A Spatial Connectivity Approach to Landscapes of Conflict: Julius Caesar and the Assault to Puig Ciutat (NE Iberian Peninsula)

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Abstract

Landscape plays a vital role in the development of military campaigns through the definition of geostrategic landmarks that structure the control of the territory, the imposition of constraints to the movement of armies and the identification of features that facilitate defence against attackers. These factors are linked to the study of past spatial mobility which is typically done by finding optimal pathways between pairs of points using Least-Cost Path analysis. This emphasis on optimality may not be ideal for case studies that need a general approach to spatial connectivity such as the study of conflict-related dynamics. Connectivity modelling based on Circuit Theory (CT) is an alternative approach to spatial mobility that captures the connectivity of an entire region identifying not only optimal paths but also bottlenecks, dead-ends and any other spatial feature that may impact movement. We present here a framework to study landscapes of conflict using connectivity modelling; the framework combines CT, visibility analysis and statistical hypothesis testing to understand the reasons behind the assault and destruction of Puig Ciutat (NE Iberian Peninsula) during Julius Caesar's civil war. Results suggest that the site exerted decisive control over a highly connected area linking two possible logistical bases (Emporion and Massalia) to the armies fighting at Ilerda (49 BC).

Keywords Conflict archaeology · Landscape archaeology · Spatial analysis · Julius Caesar · Computational archaeology · Ilerda

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Introduction

The study of violent conflict through material culture has received growing interest in the last two decades (Bleed & Scott, 2011; Pollard & Banks, 2005). Conflict archaeology studies the origin, development and consequences of warfare with a particular focus on direct engagements such as pitched battles and sieges (Foard *et al.*, 2003; Scott & McFeaters, 2011). Recent works are widening the perspective of the field by integrating additional conflict-related sites and activities like logistical infrastructures (Tunwell *et al.*, 2015), heritage and memory (Hernández-Cardona *et al.*, 2019), aerial bombings (Moshenska, 2009) or repression events (Jerez Farrán & Amago, 2010). At the same time, the field is also diversifying the periods under study which currently include all chronologies from Bronze Age battlefields (Lidke *et al.*, 2017) to recent conflicts (Schofield, 2009).

Interestingly enough, a majority of works in conflict archaeology study recent periods as opposed to the common focus on prehistory within archaeological research. Written accounts and other historical sources (photography, cartography, oral memory) pinpoint the location where conflict-related events happened, thus facilitating the identification of battlefields. This is particularly true for battlefields because these violent engagements seldom generate any kind of structure; the archaeological evidence that can be recovered in battlefields is composed of small metallic artefacts (*e.g.* ammunition, armour fragments) collected through field surveys using metal detectors (Foard *et al.*, 2003). Sieges and assaults on fortifications are more easily identified because they happened within settlements and other sites with structures (*e.g.* walls, forts, pillboxes), but the archaeological investigation of these events also relies on written accounts; the lack of historical sources inhibits a robust interpretation of the collected evidence because several questions will be hard to answer solely based on the archaeological record: who were the attackers and the defenders? Why was the place attacked? How did the siege develop? Did it succeed? For example, a modern-era European city siege is a highly complex event involving thousands of defending and attacking soldiers, besieged civilians, trenches, large artillery trains, huge logistical requirements and several types of actions (*e.g.* skirmishes, artillery fire, naval blockades, assaults). The analysis of one of these sieges generates a large body of highly detailed textual and cartographical data that will allow us to track casualties and activities at a daily level, thus complementing the insights generated by archaeological works (Rubio-Campillo *et al.*, 2015). This information will simply not be available to the study of a prehistorical site or a historical event that was not considered relevant enough to be mentioned in written sources. As a consequence, the interpretation of conflict-related archaeological evidence is extremely challenging without additional sources linked to the examined event.

A possible solution to the lack of context of prehistorical battlefields is offered by the study of its landscape (Carman & Carman, 2006). First, opposing armies fought to control key strategic locations during a military campaign and the decisions of commanders towards this goal had to take into account how landscape

constrained the movement of large military forces. Second, the deployment of a pre-contemporary army in battle formation took several hours and for this reason the location of the battlefield was typically agreed by both sides with the exception of ambushes or small scale skirmishes. Finally, landscape plays a decisive role during the battle itself by providing defensive positions, generating visual control and channelling the movement of soldiers. Landscape studies able to cover these three scales may strengthen the interpretation of battlefield archaeology even without the support of alternative sources (Nolan, 2009; Rubio-Campillo, 2008).

The multiscalar study of conflict landscapes typically uses spatial analysis and particularly two concepts: (a) visibility and (b) mobility (see examples in Canosa-Betés, 2016; Murphy *et al.*, 2018; Rubio-Campillo & Hernández, 2015; Sivilich & Sivilich, 2015). Visual control is an essential trait of warfare because commanders needed constant updates on the position, size and intention of opponents as a means to avoid ambushes while maximising their geographical advantage in case of engagement. The most common computational approach to visual control is viewshed analysis; this technique quantifies to what extent a location is able to 'see' its surroundings (Wheatley, 1995). Conflict archaeology uses techniques such as cumulative viewshed analysis (*i.e.* combining visibility from multiple locations) and inter-visibility analysis (*i.e.* defining networks of visibility between locations) to identify visual cues that may explain the effectiveness of multiple defensive positions or define the visual limitations of commanders' locations during a battle. A distinctive idea for the use of viewshed analysis within conflict scenarios is that visual control is always subjective and depends on two actors (*i.e.* both armies); visual control of a battlefield is linked to the probable actions and movements of the enemy forces and there is no point on dominating an entire area where the enemy will never march due to a diversity of factors (*e.g.* the region is already controlled by friendly units, landscape prohibits military movement). For this reason, the study of battlefield landscapes needs to combine visibility analysis with additional parameters able to model the behaviour of armies.

