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The methodological centrality of geo-archaeological surveys in ceramic provenance analysis: A re-assessment of El Argar pottery production and circulation☆

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ABSTRACT

The abundance and variety of clay sources found in many parts of the world make the issue of prehistoric pottery provenance and circulation more complex than what purely petrographic characterisation studies often suggest. In this study we use a specific combination of petrographic analysis, geoarchaeological survey, and spatial analysis to determine the origin of the clays used in pottery production. Specifically, we focus on pottery production within the core area of El Argar, an archaeological entity that developed during the Early Bronze Age (2200-1550 BCE) in the southeast of the Iberian Peninsula. Following the analysis of the natural conditions under which the identified El Argar clays had formed, an archaeological survey was conducted, locating the raw materials within geographically confined sedimentary deposits of the Inner Betic mountain range. By examining the distance between clay deposits and Early Bronze Age settlements, we conclude that the majority of El Argar ceramics were not produced locally. The spatial analysis strongly supports the idea of a specialized production, likely concentrated around specific clay deposits, with a high degree of productive standardisation. These patterns align more with regional and supra-regional political systems and exchange networks, than with a domestic mode of production. The proposed investigation shows how the combination of petrographic optical microscope analysis, systematic geological and geomorphological survey, and spatial modeling aided by GIS provides a powerful tool for identifying forms of economic and political organization of pottery manufacture and circulation.

1. Introduction

Pottery is the first product created by human societies through the physical and chemical transformation of a mineral assemblage. The transformation of ceramic paste during firing can be compared to the metamorphism of sedimentary rocks. As a result, petrography becomes crucial when determining the nature of the original components of these artificial rocks (Shepard, 1956). However, the main goal of pottery studies in archaeology is not merely to identify raw materials, but to understand the social relations involved in the manufacture, circulation, use, and discard of ceramics. Petrography alone is clearly insufficient to achieve these goals, no matter how detailed and accurate the characterization of the components may be. The presence, or even abundance, of clay sources in many regions is often used as a shortcut in pottery petrography to claim a local origin for most prehistoric pottery productions. These assumptions are frequently based on geological maps that describe rock formations. However, this methodology has notable limitations. Geological maps are often generalized and lack detailed accounts of geomorphological and sedimentary processes or the spatial distribution of deposits relevant to pottery production. This lack of

☆ This study is dedicated to the memory of Rafael Armenta (Écija, September 21, 1949 – Écija, September 2, 2025), sculptor and clay artist, whose creativity and spirit continue to inspire us.

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precision and the fact that clay compositions can differ significantly from the rocks cropping out in a region can lead to misleading or ambiguous conclusions, particularly when attempting to connect social practices with natural resources.

A more accurate and meaningful approach to the provenance of pottery emerges when the focus is shifted from the petrographic description of the clays and temper to understanding the complex interplay of natural processes that condition the availability and characteristics of raw materials (Heidke et al., 2002). From this *genetic* perspective, sedimentary, geomorphological, and edaphological formation processes can be more relevant than the geological mapping of rocks and their minerals. A comprehensive analysis of past clay sources requires targeted geoarchaeological surveys and sampling of sedimentary deposits, combined with a petrographic analysis to assess their composition, as well as their structure and suitability for ceramic production. This integrated approach goes beyond the static representations provided by standard geological maps and it offers deeper insight into the interactions between ancient communities and their environments. Over the past two decades, multiple studies have demonstrated how such a geoarchaeological methodology can foster a more dynamic and nuanced understanding of material provenance strategies (e.g., Kiriatzi, 2003; Kibaroğlu et al., 2023; Kiriatzi and Gardner, 2024).

The development of a geoarchaeological method to reliably trace the provenance of pottery pastes is essential for understanding the socio-economic contexts of pottery manufacture and circulation in the past. Although ethnographic as well as archaeological studies have shown that household production can exceed self-sufficiency and generate surpluses for distribution in local or supra-local markets (Köhler, 2017; Risch, 2018), the discovery of a high percentage of non-local pottery in one or several nearby settlements is often considered a clear indicator of specialized production (e.g., Blackman et al., 1993; Fragnoli, 2021; Roux and Karasik, 2018). This form of craft organization, where potters work full- or part-time in large-scale workshops linked to regional or trans-regional distribution networks, is typically associated with more complex and hierarchical socio-political systems. The degree of specialization and scale of pottery production have been central themes in research on political and economic centralization, as well as early state formation in the Eastern Mediterranean (Todaro, 2012; Fragnoli, 2021; Derenne et al., 2022).

The aim of this study is to present a rigorous geoarchaeological approach to trace the provenance of ceramic materials and evaluate its heuristic potential for understanding standardisation, craft organization, and the circulation of pottery in El Argar. In combination with a high-resolution petrography of the pottery of four El Argar settlements located in the southern part of the present-day province of Murcia, an extensive and sedimentologically informed survey was carried out in an area of ~5200 km^2. Over 140 clay deposits were examined and compared to the prehistoric pastes. This multidimensional approach allowed us to detect discrete raw material sources and to reconstruct clay procurement territories at a regional scale. Based on these results, spatial models of access to the appropriate clay deposits and pottery circulation were created to understand the dimensions of the economic networks. By doing so, we moved beyond current assumptions based solely on macroscopic similarity or static geological mapping, proposing instead a materially grounded and spatially explicit model of ceramic production in the core zone of El Argar. A final step consisted of conducting an experimental program with an expert clay artist to assess the workability and quality of the typical El Argar clays (SM 1.7). These aspects proved equally important for understanding the social and technical conditions of pottery production in El Argar.

El Argar represents one of the most remarkable archaeological entities of the Early Bronze Age in Europe, which experienced rapid development in the southeast of the Iberian Peninsula between ~2200–1550 BCE. In addition to large hilltop settlements and their intramural burials, one of the most distinctive features of El Argar is its highly uniform, undecorated pottery, which can be classified into only eight easily recognisable morphotypes that evolved over 650 years (Siret and Siret, 1890; Lull, 1983; Velasco, 2021).

At the peak of El Argar's economic and political development (~1750–1550 cal BCE), this pottery was produced and used in large quantities within a network of settlements that controlled a territory of ~ 35,000 km^2. This area extended throughout southeast Iberia and included strategic locations in the south of La Mancha (Lull et al., 2011a). The prominence of this highly standardised pottery in El Argar funerary practices across age, biological sex, and wealth of the buried individuals, suggests a specific habitus of consumption and a shared aesthetic and ideological identity among the inhabitants of this large, geographically interconnected territory (Bonora, 2021). The rare occurrence of such pottery and associated burials beyond the territorial boundaries of El Argar further underscores its distinct economic and ideological significance within the broader Iberian context (Peres and Risch, 2022, 2023a, 2023b; Moreno Gil et al., 2023, 2025). Surprisingly, despite the distinctive social and ideological role pottery appears to have played in this complex Early Bronze Age society, relatively little is known about its manufacturing processes, production rates, or circulation mechanisms. Evidence of ceramic production, such as kilns or specialized workspaces, remains absent, and only a limited number of technological and archaeometric studies have been conducted to date (Contreras and Cámara, 2000; Aranda Jimenez, 2004; Colomer, 2005; Padilla et al., 2020; Velasco, 2021; Vico Triguero, 2021). The question of whether the dominance and persistence of El Argar pottery over time and space resulted from production and distribution controlled by specific settlements or political entities remains unresolved. The provenance of the raw materials used in El Argar pottery manufacture and the motivations for their selection from the numerous clay sources existing in southeast Iberia are crucial research issues in the ongoing debate about the economic organization of one of Europe's most innovative and prominent Early Bronze Age societies.

2. Towards a comprehensive approach for characterizing clays and rocks

Our methodological framework draws upon established approaches in Mediterranean ceramic studies, particularly those developed by the Fitch Laboratory of the British School at Athens (Whitbread, 1995; Kiriatzi, 2003; Kiriatzi and Gardner, 2024), as well as more recent contributions from regions such as the Peloponnese (Xanthopoulou et al., 2021), Sicily (Montana et al., 2009), Dalmatia (Miše et al., 2021), and the Negev (Burton et al., 2019). While our study shares core analytical tools –such as ceramic petrography and fabric comparison– it introduces a distinct, integrated approach specifically adapted to the geological and geomorphological setting of southern Iberia. Building on the methodology proposed by Heidke et al. (2002), which focused on sand temper provenance, we adopt a *genetic geoarchaeological framework* grounded in systematic, large-scale, and sedimentologically-informed prospection. Crucially, the data generated through this geoarchaeological strategy allow us to model patterns of raw material acquisition, pottery distribution, and human mobility with unprecedented resolution.

