to other marbles in the Mediterranean circuit, or even from Betic area, with lower extraction costs and greater fame. This is why it is possible to hypothesize that the transport did not work in this dynamic but was managed, or at least regulated. There are no certain indications as to how these quarries were managed and the absence of known epigraphy about marble extraction on Estremoz Anticline. However, the exploitation of marble in this center could have imperial concessions during Augustus governance or belong to the exploitations of one of the prefectures of *Augusta Emerita*. In either case, the transport costs would not be relevant, given the need to supply this great city. However, many of the pieces found in other environments and chronologies show different uses (see Moreira, 2022 for more information), so there could be another system of supply and demand.

This trade may have been regulated by some kind of guild, as is known in other parts of the empire. Major studies on this subject are lacking, but they may be related to the purpose of the trade, private or public, as well as the chronology in which the exchanges took place. All of these questions need to be reconsidered, and more data is required.

The imposition of export fees on products outside the provinces by means of a portorium (Rodríguez Fernández, 2019) is the clearest case. The redistribution circuit of these products could be directly between the marble producer and the final user, but it is very likely that there are some intermediaries who, during the first phase of the trade, took the product to a port such as *Olisipo*, where it could be redistributed to other places. Marble is certainly not an easy load to transport, so it seems unlikely that the vendor would have been itinerant with his wares through country houses and towns.

CRediT authorship contribution statement

Pedro Trapero Fernández: Conceptualization, Methodology, Software, Formal analysis, Visualization, Writing – original draft, Writing – review & editing. **André Carneiro:** Conceptualization, Resources, Validation, Writing – original draft, Writing – review & editing. **Noel Moreira:** Conceptualization, Validation, Formal analysis, Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

Acknowledgements

This work is the result of the financial support given through the project PHIM3 (Marble Industry Heritage and History, 3rd Phase - Ref: ALT20-08-2114-FEDER-000213). Noel Moreira is funded by National Funds through FCT - Foundation for Science and Technology, under the funding program of the Institute of Earth Sciences (ref. UIDB/04683/2020 and UIDP/04683/2020).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jasrep.2023.103962.

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