The study of mobility is even more complex than visibility because movement needs to take into account multiple scales (see this diversity of scales in Güimil-Fariña & Parcero-Oubiña, 2015; Murrieta-Flores, 2012; Yubero-Gómez *et al.*, 2015); in contrast, the scale of visibility studies is strictly limited to the distance that can actually be observed (*e.g.* a few kilometres). At a large scale, mobility analysis allows us to understand the challenges of moving large military forces of thousands of soldiers as well as the logistical burden they require: draught animals, cattle, food and water, and even groups of accompanying civilians. At a small scale, mobility is useful to explore the path followed by military units and the way landscape was used to hinder attacks through the choice of optimal defensive positions. The most common tool to assess mobility in archaeological contexts is Least-Cost Path (LCP) analysis (Verhagen *et al.*, 2019). This technique estimates the optimal route between two given points given a friction surface of varying costs affecting movement across the area. While useful, the optimality of LCP is open to critique because the friction surfaces may be biased by the inherent uncertainty of the archaeological record and it may generate weak results in situations where costs are difficult to

assess or optimality is not desirable (Herzog, 2014; Supernant, 2017). For example, large pre-contemporary armies split their forces across multiple routes to simplify the logistical challenges of feeding thousands of humans concentrated within a small area. Additionally, the threat posed by the enemy activity may radically change the perception of costs for different paths because the optimal path may be prone to ambushes in narrow passes or it could leave enemy garrisons at the rearguard of the main body, thus putting in danger the vital line of communication linking an army with its supply source.

A computational model including mobility and visibility approaches can help us strengthen our study of pre-modern conflict by facilitating the exploration of three questions: (a) why there was a battle fought at a specific region?, (b) to what extent the choice of battlefield can be explained by its geographical features? and (c) how a battle was influenced by its geographical setting and landscape once armies finally clashed? We present here a novel multiscalar analysis to landscapes of conflict used to contextualise a military engagement with very scarce written accounts. The approach is applied to the case study of Puig Ciutat (region of Catalonia, NE Spain) where a Roman army assaulted and destroyed a Roman garrison during the opening moves of Julius Caesar's civil war at the campaign of Ilerda (49 BC). The computational model presented here integrates the specific dynamics of Roman conflict as opposed to other human activities. The method offers a combined study of visibility and mobility by replacing traditional LCP analysis with a more suitable approach to mobility in the face of uncertainty known as Circuit Theory (CT) connectivity.

The next section presents the archaeological site of Puig Ciutat and the challenges posed by the absence of written accounts describing the assault. This is followed by the definition of the materials and methods used in the analysis with an emphasis on the CT algorithm. The “[Results](#)” section presents the results of the analysis, while the “[Discussion](#)” section discusses these results in the context of the original research questions. The paper concludes with a summary of the potentials and limitations of this methodology not only for conflict archaeology but also for the general study of archaeological landscapes.

Julius Caesar and the Assault to Puig Ciutat

The archaeological site of Puig Ciutat (Catalan for ‘city on the hill’) is located in the area of Lluçanès, 60 km north of Barcelona (NE Spain). The site was identified as early as 1980s but archaeological works did not start until the twenty-first century. In 2006, a systematic geophysics survey revealed a large urban grid and yearly excavations started in 2010 (García *et al.*, 2010; Padrós Gómez *et al.*, 2019; Pujol *et al.*, 2019).

Puig Ciutat occupies a 5-ha plateau at a meander of the Gavarresa River. The main part of the perimeter is formed by steep cliffs except for two segments (E and SW) where walls were built to enclose the plateau (see Figure 1); the Eastern section of the defensive wall was partly uncovered by excavation campaigns undergone between 2010 and 2014 while the South-Western section was located in a trench excavated during the 2017 summer campaign.

Fig. 1 The location of the Puig Ciutat site within the current boundaries of Catalonia and Barcelona province. Excavated buildings are displayed in black while evidences of walls are shown in red

Early geophysics surveys (*e.g.* Ground Penetrating Radar and magnetic) revealed a complex urban grid affected by widespread fires which were later confirmed by excavations. Both stratigraphical information and recovered artefacts suggest that the plateau held an Iberian settlement that was later occupied by a Roman military garrison as a *praesidium* or *castellum* (Padrós Gómez *et al.*, 2019). This dating aligns Puig Ciutat with the already existing large corpus of conflict archaeology works studying Roman battlefields (*e.g.* Bellón *et al.*, 2016; Fernández-Götz & Roymans, 2017; Morillo *et al.*, 2020; Uribe *et al.*, 2021; Wilbers-Rost *et al.*, 2012). In fact, archaeological work suggests that Puig Ciutat hosted a Roman garrison which was assaulted and destroyed by another Roman force. This battle between Roman opponents is supported by several lines of evidence including (a) widespread fires covering the entire final phase of the site, (b) a large amount of intact artefacts found in several rooms (*e.g.* amphorae, tableware, game sets), (c) complete cattle and dog remains in anatomic connection, (d) human remains in anatomic connection under a collapsed roof and (e) a wide range of Roman military weaponry and equipment found both inside and around the site (*e.g.* catapult bolts, slingshots, sandal hobnails, a *pilum* and a *pugio*) (Ble Gimeno, 2016, pp. 107–109). The analysis of pottery typologies dates the destruction around mid-first century BC (Padrós *et al.*, 2012); this combination of conflict evidence and relative dating strongly suggests that the assault is linked to the early phases of Julius Caesar's civil war and particularly to the Ilerda campaign (49 BC).