The concept *petrofacies* is used to transcend a purely petrographic classification of pottery pastes. In geology, it refers to the distinctive compositional characteristics of clastic rocks, determined by the percentage of various grain types (Mansfield, 1971; Dickinson and Rich, 1972), but it also applies to sedimentary units sharing significant compositional similarities, typically resulting from analogous generative processes (Gómez-Gras et al., 2016). In the context of ceramic pastes, petrofacies denote the mineralogical and textural attributes of the matrix and antiplastic inclusions that constitute a ceramic vessel, providing insights into the selection and processing of raw materials (e.g., Garrido-García et al., 2023; Moreno Gil et al., 2025).

Drawing on Roux's (2019) operational chain analysis, the term *petrofabric* describes the multi-scale organization of the fine matrix, the presence or absence of tempering agents, the arrangement of coarse components, and grain size selection. Petrofabrics reveal how clay materials were prepared and the processes involved in manufacturing ceramic vessels. They not only reflect material transformations but also highlight the adjustments made to adapt the final product to specific functions, taking into account material properties and design concepts (Buxeda et al., 2008).

The following interdisciplinary approach was followed to characterise ceramic petrofacies and petrofabrics, as well as raw material sources (SM 1, 2, 3, 4, & 5).

- Mesoscopic approach: Using a binocular loupe (10-60 X), a representative selection of ceramic fragments was analyzed based on key attributes, including color, homogeneity, ceramic matrix type, texture, inclusion shape and proportion, and porosity. This semi-quantitative approach relies on visual comparisons with modal proportion tables (Fieller and Nicholson, 1991). Increasing the number of analyzed samples improves the robustness of group classification, ensuring better representativeness of the dataset.
- Microscopic approach: Optical polarization microscopy enabled the precise identification of rock fragments and minerals. This technique evaluates mineralogical components, their qualitative characteristics, and their organization within rock fragment lithologies, distinguishing whether they belong to the ceramic matrix or form the coarse fraction (Delgado-Raack et al., 2009). The analysis also determines whether inclusions are the result of intentional mixing during manufacturing processes (petrofabrics) or are naturally occurring petrofacies associated with specific geological environments (Eramo, 2020). Nevertheless, distinguishing antiplastics from tempering agents based solely on textural properties remains a challenge, as these characteristics are closely tied to the formation processes of the sedimentary deposits (Gómez-Gras, 1997; Nichols, 2009).
- Microscopic analysis was also used to quantify the matrix, framework, and porosity components of ceramics through point-counting (Galehouse, 1971). A minimum of 300 points per thin-section was analyzed to ensure representativeness and to establish the relative percentages of each component.
- X-ray Diffraction (XRD) enabled the identification of minerals present in ceramics, particularly in cases where particle size was extremely fine, i.e. below the detection threshold of optical microscopy (5–15 μm). Although not directly applicable for determining petrofacies, XRD provides valuable insights into firing temperatures by identifying mineral transformations (Shepard, 1956; Capel et al., 1979; Linares et al., 1983).

After the identification of the petrofacies, we evaluated the processes that could have led to the formation of these sediments. Specifically, we searched for deposits capable of providing the clayey fine fraction and the temper observed in El Argar pottery. Such deposits may occur in broader or entirely different areas than the rocks supplying the raw materials for these sediments. This could, in turn, have a substantial impact on the distances between potential raw material sources and prehistoric settlements. Considering this, we developed a three-stage strategy to approach the raw-material sourcing of Argaric pottery.

- Geoarchaeological surveys focused on identifying raw material sources by analyzing geological and edaphological maps as well as satellite images to locate lithological outcrops with distinctive petrological features categorized by age. Collected samples were then examined for their textural and compositional properties, facilitating the assignment of ceramic petrofacies to potential raw material sources. In total, 242 outcrops were inspected and 148 clay deposits were examined, selected not merely by proximity to the settlements but by petrographic criteria derived from the analysis of the potential geological resources. The sampled deposits were analyzed petrographically and mineralogically, enabling direct and quantitative comparison with ceramic pastes through compositional ternary diagrams and point-counting methods (see SM 1.3 and SM 3 for a detailed explanation of the survey strategy and the totality of deposits surveyed and sampled).
- The *Ceramic Resource Threshold Model* proposed by Arnold (1981, 1985, 2006) was used to establish whether ceramic production could be defined as local or non-local. The model defines three procurement thresholds for clay and temper at distances of 1 km, 4 km, and 7 km. These thresholds encompass 85.5 % of the ethnographic cases studied for clay and 91.4 % for tempering agents, with exceptions typically involving modern transport methods or minority production sectors. This model, based on Browman's Territory Threshold Model (1976), is grounded in five core assumptions: that resource procurement distances follow patterned behaviors; that energy expenditure by potters is minimized; that transport is pedestrian, limiting load capacity to 25 kg per person; and that the model applies to sedentary or semi-sedentary societies. Unlike the often vague and inconsistently used notion of "local pottery" in archaeological literature—which frequently conflates cultural types with spatial origin—Arnold's model provides a replicable, spatially explicit framework that allows for empirical testing of local production hypotheses.
- Advanced GIS analysis (QGIS), such asisochrone maps and least-cost path models, were performed to refine the implementation of Arnold's model. We first delimited the catchment areas of the four archaeological sites using the *r.walk.points* plugin of GRASS GIS, based on a 5 m resolution DEM provided by the Spanish National Cartographic Institute. Isochrones were generated to represent a maximum walking time of 90 min (approximately 6.5–7.5 km), aligning with Arnold's third threshold. We then used least-cost path analysis (*cost distance analysis* plugin in QGIS) to determine the most efficient routes between sites and compatible clay deposits, as suggested by petrographic correlation (SM 1.5). Euclidean distances were also calculated to assess whether shorter, more direct routes may have been chosen, even if energetically more demanding.

3. Archaeological context and materials

The lower Guadalentín valley in southern Murcia (Figs. 1 and 4), together with the Vera basin in Almería, forms the core region of the El Argar archaeological entity, which expanded over the whole of southeast Iberia at the height of its development. These pre-litoral Tertiary basins not only count with some of the earliest and largest El Argar settlements, established around 2200 BCE, but also boasts one of the highest site densities within the El Argar domain. Settlements such as La Bastida and Lorca stand out as prominent political centers of El Argar, both maintaining uninterrupted occupations throughout the entirety of Argaric development, which ended ca 1550 BCE (Fontenla et al., 2004; Lull et al., 2011b, 2014, 2015).

Four settlements placed in the same region but in different geographical settings were chosen for the present study (SM 1.1). Tira del Lienzo is the only site to have been nearly fully excavated in recent years. This small settlement, spanning approximately 0.09 ha, was occupied between ~2000 and 1650 BCE in three successive phases. It appears to have functioned as an administrative node with important storage facilities and specializing in activities such as silver craftsmanship. This site is located roughly 7 km from La Bastida, in the Tertiary basin of the lower Guadalentín (Delgado-Raack and Risch, 2016; Lull et al., 2018; Ache, 2019).

The arc-shaped mountain chain formed by the sierras of Moreras and Almenara, separates the lower Guadalentín valley from a small geographical niche which opens towards the Mediterranean Sea (Fig. 1). This region is home to three prominent El Argar settlements. Cabezo Negro, covering ca. 2 Ha, a brief excavation in the 1970s revealed three Argaric phases (c. 1900–1550 cal BCE) and an earlier Chalcolithic