The Ilerda campaign saw two large Roman armies manoeuvring around the present-day city of Lleida and the lower course of the Ebro River. One army was led by Julius Caesar himself while the other was commanded by two legates loyal to Pompeius and the Senate: Lucius Afranius and Marcus Petreius. The campaign overlapped to Caesar's siege of Massalia (present-day Marseille, France); the outcome of these two campaigns determined the Caesarian control of the Western Mediterranean. At Ilerda, both opponents struggled to outmanoeuvre the other army and block its lines of communication and logistics. The written sources narrate these events as

a generalized struggle around Ilerda between Iberian groups gradually shifting supports from Pompeius towards Caesar. The Ilerda campaign concluded without any large engagement as the Caesarian legions managed to isolate the entire Pompeian force, thus forcing its surrender due to the lack of supplies.

The Ilerda campaign is described in detail on a diverse set of written accounts but this body of sources do not mention any assault that could match the assault to Puig Ciutat. This case study is a perfect example of the previously discussed interpretative challenges regarding conflict-related events not covered by written sources. We focus here on exploring the role played by Puig Ciutat within the Ilerda campaign: was Puig Ciutat a key strategic location to control NE Hispania? Was this military garrison controlling a supply path to Ilerda? Why did a Roman army defend this location against another Roman army? These questions need a multiscalar approach beyond the site itself because they require additional tools able to analyse the conflict event from a larger perspective.

Materials and Methods

Study Region

The Ilerda campaign developed around the current city of Lleida (Catalonia), but written sources mention several skirmishes across a larger triangular region defined by the Ebro River, the Pyrenees and the Catalan coast. The study region has been defined by a 100-km buffer beyond this triangle to avoid potential edge-effects bias to planned spatial analysis (see Figure 2).

A 30-m resolution Digital Elevation Model (DEM) of this region was acquired from the current ASTER Global Digital Elevation Model (NASA/METI/AIST/Japan Spacesystems and US/Japan ASTER Science Team, 2019). The DEM was then edited to align the Ebro River delta and the Narbonne plain to the coastline of the Roman period. These modifications were made to improve the accuracy of the topography, but it is worth mentioning that changes in the coastline do not have a significant impact on this case study because both Ilerda and Puig Ciutat were far from the Mediterranean coast. The final DEM was resampled at 100 m; this resolution was deemed detailed enough to develop large-scale analysis while it optimized computational requirements. The resulting DEM was a raster map of 3840×3677 pixels (see Figure 3).

The large size of the involved armies (at least 40,000 soldiers each) suggested that any spatial analysis should take into account areas instead of specific points of interest; we used this approach to define the region where both armies deployed around Ilerda. It can also be observed that the city of Massalia is far from our study region; Caesar's force was connected to the besiegers deployed there, so it was decided to define an area of interest covering the path of the Via Domitia between Massalia and the Pyrenees (*i.e.* the current French coast between Montpellier and Béziers); any supply route moving from Massalia to Ilerda would need to use this road before crossing the Pyrenees mountain range.

Fig. 2 Map of the Western Mediterranean outlining the study region (red area). Five landmarks are also highlighted: Ilerda, Massalia, Puig Ciutat and the two main harbours of the Catalan coast at the time of Caesar's civil war (Emporion and Tarraco)

Two additional key locations for the case study are the main harbours of the region during this period: Emporion and Tarraco. Emporion (literally ‘market’) was a Greek colony founded by the Phocaeans, the same people that founded Massalia. This common origin suggests that Emporion was allied to Pompeius as Massalia was. Tarraco was the earliest Roman settlement in the Iberian Peninsula and its harbour supplied Roman military forces in the region since the Second Punic War. The political position of Tarraco within the Roman civil war is unknown but the city probably supported Julius Caesar as the nearby Iberian groups did.

The third research question explores on the local prominence of Puig Ciutat and for this reason it requires a smaller scale of analysis. A local region was defined as a 30-km buffer around Puig Ciutat (*i.e.* the maximum daily march distance for a Roman military unit). This perimeter covered natural corridors across the region while discarding any mountainous areas not suitable for military operations as seen in Figure 4. This second DEM kept the 30-m resolution used by the original dataset and consisted of a raster map of 2485×1594 pixels.

Fig. 3 DEM of the study region highlighting the 4 areas of interest for connectivity purposes: Ilerda, the route to Massalia and the harbours of Emporion and Tarraco. The map also shows the perimeter of the region defined for local analysis in red shape

Computational Approaches to Spatial Mobility

Current spatial analysis approaches offer a diversity of methods to explore mobility. Present-day movement patterns are commonly studied through graph networks composed by sets of nodes and edges connecting them (*e.g.* cities and roads). While useful, this approach is difficult to apply to mobility dynamics of archaeological regions

Fig. 4 Digital Elevation Model of the local region. The area is characterized by uneven terrain populated by several small hills and river valleys. The map displays the two main historical corridors: the Vic plain (eastern North-South plateau) and the East-West southern corridor that was used to build a highway during the twentieth century (the current C-25 road)

due to inherent uncertainties on the location, dating and even co-existence of settlements and pathways. The most common alternative to network analysis is offered by Least-Cost Path (LCP) analysis (Conolly & Lake, 2006, pp. 252–255). LCP does not require data for edges or nodes because it is based on a cost function defined by the researcher. This cost function is built upon variables that may hinder movement (*e.g.* slope, ruggedness indexes) and is typically expressed as a cost surface map; LCP uses the cost estimation to compute the optimal route connecting any two given points based on its minimal accumulated cost.

One of the limitations of LCP analysis for archaeological research is that the approach is designed to identify one single optimal pathway between two points and it is not well suited to explore general mobility patterns within an entire region. Some variations to the basic algorithm introduce stochasticity as a means to add more flexibility to the method (Palmer *et al.*, 2011), but the fact remains that LCP was not designed for the task of analysing regional connectivity at a broader scale than optimality. A possible solution is taken by the studies exploring natural corridors: a set of random points is defined at the perimeter of the archaeological region and then, LCP is computed for each possible pair. The final step is to quantify the density of optimal pathways at each cell of the map, thus generating a connectivity map for the region (Murrieta-Flores, 2012; Yubero-Gómez *et al.*, 2015). This approach allows archaeologists to identify the most important regional pathways

independently of the archaeological data, but it still is limited by the optimality of the paths. For example, imagine a region where several suboptimal paths are present; none of the optimal paths will move through this location, even if intuitively we may argue that the spot should have a high connectivity value because it would be an important crossroad for multiple secondary routes. In addition, if the optimal path is not available for any reason (*e.g.* snow), then the analysis will have to be recreated with a different cost surface map instead of just identifying alternative suboptimal paths.

Connectivity modelling is a widely used alternative to LCP in ecological studies (McRae *et al.*, 2008). Spatial connectivity is understood as the degree of interaction between areas of a given region; it can be quantified as the chances that an individual moving between two areas will visit any location within a delimited region. A popular approach to connectivity is Circuit Theory (CT) modelling which uses the metaphor of voltage-current relationships to explore the intensity of spatial interactions. The algorithm does not generate a single path like LCP does and for this reason it seems better suited to identify key mobility landmarks, bottlenecks, crossroads and secondary routes because it does not seek optimality. In ecology, the versatility of CT is a useful complement to LCP for policy making on wildlife conservation management because it generates an overview of connectivity beyond optimality and specific locations (Dickson *et al.*, 2019). It can be argued that this versatility should make CT the preferred choice for archaeological studies in regional mobility due to the high uncertainty inherent to past mobility dynamics. In fact, CT has been applied to a number of archaeological case studies (Domingo Ribas, 2018; Howey, 2011; McLean & Rubio-Campillo, 2022; Thayn *et al.*, 2016). These works suggest that CT modelling complements traditional LCP-based mobility analysis of past societies, thanks to its broader perspective on the connectivity of archaeological regions.

CT analysis requires three main elements: (a) sources of energy, (b) destinations attracting this energy and (c) friction costs of movement between locations. The algorithm simulates a flow of energy moving from the sources towards the destinations, and quantifies the amount of this energy that crosses each area of the region (*i.e.* every single raster map cell). The spots that channel a large amount of the produced energy will have higher connectivity values while the areas with low values of energy will be defined as spatial clusters of low values (*i.e.* cul-de-sacs). CT modelling has limitations, as any other research tool does. The most important issue for archaeological studies is that the output is most useful as a comparative tool within the region; it will allow the researcher to establish areas of higher and lower connectivity, but the outcome is hardly translatable to time or energy. As a consequence, it would be difficult to define absolute values of travel cost or to compare the CT results amongst multiple different regions.

Definition of Mobility Costs

The definition of elements required by CT will depend on the specific hypotheses to assess. The choice of origins and destinations is straightforward (*e.g.* Tarraco and

Ilerda) while the model of friction costs requires more thought. The cost of mobility for this case study has been modelled after the limitations faced by the logistical system of Roman armies. In the absence of maritime and/or riverine transport, food, water, weapons and the other supplies required by armies were moved by porters, pack-animals and animal-drawn carts such as mules, horses and cattle (Roth, 1999, pp. 198–222). This logistic system was heavily hindered by any terrain feature beyond roads and plains and for this reason friction costs were derived from slope values. A slope raster map was computed based on the existing DEM model and then reclassified after the equation suggested by Herzog for wheeled vehicles (2013; based on the theoretical approach of Llobera & Sluckin, 2007): $\text{cost}(s) = 1 + (s/S)^2$, being s the slope of the cell as a percentage and S a *critical slope* parameter typically between 8 and 16. This reclassification will heavily penalize values higher than the critical slope; for this case study, a critical slope of 8 was chosen as higher gradients would be considered unfeasible for the march of large military forces comprising thousands of soldiers, horses, mules and carts. Figure 5 displays the cost surface map for the region under study; Supplementary Information 1 and 2 show alternate cost surface maps for higher critical slopes (10 and 16) which rendered very similar friction distributions. Generally speaking, any N-S path from Massalia to Ilerda is dominated by the Pyrenees mountain range while mobility from the main harbours to the area where both armies were deployed is obstructed by smaller mountain ranges with moderate friction values.

Visual Control

The study of the local dominance of Puig Ciutat needed to assess to what extent Puig Ciutat controlled the local area around the plateau where the site is located. Viewshed analysis allows the researcher to create maps of visual control from a given point of observation using a DEM. The algorithm uses the elevation model to compute whether each location within a given radius can be seen from the point of observation; if the line of sight is not blocked by any intermediate cell at a higher elevation, then it is assumed that both points can see each other (for an overview, see Conolly & Lake, 2006, pp. 225–233).

Viewshed analysis is much more sensitive to landscape alterations and archaeological uncertainty than regional mobility analysis due to the higher resolution that it requires and its limitations have been extensively discussed elsewhere; they encompass issues such as (a) terrain modifications between the palaeoenvironment and the current DEM (Rubio-Campillo *et al.*, 2015), (b) palaeovegetation (Llobera, 2007) and (c) variability caused by atmospheric conditions (Murphy *et al.*, 2018). The assessment of these issues for our case study does not suggest any substantial impact on the final outcomes. First, the region around Puig Ciutat has not seen major landscape alterations since the Roman period beyond agricultural works and local roads which would not change the elevation at Puig Ciutat and the surrounding area. Second, vegetation in the area would be similar to the current one which follows a typical Mediterranean pattern: wheat crops intermixed with dispersed forests of red pine and oak. This landscape would not deter an observer from identifying the large

Fig. 5 Surface cost map for the theatre of operations reclassified from slope values and a critical slope of 8

body of a marching Roman military unit including thousands of soldiers, animals and carts. Finally, atmospheric conditions would be dominated by the fact that the Ilerda campaign developed during spring and summer. Weather in the Lluçanès area would be typically clear beyond isolated cloudy days and rainstorms. In any case, the local analysis of Puig Ciutat has been performed for three maximum visibility radius (5 km, 10 km and 20 km) to take this variability into account.