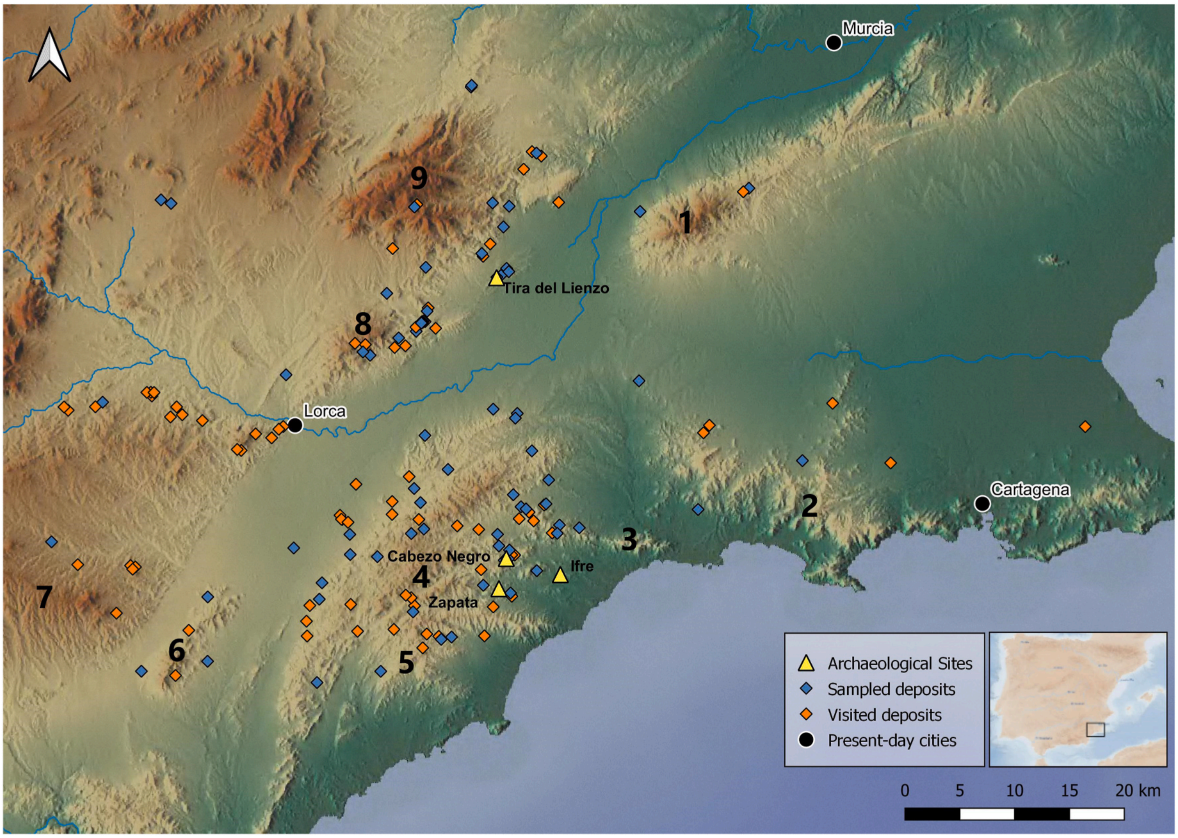

Fig. 1. Topographic location map of the southern part of the Murcia region showing the different parts of the Betic Cordillera: (1) Sierra de Carrascoy; (2) Sierra del Algarrobo; (3): Sierra de las Moreras; (4): Sierra de Almenara; (5): Loma de Bas; (6): Sierra de Enmedio; (7): Sierra de las Estancias; (8): Sierra de la Tercia; (9): Sierra Espuña.

occupation. Finds included grain storage, ceramics, and looted tombs (Aubet, 1979; Lull, 1983; Risch, 1995). Ifre (ca. 0,6 Ha) was excavated by the Siret brothers in the 19th century, who uncovered charred cereals, ceramics, and six graves in a complex architectonic structure. At least two phases of occupation are suggested (Siret and Siret, 1890; Lull, 1983). Finally, Zapata (ca. 1 Ha), also excavated by the Sirets yielded pottery, agricultural tools, and 38 graves, with evidence also pointing to two phases of occupation (Siret and Siret, 1890; Risch and Ruiz, 1994).

A total of 439 ceramic sherds from these four El Argar settlements were sampled and petrographically analyzed. During the initial phase of the research, 289 pottery sherds recovered from Tira del Lienzo (hereafter TL) were examined using a binocular loupe (10–60 ×) (Garrido-García, 2017). In addition, 50 representative pottery fragments collected from the surface of each of the sites Ifre (IF), Zapata (ZP), and Cabezo Negro (CN) were analyzed in the same way. Subsequently, 79 representative samples from the three occupational phases of TL (27.3 %) were selected for further examination using thin-section under a polarizing optical microscope. Given the apparent compositional homogeneity of all surface sherds, four individuals from each of the other sites (IF, ZP, and CN) were also selected for thin-section petrographic analysis. Once the petrofacies were identified and characterized, an XRD analysis was performed on each petrographic group (SM 4). Finally, all thin-section samples that were sufficiently large to allow the identification of at least 300 mineral or rock components were subjected to point counting: 63 from Tira del Lienzo (TL) and all 12 samples from the other three sites.

4. Geological setting

The study area is situated in the eastern part of the Betic range (Fig. 1), a mountain system formed during the Alpine orogeny. Geologically, the Betic system is composed of four major complexes: the External Betic Zones, the Internal Betic Zones, the Campo de Gibraltar Complex, and the post-orogenic Neogene Basins (Vera, 2004) (Fig. 1).

All four El Argar settlements investigated in this study are located within the Internal Betic Zone, which is characterized by sedimentary, igneous, and metamorphic rocks dating from the Precambrian, Palaeozoic, and Triassic periods. Within this zone, three geologically distinct units can be differentiated based on lithology and stratigraphic age: the Nevado-Filábride, Alpujárride, and Maláguide complexes (Vera, 2004) (Fig. 1).

The *Nevado-Filábride Complex*, situated south of Tira del Lienzo (TL), includes the sites of Ifre (IF), Zapata (ZP), and Cabezo Negro (CN). It comprises two main rock assemblages: (1) high-pressure, high-temperature metamorphic rocks of a pre-Mesozoic basement, and (2) Mesozoic metamorphic formations, including mica schists, quartzites, gneisses, metabasites, and marbles.

The *Alpujárride Complex* features Paleozoic rocks composed of mica schists, quartzites, gneisses, and metabasites affected by varying grades of metamorphism. These are overlain by Permo-Triassic sequences, beginning with a unit of phyllites and quartzites (Permian–Lower Triassic), followed by a thick sequence of Middle–Upper Triassic carbonate rocks (limestones and dolostones), which have undergone partial metamorphism to form marbles in some sectors.

The *Maláguide Complex*, located north of the Guadalentín Valley (Fig. 1), differs markedly from the previous two units. It is the only complex containing Jurassic, Cretaceous, and Paleogene sediments. Its Paleozoic succession includes a basal unit of phyllites and sandstones (Ordovician–Silurian), an intermediate unit of limestones and sandstones (Devonian), and an upper unit composed of sandstones, shales, and conglomerates (Carboniferous). These strata are overlain by Permian and Triassic red sandstones and mudstones.

The Internal Betic Zone is clearly demarcated from the surrounding *Neogene basins*, such as the Guadalentín Valley where TL is placed (Fig. 1). These basins formed during the Miocene and persisted into the Pleistocene. These post-orogenic basins are filled primarily with marine sediments (marls and limestones), along with significant accumulations of red mudstones, sandstones, and conglomerates indicative of terrestrial depositional environments.

5. Results

5.1. Petrographic characterisation of the ceramics

Mesoscopic petrographic analysis of the pottery of Tira del Lienzo identified two major petrographic groups distinguishable by their clay matrix composition, which are either phyllosilicate-rich (argillaceous) or carbonate-rich (Table 1). Subsequently, thin-section analysis under polarizing microscope revealed five petrofacies, two with carbonate matrix (MC-1 and MC-2) and three with argillaceous or phyllosilicate clay matrix (MA-1, MA-2, and MA-3). It is important to mention that most of the carbonated vessels or vessel fragments were subjected to microscopic analysis, given the difficulty to classify them into one of the three petrofacies. Proportionally, less phyllosilicate-rich pottery underwent thin-section analysis, given that it is easier to classify correctly even with a loupe.

5.1.1. Carbonate-rich matrix petrofacies

Petrofacies MC-1 includes a single vessel from Tira del Lienzo (TL). It is characterized by a marly matrix containing microforaminifera and silt-sized grains of quartz and calcite, which also form part of the antiplastic fraction (Fig. 2). Pseudomorphs of gypsum crystals are present, displaying brownish coloration that may result from thermal alteration during the firing process (Fig. 2D). MC-1 qualifies as both a petrofacies and a petrofabric, as it includes chamotte (grog temper) composed of an argillaceous (MA-type) matrix (Fig. 2A, B, and 2D). X-ray diffraction (XRD) analysis confirms the presence of quartz, clay minerals (illite–muscovite), and calcite, consistent with the carbonate-rich matrix observed under the polarizing microscope (SM 1.2).