Beyond specific issues, the most important limitation of viewshed analysis is linked to its sensitivity to the quality of the elevation model. The DEM accuracy may heavily affect the computation of a line of sight from a specific location in the map as the elevation is typically recorded in each raster cell as a summary statistic (*e.g.* mean, maximum value). Small variations in elevation may have significant impact in the result if viewshed analysis is used to explore the visibility of individual spatial locations. Elsewhere has been suggested that this issue limits the use of viewshed analysis for individual sites while a better approach would be its use within a statistical framework capable of minimizing these issues (Lake & Ortega, 2013). The visual control model of this study is inspired by this approach: viewshed analysis combines results from a set of points within Puig Ciutat's perimeter following a Poisson process, thus minimizing the reliance on exact intervisibility.

Identification of Strategic Paths

The first research question aims at exploring to what extent Puig Ciutat was able to control natural corridors across the study region. Natural corridors can be defined as the most probable routes to be used for someone moving across a region (Murrieta-Flores, 2012). These routes play a key role in geostrategic connectivity because they are time-independent at a regional scale: the optimal route may vary, but the topographic features that define them (*e.g.* mountain ranges and valleys) will not change at a human time-scale, thus identifying regional natural corridors independently from specific phases or sites.

The algorithm used here to identify these natural corridors is inspired by previous archaeological research that applied LCP and is defined as follows (based on Yubero-Gómez *et al.*, 2015):

1. Define a set of regularly spaced points over the boundaries of the region
2. Compute the connectivity raster map using the surface cost map and every pair of points as origin/destination
3. Create an accumulated connectivity map by adding all connectivity maps produced by step 2

Distance between points was defined at 25 km for a total of 61 points as can be seen in Figure 6. This point density was enough to identify the main natural corridors of the region under study while avoiding further computational costs caused by the exponential nature of algorithms performing pairwise calculations.

Tracing Supply Routes to Ilerda

The second question moved the focus from time-independent geostrategic routes towards the dynamics of the Ilerda campaign. We explored here if the attack to Puig Ciutat could be linked to the supply lines of the armies deployed at Ilerda. Three possible origins were identified for the logistical system of both forces: the overland route to Massalia, the city of Tarraco and the Phocaeen colony of Emporion.

Fig. 6 Boundary points used to identify natural corridors are displayed here over the surface cost map

Military control does not only rely on the deployment of garrisons at specific locations but more importantly on the zone of control that these garrisons may exert over the neighbouring territory (*i.e.* the area where they can identify and intercept enemies). CT models are particularly suited to explore this spatial control because the algorithm quantifies connectivity for each raster cell within a region, thus allowing us to assess whether the area around a point has a higher connectivity than expected. To perform this analysis, three buffers around Puig Ciutat were defined at 5, 10 and 20 km, being the rationale that 20 km is the average daily rate of march for military units since prehistory until the twentieth century (Moore, 1960; Neumann, 1971). Effective control would decrease as the distance to the site increased and for this reason we added two smaller buffered areas for the sake of comparison.

For each of the three possible origins (route to Massalia, Tarraco and Emporion), the following Monte Carlo simulation was applied to test for high connectivity values around Puig Ciutat:

1. Compute raster connectivity values from the logistic origin to the area of Ilerda
2. Create three circular buffer zones with 5, 10 and 20 km radius centred at Puig Ciutat
3. Generate four sets of random points with similar density based on a Poisson process (*i.e.* random spatial coordinates) delimited by (a) the entire region (100k points), (b) 5 km buffer (1k points), (c) 10 km buffer (1k points) and (d) 20 km buffer (20k points) around Puig Ciutat (see Figure 7).
4. Sample the connectivity values from the raster map computed in step 1 for each random point created in step 3.
5. Use null hypothesis significance testing to reject the null hypothesis that the connectivity values within each buffer follow a similar distribution than the rest of the territory.

Step 5 used permutation test to assess to what extent the connectivity near Puig Ciutat was higher than expected if the site was not relevant to the examined origin and destination. The approach confronted the mean connectivity value within each given radius (5, 10 and 20 km) against 1000 same-sized samples from the Poisson process values; we defined the threshold of significance at the highest 1% quantile of their means. In other words, for each source we would assess if the mean value within the buffer was lower or equal than 99% of the mean values from the 1000 random samples; if this threshold was not achieved, then the connectivity around Puig Ciutat would not be deemed as statistically significant.

This second question was linked to the exploration of optimal routes between Ilerda and potential supply sources. For this reason, a final step was to compute LCPs from each origin towards Ilerda for the sake of comparison. The analysis

Fig. 7 Example of random points generated by Poisson processes for the different datasets: the entire theatre of operations (white) and the 20 km buffer around Puig Ciutat (red)

was performed using QGIS-based ‘Least-Cost Path plugin’ with the same cost surface used for CT analysis.

The Local Dominance of Puig Ciutat

The last question of this study focused on the local dominance of Puig Ciutat. Two intertwined factors need to be explored here: visibility and mobility. The basic approach to visual control is to compute the viewshed area as seen from the site, its centroid or its perimeter (Canosa-Betés, 2016; Lake & Ortega, 2013; Murphy *et al.*, 2018; Rubio-Campillo & Hernández, 2015). However, the amount of territory visually controlled by Puig Ciutat is not significant here because the garrison would only be interested on the logistics routes towards Ilerda. Visual control over distant mountain ranges and unconnected valleys would not accomplish much in terms of military control; as a consequence, the size of the viewshed observed from Puig Ciutat would not be a good proxy for visual dominance.

The approach developed here computes the visual control of highly connected areas (*i.e.* visual control of strategic routes) and it is inspired by previous works using LCP (Bell *et al.*, 2002; Canosa-Betés, 2016). The method is defined by 3 processes; first, a connectivity map is calculated for the local region based on the work developed for the first question:

1. Define a set of regularly spaced points over covering the boundary of the local region around Puig Ciutat. The distance between points was defined at 5 km for a total of 44 points.
2. Compute a raster map of connectivity between every pair of points
3. Create an accumulated connectivity map by adding all connectivity maps produced by step 2

Second, viewshed analysis was used to assess the visual control from Puig Ciutat using a Monte Carlo process:

1. Generate a set of 100 random points inside the perimeter of Puig Ciutat
2. Compute a binary viewshed from each point of step 1. The viewshed was performed at an added height of 3 m over the DEM to account for the existence of walls and watchtowers. The output was a binary raster map where cells were either 1 (*i.e.* it can be seen from Puig Ciutat) or 0 (*i.e.* it cannot be seen from Puig Ciutat). Maximum visibility distance was fixed at 10 km because a larger distance would render control ineffective due to weather, vegetation and other unaccountable factors.
3. Create a combined visibility map by performing a logical AND operation on the 100 binary viewsheds computed at step 2. The result is a raster map where each cell has a value of 1 if it was observed by at least 1 point and a value of 0 if it was not observed by any point within Puig Ciutat.

Finally, a Monte Carlo simulation similar to the one designed to answer the second question was used here to assess whether Puig Ciutat controlled areas with high connectivity values (either by distance or visibility):

1. Generate three sets of 1000 random points based on Poisson processes: (a) the entire region, (b) visible points within 10 km of Puig Ciutat and (c) non-visible points within 10 km of Puig Ciutat
2. Sample the connectivity values from the previously computer raster map for each random point of the three sets
3. Use significance testing to quantify differences between the distribution of connectivity values amongst the three datasets

The boundaries for the region, the 10 km buffer and the perimeter of the site can be seen in Figure 8.

Step 3 used the non-parametric Kolmogorov-Smirnov test to reject the null hypothesis that connectivity distributions between pairs of datasets (Poisson, visible and non-visible) were generated by the same process (*i.e.* there is the same level of connectivity inside and outside Puig Ciutat's control).

It is worth noting that the parameter values used for the three analyses were informed by an initial parameter space exploration designed to assess the sensibility of the algorithms. Beyond the two alternate critical slope values previously discussed and displayed as Supplementary Information, other explorations focused on the impact of larger buffer radius and the sample size of the Poisson

Fig. 8 Analysis of local dominance for Puig Ciutat. The red line defines the boundary of the local region while white points display the locations used to create the pairwise CT model. The shaded blue circle is the 10 km buffer around Puig Ciutat used to perform viewshed analysis

processes. The results of these two explorations are not presented here due to limitations of space but readers interested on the experiment design can easily explore and modify the analysis with the openly available source code and datasets. Ultimately, outcomes proved to be robust to changes on parameter values as natural corridors, logistic routes and statistical results remained consistent across reasonable parameter values.

Results

We present here the outcome of the three analyses based on the algorithms and parameters defined in the previous section.

Fig. 9 Cumulative current map for the theatre of operations. The colour gradient is divided in 10%, 25%, 50%, 75% and 90% quantiles; the same gradient of relative values has been applied to the rest of the connectivity maps to facilitate comparison

Strategic Paths

The CT model of regional natural corridors can be seen in Figure 9; the colour gradient of the map has been defined to highlight regions with particularly low or high connectivity. It can be observed that the main natural corridor is a North-South pathway near the Mediterranean coast which would be used later to build the most important Roman road in Hispania: the Via Augusta (and the current AP-7 highway). A second highly connected area extends on a West-East axis from the central coast towards Ilerda (covering the route of the current A-2 motorway).

The lowest tail of the distribution of connectivity values can be found in some coastal cul-de-sacs and the Pyrenees. Three highly connected passes on this mountain range can be distinguished here which were also used to build past and current roads (from west to east: La Cerdanya, Coll d'Ares and Coll del Pertús). These three mountain passes channel the energy flow across the Pyrenees and for this reason they have always been key geostrategic locations for any military conflict in the region including Roman wars, modern conflicts between Spain and France or the Republican retreat at the end of the Spanish Civil War.

The connectivity map shows that Puig Ciutat is not located near any natural corridor. There are a small number of highly connected clusters around this location, but they are not particularly relevant at this scale because they are isolated from both the main pathways and the Pyrenees passes.

Supply Routes to Ilerda

Results for the second analysis explored to what extent the assault could be linked to the control of supply lines as seen in Figure 10a–c. Puig Ciutat does not seem to be located around highly connected areas in any map yet significant differences appear depending on the origin. The long distance from Puig Ciutat to highly connected pathways is also supported by the LCP analysis as seen in the same figures.

The path from Massalia to Emporion is constrained by the few possible passes of the Pyrenees. The energy flow as generated by the algorithm is spread over the three main passes. The eastern pass of Pertús shows a higher intensity due to its proximity to the coastal area and a wider corridor than the other passes. A smaller percentage of the flow crosses the other passes (Cerdanya and Coll d'Ares) and moves near Puig Ciutat, thus suggesting that its garrison may exert a significant control over some of the secondary routes. The second output shows that easier terrain between Tarraco and Ilerda would make Puig Ciutat irrelevant as no supply line from Tarraco to Ilerda would remotely move near the site. Finally, the location of Puig Ciutat seems more relevant if the logistic source was the harbour of Emporion as explored by the third map. This output shows two routes moving from Emporion towards Ilerda: (a) the North-South corridor linked to the Via Augusta and (b) a network of secondary flows crossing the area controlled by Puig Ciutat on an East-West general direction.