Petrofacies MC-2 includes fifteen vessels from Tira del Lienzo (TL) and is characterized by a detrital marly matrix with well-rounded terrigenous antiplastic inclusions (Fig. 2). These inclusions are fragments of Paleozoic metamorphic rocks (quartz-feldspathic schists and slates), Permo-Triassic sedimentary rocks (limestones and sandstones), Mesozoic dolostones and limestones, Miocene limestones, as well as bioclasts reworked from Mesozoic and Tertiary strata. Among the monomineral grains, quartz is the most frequent, with some grains attributable to Triassic sources. Feldspar and biotite are also present. A distinct petrofabric was defined based on the presence of grog temper (Fig. 2E and F), whose composition corresponds to the MA-1 and MA-2 petrofacies. X-ray diffraction (XRD) analysis of MC-2 indicates quartz as the dominant mineral, along with clay minerals (illite–muscovite and chlorite) and calcite. Notably, garnet was identified in some samples, likely introduced through the addition of chamotte derived from MA-2 pottery (SM 4).

The presence of phyllosilicates such as illite and chlorite, as identified by XRD analysis, suggests that firing temperatures did not exceed 800–850 °C (Zussman, 1967; Linares et al., 1983). Moreover, the absence of thermal alteration in the calcite indicates that firing temperatures likely ranged between 600 and 700 °C (Risch and Gómez-Gras, 2003).

The two carbonate petrofacies and their associated petrofabrics were identified in a small number of vessels from Tira del Lienzo, most of which date to the early occupation phase (Table 1). These include simple bowls and a few medium-sized storage jars. No vessels from IF, ZP, or CN were assigned to either of the carbonate-rich petrofacies.

5.1.2. Phyllosilicate-rich, argillaceous matrix petrofacies

Petrofacies MA-1 is characterized by a fine-grained, phyllosilicate-rich clay matrix with a distinctive deep red-garnet coloration (Fig. 3). The antiplastic fraction consists of poorly sorted, very angular fragments of low-to medium-grade Paleozoic metamorphic rocks, primarily schists and phyllites. The most abundant monomineralic components, in decreasing order, are quartz, muscovite, biotite, feldspar, tourmaline, pyroxenes, and a range of opaque minerals, predominantly iron oxides (hematite). Fragments of limestone and dolostone—likely of Triassic origin—are also present. Occasional carbonate grains, identified as soil nodules, are interpreted as originating from the erosion of calcrete-type soils (Fig. 3). MA-1 is by far the most common petrofacies at Tira del Lienzo and is the only petrofacies identified in the other three settlements (IF, ZP, CN).

Petrofacies MA-2 is represented by seven vessels, all of them coming from TL. It is characterized by a phyllosilicate-clay matrix of fine to medium grained, with frequent muscovite and quartz grains. The coarse fraction is dominated by mica schists (5 %), and single minerals as quartz, muscovite, garnet, kyanite, and chloritoid, which are indicative of medium to high grade metamorphic rocks. Rock fragments of quartzite and schists are also frequent (Fig. 3). Garnets or garnet bearing schist are the most distinctive components of this petrofacies under mesoscopic observation.

Petrofacies MA-3 is characterized by an abundant clay matrix in which very fine grain quartz and feldspars grains appear and rock fragments like meta-sedimentary and sedimentary rocks, and minor proportions of low-grade metamorphic fragments (slates and phyllites) as antiplastics. This petrofacies also contains carbonate grains such as soil nodules, like the ones identified in MA-1. Only six vessels from TL belong to this compositional group (Fig. 3).

XRD (SM 1.2 & 4 3) showed that the main phases identified in all the clay-rich petrofacies (MA-1, MA-2, MA-3) correspond to clay-group minerals such as illite-muscovite and chlorite, with paragonite also identified in petrofacies MA-2. These clay-group minerals are mainly components of the matrix, which is consistent with the thin-section petrographic observations. In addition, minerals such as quartz, feldspars as well as hematite and calcite are frequent and again can be easily linked with the coarser fraction of these petrofacies. It is worth mentioning the presence of gypsum in one sample of the MA-1

Table 1
Number of ceramic samples and their representativity, grouped by chronological phase and matrix composition (clay or carbonate rich) determined by meso- and microscopic analysis for TL, IF, CN, and ZP.

Settlement	Chronology	Binocular loupe			Microscopic petrography		
		Nr.	Argillaceous-clay matrix	Carbonate clay matrix	Nr.	Argillaceous-clay matrix	Carbonate clay matrix
Tira del Lienzo	Phase I (∼2000–1900 BC)	58	84.5 %	15.5 %	30	66.7 %	33.3 %
	Phase II (∼1900-1775 BC)	141	93.6 %	6.4 %	35	88,6 %	11,4 %
	Phase III (∼1775-1650 BC)	90	97.8 %	2.2 %	14	85,7 %	14,3 %
Ifre	∼1900-1550 BCE	50	100 %	0 %	4	100 %	0 %
Cabezo Negro	∼1900-1550 BCE	50	100 %	0 %	4	100 %	0 %
Zapata	∼1900-1550 BCE	50	100 %	0 %	4	100 %	0 %
TOTAL		439	95,4 %	4,6 %	91	82,4 %	17,6 %

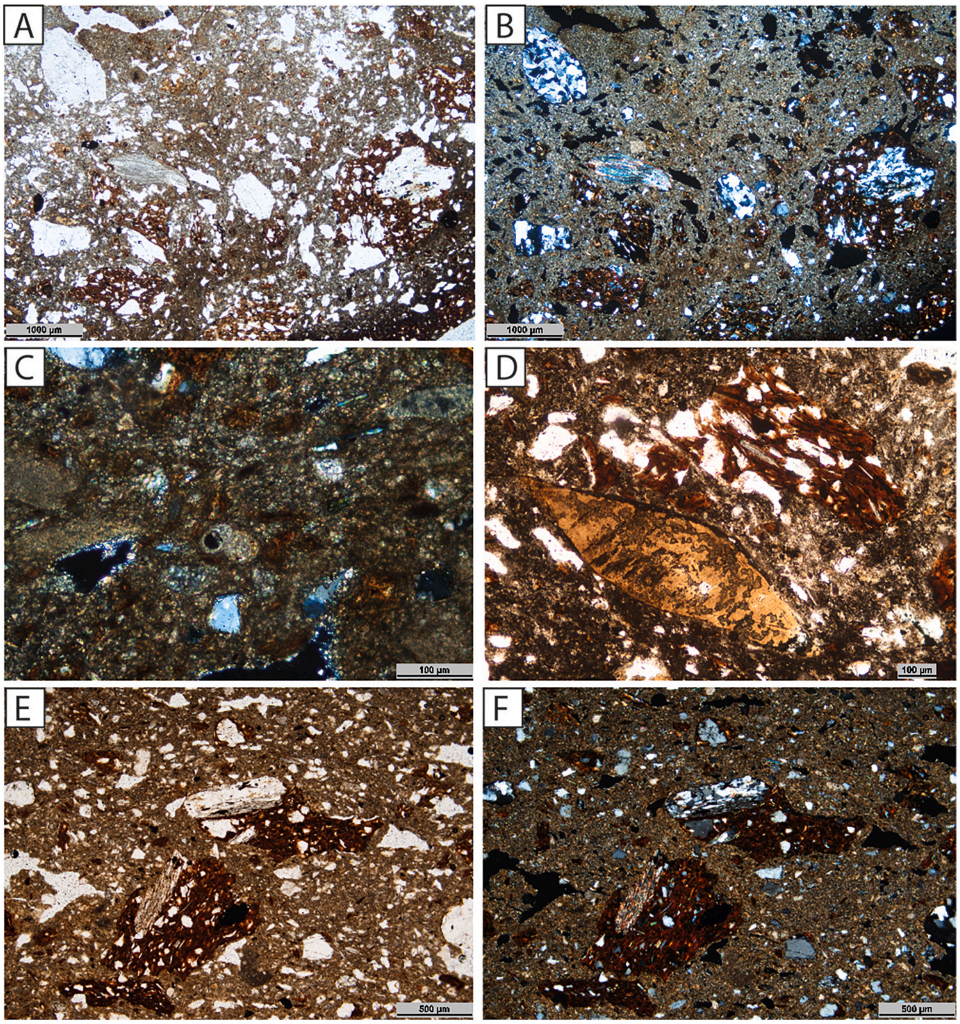

Fig. 2. (A–D) Petrofacies MC-1 under microscope (sample TL-005). (A) view obtained using one polarizer (PPL) and (B) the same image obtained with two polarizers (XPL) where the chamotte fragments and the quartz grains with gray tones stand out. (C) Detail of the marly carbonate matrix, where a bioclast of foraminiferal type can be observed (XPL). (D) Pseudomorph of a gypsum crystal (thermally altered) next to a reddish fragment of chamotte. (E) and (F) Microscopic view of petrofacies MC-2 (XPL) showing a higher content of detrital grains, frequently gray-colored quartz and feldspar, and the chamotte fragments (red arrows) immersed in the marly matrix (sample TL-003).

petrofacies, already identified in thin-section, which can be interpreted as a post-depositional cement filling the porosity (Fig. 2B).