The previous maps are complemented by Figure 11. The relative connectivity of the random points generated by the Poisson process (*i.e.* null hypothesis) is

Fig. 10 Fig. 10 **a–c** Cumulative current map to Ilerda from the three defined origins: **a** the path to Mas-salia, **b** Tarraco and **c** Emporion. All maps show the 20 km buffer around Puig Ciutat used for the algorithm (black circle) and the LCP route (white path)

compared to the connectivity values sampled within 5, 10 and 20 km of Puig Ciutat using Monte Carlo methods.

Fig. 11 Boxplot of connectivity values for the three origins. Values were sampled from random points in the region and points at 5, 10 and 20 km from Puig Ciutat. Results have been normalized between 0 and 1 to facilitate comparison

Permutation tests support these trends by rejecting the null hypothesis of similar distribution for Emporion (*i.e.* mean connectivity within 20 km radius higher than .99 quantile of random simulations). The same null hypothesis can also be rejected for Massalia with a closer margin, while it cannot be rejected for Tarraco. All these results show that the area around Puig Ciutat does not exhibit significant higher connectivity values than the ones sampled from the Poisson process for Massalia and Tarraco. The CT model for Emporion exhibits a different pattern: connectivity values around Puig Ciutat are much higher than the ones provided by the Poisson distribution. These results suggest that the assault

Fig. 12 Cumulative current map for the local region around Puig Ciutat. The map also displays the 10 km buffer used for viewshed analysis (white circle)

to Puig Ciutat would be better explained if Emporion was playing a key role for the logistical needs of the armies fighting at Ilerda.

Puig Ciutat Local Control

The third set of results explores the local prominence of Puig Ciutat. Figure 12 portrays the cumulative current map generated by the CT model of natural corridors. The site does not seem to be located at a particularly connected area as compared to the N-S corridor traversing the eastern area or the E-W corridor at the southern border.

The second component required by this analysis is the binary viewshed computed from points within the Puig Ciutat's perimeter (see Figure 13). The outcome does not reveal particularly good visibility from the site beyond the closest valleys.

Three Monte Carlo simulations were ran to compare connectivity values between visible, non-visible and the baseline of a Poisson process (see Figure 14).

The distribution of connectivity values sampled for these three groups can be seen in Figure 15.

Kolmogorov-Smirnov was finally computed to complement this visualization with null hypothesis significance testing. Results were adjusted for multiple hypothesis testing with Bonferroni correction and revealed statistically significant differences for the two groups within 10 km of Puig Ciutat versus the random points (p value < 0.001 for both tests). In contrast, the null hypotheses of identical distribution cannot be rejected for visible vs non-visible points (p value = 1). The outcome

Fig. 13 Binary viewshed analysis performed within a 10 km buffer of Puig Ciutat

indicates that the locations near Puig Ciutat had higher connectivity values than the average on the region independently of their visual control from the site.

Discussion

The outcomes of the three analyses are interpreted here in the context of the assault to Puig Ciutat and its potential role within the Ilerda campaign. First, the CT model of natural corridors suggests that Puig Ciutat does not exert any geostrategic control over the key routes crossing the NE Iberian Peninsula. This negative result is strengthened by the fact that the area where the site is located (*i.e.* Lluçanès) has seldom been important for other military campaigns. The few cases where the region saw military operations are associated with asymmetric warfare. A good example of these dynamics is the epilogue of the War of the Spanish Succession where a joint

Fig. 14 The Monte Carlo method required generating three random sets of points to sample the connectivity values for (a) points visible from Puig Ciutat within 10-km radius (blue), (b) points not visible from Puig Ciutat within 10-km radius (red) and (c) complete random points (white)

French-Spanish army besieged Barcelona for an entire year (1713–1714). During the siege, a Catalan army moved across this territory and harassed the lines of the communication of the invading forces using specialized light infantry military units known as *miquelets* (see an example in Rubio-Campillo, 2008). Overall, this lack of geostrategic relevance of Lluçanès suggests that the importance of Puig Ciutat was directly linked to the Ilerda campaign.

The outcome of the second analysis reveals that Puig Ciutat did not directly control any optimal path from the analysed origins towards Ilerda. However, it could have exerted control over alternative lines of communication from Ilerda to the coast and particularly to the Greek colony of Emporion. If this harbour was supplying one of the armies deployed at Ilerda, then Puig Ciutat would be a key location dominating a network of secondary routes crossing the region in a W-E direction; the location would be even more relevant if the enemy blocked the main communication

Fig. 15 Density plot of cumulative current value samples from sampled points: **a** points visible from Puig Ciutat within 10-km radius (blue), **b** points not visible from Puig Ciutat within 10-km radius (red) and **c** complete random points (white)

route from the coast towards Ilerda (*e.g.* the Via Augusta). This scenario (*i.e.* one side controlling the main path and forcing the other one to rely on secondary routes) seems plausible due to the shifting alliances of the local population as Iberian support alternated between Roman military forces. These outputs can be combined with the written account of Julius Caesar to argue that the garrison defending Puig Ciutat was part of the Pompeian army while the assaulting force was commanded by Caesar. Specifically, Caesar mentions that the Pompeian commanders sent garrisons to protect the Pyrenees passes but the Caesarian legions defeated them, thus granting Caesar control over these key pathways. The assault to Puig Ciutat fits Caesar's interest on controlling the lines of communication around the region while there is no mention to Pompeian forces moving from the coast towards Ilerda.