The presence of phyllosilicates indicates firing temperatures below 800–850 °C (Zussman, 1967; Linares et al., 1983), while the presence of paragonite is indicative of temperatures below 700° (Comodi and Zanazzi, 2000).

5.2. *Geoarchaeological prospections and clay characterisation*

The five petrofacies identified among 439 samples of ceramic vessels from four El Argar settlements provided crucial information on the formation and the origin of the raw materials used to manufacture ceramics. Following the above described criteria, prospections of sedimentary and geological deposits were carried out in different locations (Fig. 4).

5.2.1. *Prospection of carbonate-rich matrix deposits*

Based on its petrological composition, the raw material used for MC-1 must have been sourced from a geological formation deposited in a marine environment. The late Miocene sandy marls containing marine bioclasts –on which the Tira del Lienzo site is situated– exhibit a very similar petrographic composition (SM 1.3), making them the most probable source of raw material for this ceramic petrofacies (Fig. 5).

In contrast, the presence of sub-rounded antiplastic inclusions and the high compositional variability observed in the MC-2 petrofacies suggest the use of raw materials derived from a terrestrial sedimentary formation with significant terrigenous input. In the vicinity of the Tira del Lienzo site, an extensive late Miocene terrestrial deposit composed of sandy marls, sandstones, and conglomerates is present. The sandstone and conglomerate layers include rock fragments originating from Paleozoic, Mesozoic, and Tertiary formations that outcrop in the Sierra Espuña (Fig. 4). Thin-section analysis of these geological deposits (Fig. 5) revealed components that are both texturally and compositionally comparable to those identified in MC-2, strongly indicating their use as a raw material source (SM 2). This interpretation is further supported by XRD results from the late Miocene deposits surrounding Tira del Lienzo (SM 4).

5.2.2. *Prospection of argillaceous matrix deposits*

The three phyllosilicate-rich, or argillaceous matrix petrofacies (MA-1, MA-2, and MA-3) exhibit similar petrological characteristics, suggesting that the raw materials used were derived from comparable geological formations, likely formed under specific paleo-climatic conditions. This led the prospection efforts to focus on red clay terrestrial

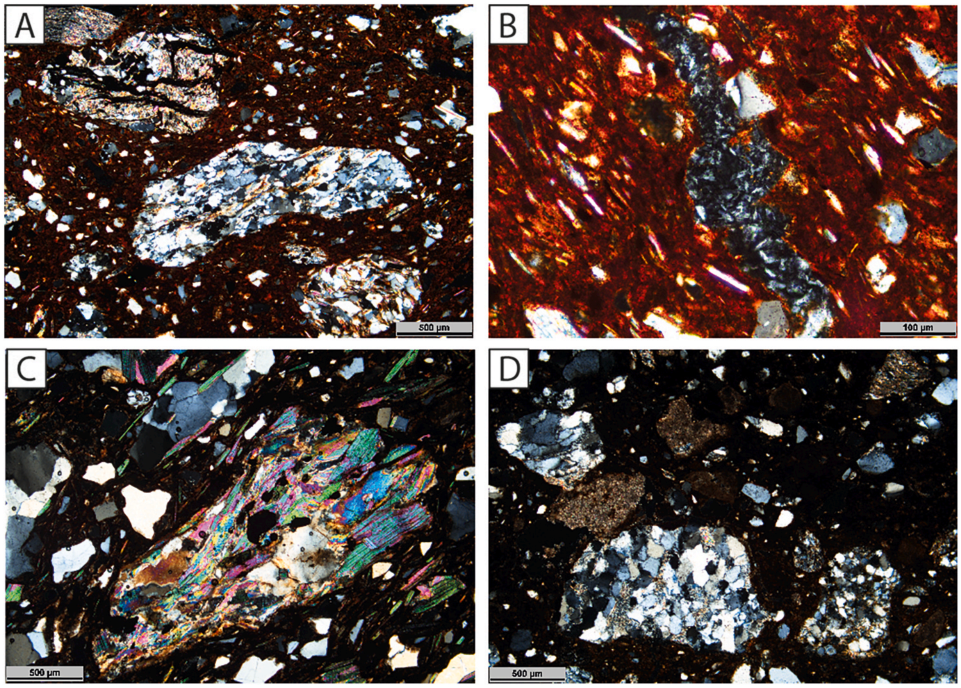

Fig. 3. Thin-section micrographs under XPL. A) MA-1 petrofacies (sample TL-001): fragments of quartz schist-type metamorphic rock embedded in a red phyllosilicate-rich clay matrix with dispersed silt-sized quartz grains; B) MA-1 petrofacies (sample TL-001): close-up of the red phyllosilicate matrix showing elongated pores filled with small gypsum crystals (gray), interpreted as post-depositional cement; C) MA-2 petrofacies (sample TL-002): large fragments of mica schist containing diagnostic high-grade metamorphic minerals, including garnet; D) MA-3 petrofacies (sample TL-081): sandstone-type sedimentary fragments (gray), a limestone fragment, and caliche (calcrete) nodules set within a dark red clayey matrix.

deposits associated with alluvial fans, colluvial settings, and even soil formations. Suitable candidates include Permo-Triassic units, terrestrial Miocene formations, and Plio-Pleistocene red deposits, all of which were systematically examined. Field surveys were conducted in the Espuña, Tercia, and Carrascoy mountain ranges, as well as in more distant ranges such as the Sierras de las Estancias and Enmedio near Lorca, and the Sierra de Almenara, Moreras, and Algarrobo, which form the geological backdrop of IF, ZP, and CN (Fig. 4).

The Permo-Triassic red deposits were discarded after thin-section petrographic analysis revealed a very low content of quartz grains and metamorphic rock fragments compared to the MA petrofacies. Similarly, the Miocene alluvial fan deposits (Burdigalian to Lower Tortonian) were excluded due to their high abundance of sedimentary rock fragments (limestones, dolomites, and sandstones) and a notably low proportion of quartz, making them incompatible with the composition observed in the ceramic samples.

Finally, the Plio-Pleistocene red deposits were found to closely match the characteristics of the argillaceous matrix petrofacies (MA), displaying poor sorting and abundant angular grains embedded within a red phyllosilicate-rich matrix. These deposits correspond to the Sucina Formation (Montenat and Martínez, 1970). The lower part of this formation (Pliocene) consists of red clay deposits interstratified with sands and breccias (SM 1), attributed to fluvio-alluvial environments formed under tropical climatic conditions. Silva et al. (2017) associate these deposits with the Villafranchian warm period. Red alluvial horizons within the formation, also classified as Rhodoxeralfs, have been specifically dated to the Early Pleistocene (Schulte and Julià, 2001).

Conversely the upper part of Sucina Formation (Pleistocene) also presents a succession of red clays beds but interstratified with carbonate soil levels which evidence the evolution towards arid climate conditions. The widespread development of calcrete soils (aridisols) towards the top of the Sucina formation would coincide with the onset of the Mediterranean climatic seasonality which took place at the end of the Villafranchian period (Hernández Fernández et al., 2007). The absence or rareness of carbonats in the MA pottery petrofacies allows to exclude this formation as a source of raw materials.

More than 110 Plio-Pleistocene deposits were identified due to their characteristic red-colored clays through the visual inspection of satellite images of the region comprised between Sierra de los Filabres (Almeria) to Sierra de Callosa (Alicante). All of them were described on the field (see SM3) and 50 samples were collected from various locations based on their macroscopic similarity to the ceramic petrofacies (Fig. 4). Among these, eleven samples exhibited compositional and textural features closely matching those of the clay matrix petrofacies (MA), allowing them to be identified as the most likely sources of exploited raw materials. A detailed petrographic analysis using point counting was conducted on these selected samples to enable direct comparison with the ceramic assemblage (Figs. 5 and 6). The textural and compositional characteristics of these red clay deposits are so closely aligned with those of the MA petrofacies that, under microscopic observation, it was at times difficult to distinguish between the raw deposit and the ceramic paste (Fig. 6). The petrological variation among the Plio-Pleistocene outcrops is primarily compositional and relates to the relative abundance of low-to high-grade metamorphic and sedimentary rock fragments. These same variations form the basis for distinguishing between petrofacies MA-1, MA-2, and MA-3, thereby establishing a clear correspondence between the compositional variability of the Plio-Pleistocene deposits and the different ceramic petrofacies.

Consequently, petrofacies MA-1, which is rich in low-to medium-grade metamorphic rock fragments, needs to be related with Plio-Pleistocene deposits that incorporate these lithologies. Such rock types are widely present in the Alpujárride Complex, particularly in the Almenara and Estancias ranges, as well as in their genetically related Plio-Pleistocene alluvial and colluvial deposits. A similar logic applies to MA-2, which contains abundant medium-to high-grade metamorphic rock fragments, characteristic of both the Nevado-Filábride and Alpujárride complexes exposed in the Sierra de Almenara. Finally, MA-3 is dominated by metasedimentary and sedimentary rock fragments,

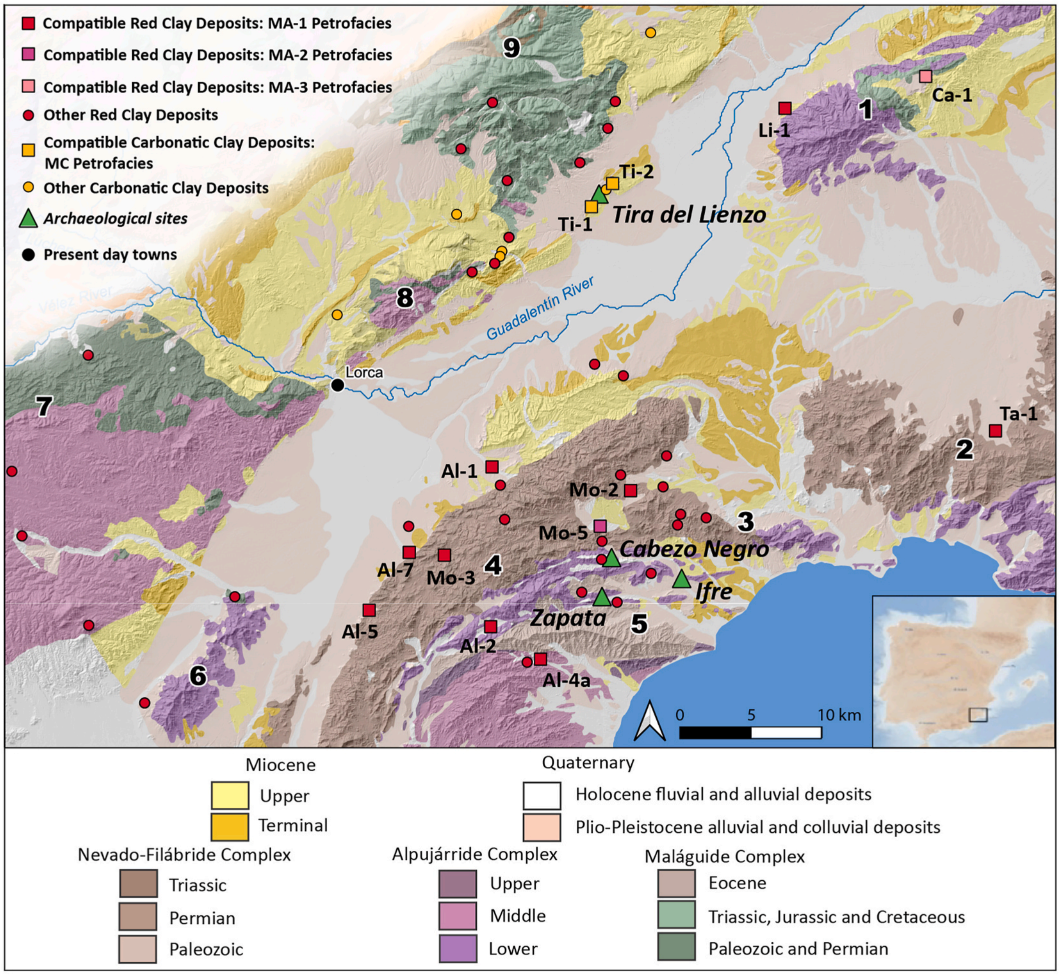

Fig. 4. Location map of the study area showing the distribution of geological deposits surveyed based on their similarity to the main petrofacies identified in the ceramic samples. Circles indicate carbonate-rich and red clay deposits that were prospected in the field due to their macroscopic resemblance to the ceramic petrofacies (MC and MA). Squares mark the deposits that exhibited both macroscopic and microscopic petrographic characteristics consistent with the ceramic materials, allowing their identification as the most likely sources of exploited raw materials. The mountain ranges are: (1). Sierra de Carrascoy; (2) Sierra del Algarrobo; (3) Sierra de las Moreras; (4) Sierra de Almenara; (5) Loma de Bas; (6) Sierra de Enmedio; (7) Sierra de las Estancias′; (8) Sierra de la Tercia, (9). Sierra Espuña. Sample abbreviations are: Al- for Almenara; Mo- for Morata; Ta- for Tallante, Ti- for Tira del Lienzo, Li- for Librilla and Ca-for Carrascoy.

along with very low-grade metamorphic components, which are consistent with lithologies found in the Maláguide Complex, particularly in the Sierras de Enmedio and Carrascoy (Fig. 4).

The compositional differences among the three phyllosilicate-rich petrofacies were quantified through point-count analysis of both the ceramic samples and the corresponding Plio-Pleistocene clayey deposits. A compositional ternary diagram (Fig. 7) illustrates the relative proportions of 1) low-to medium-grade metamorphic rock fragments, 2) medium-to high-grade metamorphic fragments, and 3) sedimentary/metasedimentary rock fragments, effectively visualizing the textural and compositional variability among the petrofacies and their raw material sources (see SM 5 & 6 for petrographic data and criteria).

Among all the surveyed Plio-Pleistocene alluvial and colluvial deposits, those outcroping in the Sierra de Almenara are most closely linked to the clay matrix petrofacies MA-1 and MA-2 (Figs. 4, 6 and 7). Specifically, the samples Almenara (Al-) 1, 2, 4a, 5, and 7, Morata-2 (Mo-2), Tallante- 1 (Ta-1) and Librilla-1 (Li-1) are very similar to petrofacies MA-1 (Fig. 4), as stated by the abundant low-grade rock fragments. By contrast, medium to high grade metamorphic rock fragments contained in the sample Morata-5 can be linked to petrofacies MA-2. For the MA-3 petrofacies the most suitable sample is Carrascoy 1 (Ca-1), where metasedimentary and sedimentary rocks predominate together with some very low-grade metamorphic rocks (see SM 3 for location of all deposits).

XRD analyses of the Plio-Pleistocene deposits revealed matrix components such as illite–muscovite, chlorite, and paragonite, along with antiplastic minerals including quartz, feldspars, hematite, and calcite. Notably, garnet was also identified in sample Almenara-7. The combined results of thin-section petrography and XRD analysis confirm that these red clay deposits closely resemble the clay matrix found in ceramics from all five settlements. Based on this strong compositional and mineralogical similarity, we propose that the Plio-Pleistocene deposits served as the primary sources of raw material for the El Argar ceramic pastes (SM 4 and 5).