These results explain why the control of the Lluçanès area could have been an operational goal for both Roman armies, but why was Puig Ciutat chosen as the key

location of the region? Archaeological evidence tells us that one side deployed a sizeable garrison at this hill while the other side invested a considerable amount of time, resources and soldiers to assault the position. The outcome of the third analysis does not reveal Puig Ciutat as being a particularly dominant location within the region so the question on why the garrison was assaulted remains open. The simplest answer is that PC offered some defensive benefit beyond its location. Two hypotheses can be suggested here: (a) the plateau where Puig Ciutat sits was the only one large enough to host a large military garrison and (b) the garrison occupied a previously fortified settlement.

This spatial analysis highlights some additional ideas relevant to the assault. First, the lack of visibility suggests that any garrison at Puig Ciutat would need to create a network of detachments, posts and watchtowers able to render an effective visual control of the region. Second, while fieldwork has found evidence of earlier settlements, there is still no clear evidence of its size or activity. Puig Ciutat hosted a fortified Iberian settlement, but we still do not know whether it was abandoned at the time of the Ilerda campaign; the Roman garrison could have occupied and extended the abandoned fortifications or expelled the Iberians living there as a means to use a fortified and easily defensible perimeter. Additional field surveys beyond the plateau may reveal other archaeological sites linked to the battle of Puig Ciutat; these smaller sites may include temporary camps built by the attackers during the assault as well as watchtowers or fortifications linked to the defensive perimeter. From this perspective, the information generated by this work will be used to inform further fieldwork activities designed to test the new hypotheses.

Beyond the case study of PC, the multiscalar analysis presented here shows how CT modelling may be used to explore a diversity of research questions where archaeologists have previously applied LCP-based approaches. The most relevant benefit of CT is the definition of a general perspective on the connectivity of an archaeological region beyond optimal paths. This is particularly useful for cases such as the one explored here because the assumption of optimality cannot be accepted in the context of violent and dynamic conflict between two armies. Furthermore, the fact that optimality is not required by CT may be interesting to cases with high levels of uncertainty; in these instances, the binary nature of LCP may be too limiting whereas the global outcome of CT models seems more flexible and prone to robust archaeological interpretation. CT is also computationally less expensive than LCP-based adaptations to general connectivity analysis (*e.g.* identification of natural corridors).

As any other method, CT has limitations. Most of them are common to other spatial analysis approaches such as sensibility to changes on the definition of the friction costs. While this sensitivity is an issue, it can be mitigated by the analysis of multiple possible surface cost maps (which was done in this research by exploring alternate *critical slope* values as seen in Supplementary Information 1) to assess to what extent results depend on specific friction values. Additionally, CT explores general connectivity instead of single optimal paths and for this reason it is less sensitive to slight variations in parameter values. If we focus on the interpretation of results, then the most relevant limitation is that CT outcomes are better understood as relative connectivity values within the region. It is difficult to transform CT

results to an estimate of time, energy or other absolute meaningful costs for mobility; as a consequence, if absolute estimates and minimum cost are relevant for the research question, then LCP is still the best existing technique to be applied within archaeological contexts (Rosenswig & Martínez Tuñón, 2020).

Concluding Remarks

Conflict archaeology is an emerging field of studies that often combines archaeological evidence with written and cartographical sources. If these sources are available, then archaeological research is guided by records and maps describing the violent event under study. This focus on historical conflicts means that our understanding of violent conflict is mostly based on the materiality of renowned battles and sieges covered by historical sources. Conflict archaeology may tend to overlook prehistoric warfare beyond the excavation of fortified sites and mass graves displaying evidence of violent trauma. As a consequence, we should be cautious in our efforts to understand past warfare and avoid a biased perspective of prehistorical chronologies with a lower intensity on violence which increases with the amount of written accounts.

Beyond biases on the intensity of research, another consequence is that conflict archaeology is focused on large events while minimizing the relevance of activities other than pitched battles and long sieges. Examples of these key activities would be reconnaissance, logistics and supply, pre- and post-battle skirmishes and pursuits, field hospitals and a long list of additional processes undertaken by armies of all periods. Some of these tasks are very difficult to observe in the archaeological record, but in other cases a conflict archaeology perspective may be particularly useful given the lack of alternative sources of evidence.

In both cases, the computational study of landscape based on spatial analysis and hypothesis testing may allow us to quantify to what extent working hypotheses at different scales are plausible even when the events were not recorded by any written source. It is important to note that the study of landscapes of conflict has some unique traits that make them different to other landscape studies, such as the existence of two actors or the dynamics of military operations. From this perspective, conflict archaeologists should not rely on embracing common analytical tools used in site-based studies; the interpretation of conflict landscapes needs alternate approaches more suitable to the challenges posed by the study of warfare. At the same time, some of the challenges of conflict studies are shared by other archaeological cases and for this reason we hope that the exploration of less well-known methods such as Circuit Theory connectivity modelling may also be adopted by landscape archaeologists studying other dimensions of the human past.

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Group at SESS-Peking University (<https://github.com/Gooong/LeastCostPath>); further spatial analysis and cartography were performed with QGIS 3.22 (QGIS Development Team, 2021) and data visualizations were created with R 3.6.3 (R Core Team, 2020) and ggplot2 3.3.2 (Wickham, 2016). All source code and data are accessible under open licenses. The authors would like to thank the constructive feedback from two anonymous reviewers, Francesc Xavier Hernández for discussions on preliminary results and everyone that has participated in the archaeological project of Puig Ciutat.

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Data Availability Dataset is available under an Open Data license as: Rubio-Campillo, Xavier (2021): Connectivity Modelling Dataset - Puig Ciutat assault. Figshare. Dataset. <https://doi.org/10.6084/m9.figshare.14995245.v3>

Code Availability Source code is available under an Open Source license at <https://github.com/xrubio/puigCiutatConnectivity>.

Declarations

Conflict of Interest The authors declare no competing interests.

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