6. Discussion: pottery production and circulation in a core region of El Argar

The petrographic analysis revealed two distinct petrofacies groups within El Argar ceramics: carbonate-rich matrix (MC) and phyllosilicate-rich, argillaceous matrix (MA). The two carbonated petrofacies (MC-1 and MC-2) are only present in small numbers in the first settlement phase of TL (Table 1). Their occasional presence in the later layers is most likely due to the redeposition of older materials during the intense construction activities at the start of each settlement phase (see SM 1.6 for a full discussion). The complete absence of these petrofacies from the

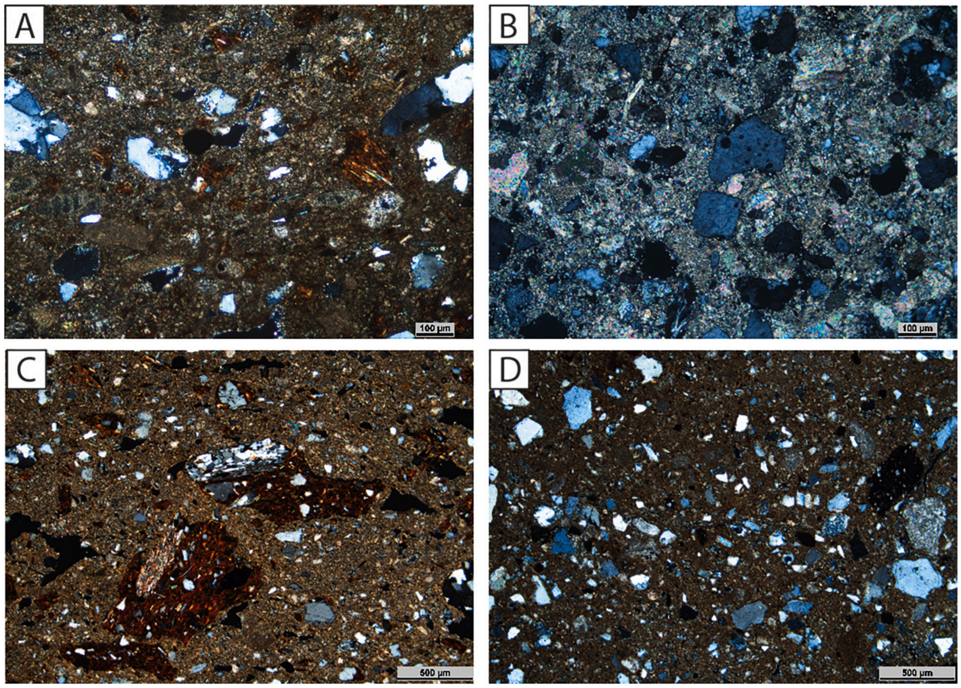

Fig. 5. Thin-section micrographs of the carbonate matrix ceramics corresponding to (A) MC-1 petrofacies (sample TL-005) and (B) MC-2 petrofacies (sample TL-003), and their compatible-surveyed clayey deposits (B) Tira-1A sample and (D) Tira-3 sample, under the polarizing microscope (XPL).

other three studied middle and late El Argar settlements support their absence by ~1900 BCE, contemporaneous with the second and third occupation phases at TL (Table 1). Among the identified ceramic groups, only the MC clay type exhibits a defined petrofabric, which occasionally includes grog temper derived from MA pottery. This confirms that both MA and MC productions were contemporaneous in the Early El Argar phase, albeit with markedly different intensities. It also indicates that potters working with MC clays were handling (and likely breaking) vessels made from MA fabrics.

The presence of argillaceous petrofacies (MA-1, MA-2, MA-3) has been documented in all the occupation phases of TL, as well as in IF, ZP, and CN. The archaeological survey carried out in the Guadalentin valley, as well as in other areas of the province of Murcia has allowed us to confirm that MA pastes dominate in all settlements (>70) with El Argar pottery (Garrido-García et al., 2023; Moreno Gil et al., 2025). The same petrofacies has also been documented in several El Argar settlements located in the province of Alicante (Seva Román, 2002). MA-1 was already dominant in the foundational phase of Tira del Lienzo, gaining in importance over time. The likely disappearance of the carbonated petrofacies in phases 2 and 3, and of the MA-2 and MA-3 clays in the final phase of TL (~1770–1650/1550 cal BCE), strongly suggests that pottery production was becoming increasingly standardized in terms of raw material selection and clay deposit exploitation. (Fig. 8).

As confirmed by experimental analysis (see SM 1.7), argillaceous petrofacies offer several technological advantages over carbonate-matrix pastes. The predominant metamorphic lithologies used as anti-plastics, their high proportion relative to the clay matrix, and their poor sorting combined with a planar morphology, promote the parallel alignment of fragments within the pottery walls. This structural orientation enhances surface resistance to fractures by reducing crack propagation and minimizing shrinkage during the drying and firing processes—more effectively than matrices with spherical-shaped anti-plastics. A notable observation of the experimental modelling was the clay's excellent workability combined with a pronounced stiffness. Due to this stiffness and independently of the amount of water added, once the pot's body was shaped, modifications such as enlarging, bending, or compressing were nearly impossible without causing cracks. Once fired, the pottery demonstrated exceptional impermeability to liquids.

This group of argillaceous petrofacies is geologically associated with alluvial/colluvial deposits of Plio-Pleistocene phyllosilicate-rich red clays, composed almost exclusively of metamorphic rock fragments and their derived minerals, such as quartz, feldspars, micas, tourmaline, and garnet. These clay deposits outcrop across the various mountain ranges of Murcia and are genetically related, having formed through a weathering process associated with the tropical climatic conditions of the Villafranchian period (Montenat and Martínez, 1970; Haug et al., 2001; Schulte and Julià, 2001; Hernández-Fernández et al., 2007; Domingo et al., 2013; Silva et al., 2017). All outcrops identified in the provinces of Murcia and Alicante were systematically explored (see SM 3), and minor compositional differences, stemming from the lithological substrate on which they developed, enabled the identification of the most suitable clay sources and soils exploited for El Argar pottery production.

Once the raw material sources had been accurately identified, we were able to examine the distribution and circulation patterns of El Argar pottery across the Guadalentín Basin. Following Arnold's Ceramic Resource Threshold Model (CRTM) (Arnold, 1981, 1985, 2006), a 7 km distance between production sites and raw material sources was adopted as the threshold for domestic-scale production. This threshold was visualized through 90-min isochrones drawn around each of the studied settlements. Subsequently, Least Cost Paths (LCPs) were calculated from each archaeological site to the identified clay deposits (Fig. 9; SM 1.21).

According to this spatial modelling, two of the thirteen identified carbonate-rich raw material sources (15 %) fall within the 7 km radius around Tira del Lienzo (TL). This supports the interpretation that carbonate-rich petrofacies were locally produced at TL, whereas the phyllosilicate-rich (clayey) petrofacies likely circulated over greater distances. We extended the spatial analysis by generating 90-min isochrones and calculating Least Cost Paths (LCPs) from each optimal MA deposit to the settlements (Fig. 9).

Our analysis revealed that up to 35 of the 122 El Argar settlements identified in southern Murcia appear within one or several the 90-min thresholds and could be locally supplied with compatible clays (Fig. 10). LCP analysis reduces this number to 24 settlements. Although only two of the 35 sites (La Roca and La Alcanara) have been excavated

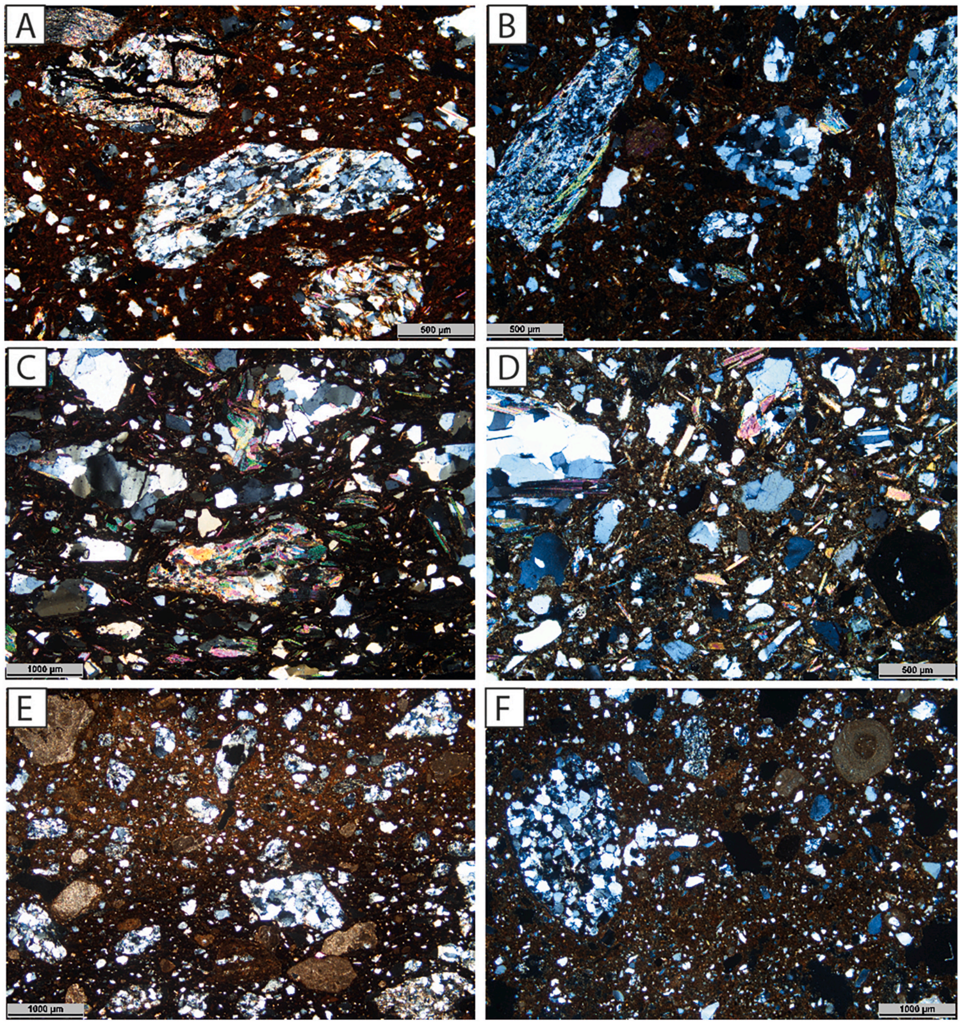

Fig. 6. Microscopic views of El Argar pottery petrofacies MA-1 sample Tl-001 (A), MA-2 sample Tl-002 (C), and MA-3 sample Tl-081 (E), alongside their corresponding best-matching clayey deposits: Almenara-1 sample (B), Morata-5 sample (D), and Carrascoy-1 sample (F), observed under crossed polarized light (XPL). (A) and (B): Fragments of quartz schist-type metamorphic rocks embedded in a red clayey matrix with silt-sized quartz grains. (C) and (D): Mica schist fragments containing diagnostic high-grade metamorphic minerals, such as garnet. (E) and (F): Sandstone and limestone sedimentary rock fragments (gray) and caliche nodules within a red clayey matrix containing dispersed silt-sized quartz grains.

(Ayala, 1978), surface materials indicate that all were small-size settlements, below 0,3 ha. Most of these archaeological sites, ranging from 28 to 20 depending if isochrones or LCP are considered, are located in the Sierra de Almenara (Fig. 9). The number of settlements within the 7 km range of compatible clay sources decreases significantly in Sierra de Carrascoy mountain and drops to one site in the case of the Algarrobo range, probably reflecting the varying economic importance of the clay resources. While Carrascoy was likely the primary source of petrofacies MA-3, identified in a small number of vessels from TL, and Algarrobo may have supplied a limited amount of MA-1 clays, the largest deposits of MA-1 and MA-2 are located in the northwestern part of the Almenara mountain chain, where numerous small settlements have been identified.

Consequently, our geoarchaeological survey and territorial analysis strongly suggest that MC petrofacies were a local, minor production of communities living in or around TL, while MA petrofacies ceramics were mostly produced in small settlements within the optimal resource threshold around the Sierra de Almenara. Given the absence of other suitable MA clay sources to the north and northeast of the lower Guadalentín Valley –despite our intensive surveys– it is likely that the productive hubs of the Almenara (MA-1 and MA-2) and Carrascoy (MA-3) mountain ranges supplied most settlements in the region, either directly or through exchange networks (Moreno Gil et al., 2025).

7. Conclusions

Our socio-economically oriented geoarchaeological survey and pottery analysis in a core region of El Argar territory, in present-day Murcia, have, for the first time, identified the most probable locations of the exploited clay deposits. El Argar potters intentionally sought Plio-Pleistocene red phyllosilicate clays, preserved in limited areas of the Nevado-Filabride and, to a lesser extent, the Alpujarride complexes of the Internal Betic mountain range. These clays offered technical advantages, as they could be fired at temperatures below 750 °C, exhibited lower shrinkage rate during drying and firing processes, and were more resistant to chemical weathering, mechanical wear, and breakage. While more widely available clay resources, such as carbonate-matrix petrofacies, were exploited at a small scale in the initial phase of El Argar by some communities, such as TL, after ~1900 BCE, pottery manufacture increasingly specialized in working of red phyllosilicate clays. In the four studied settlements of the Guadalentín and adjacent coastal valleys, the petrofacies defined as MA-1 became the exclusive raw material of potters in the last phase of El Argar (~1750-1550 BCE).

The largest deposits of the dominant petrofacies MA-1, as well as of

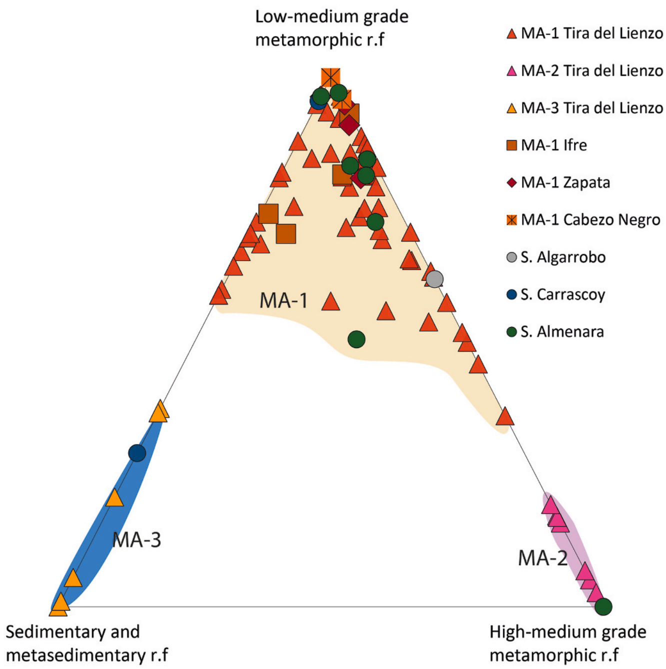

Fig. 7. Ternary compositional diagrams showing the relative proportions of rock fragment types in the clay matrix petrofacies (MA; triangle symbols) and in the Plio-Pleistocene red clay deposits (circle symbols), grouped according to the mountain ranges (S.) where the deposits were sampled (see SM 4 & 5 for petrographic data and criteria). The diagram differentiates the three main clay petrofacies: the yellow field encloses MA-1 samples, the pink field corresponds to MA-2, and the blue field represents MA-3. The overlap between ceramic and raw clay samples highlights the compositional correspondence between the petrofacies and their potential geological sources.

the less commonly used MA-2, were located in the northwestern part of the Almenara mountain range. In contrast to the situation observed at two other potential phyllosilicate clay sources, located in the Algarrobo and Carrascoy ranges –where our survey identified few El Argar sites– at least 24 settlements were confirmed within a 7 km linear distance (approximately a 90-min walking distance) from the Almenara sources (Figs. 4 and 9). Despite intensive surveying of all Plio-Pleistocene red clay deposits of Murcia and Alicante, supported by satellite image analysis, no other clay deposits of similar quality and size have been identified in the eastern part of the El Argar territory. The nearest alternative deposits we identified were associated with the metamorphic formations of the Nevado-Filábride and Alpujarride complex extending towards the southeast, into the Vera Basin of Almeria, which was another core region of El Argar. A supply from this area would have implied even higher transport distances.

The small size, density, and placement of many settlements located on lowlands or gentle slopes near the high-quality Almenara clay deposits stand out as unusual when compared to the dominant El Argar settlement pattern, which was structured around a network of large, regularly spaced hilltop sites. Although pottery production has not yet been confirmed at these mostly unexcavated locations, such a settlement pattern would be consistent with a large number of dispersed communities situated on or near the clay deposits. The existence of specialized production areas would also account for the morphometric standardization observed in El Argar pottery (Lull, 1983; Risch and Ruiz, 1994; Aranda, 2004; Velasco, 2021) and for the fact that all eight characteristic El Argar vessel shapes and all sizes (Siret and Siret, 1890) were produced using the same type of clay. The availability of fuel in the Almenara mountains, combined with a dispersed settlement pattern surrounding the firing sites large enough to produce the typical Argaric *pithoi*, aligns with expected conditions for such production centers, as documented ethnographically (R. Risch, personal observation in the region of the middle Black Volta; Ghana).

However, the question must be raised as to whether these geographically highly restricted, phyllosilicate-rich red clays were circulated among El Argar communities, or whether it was the finished vessels that were exchanged. Ethnographic and archaeometric studies consistently show that potters in non-industrial societies rarely obtain clay from beyond a short distance –typically no more than 7–10 km from their communities (e.g., Arnold, 1985; Gosselain, 2000; Stahl et al., 2008; Vidal and Molina, 2016). Consequently, the occurrence of ceramic vessels with petrographic signatures matching distant sources is more plausibly explained by the movement of finished products rather than of raw materials. The existence of itinerant potters offers another possible

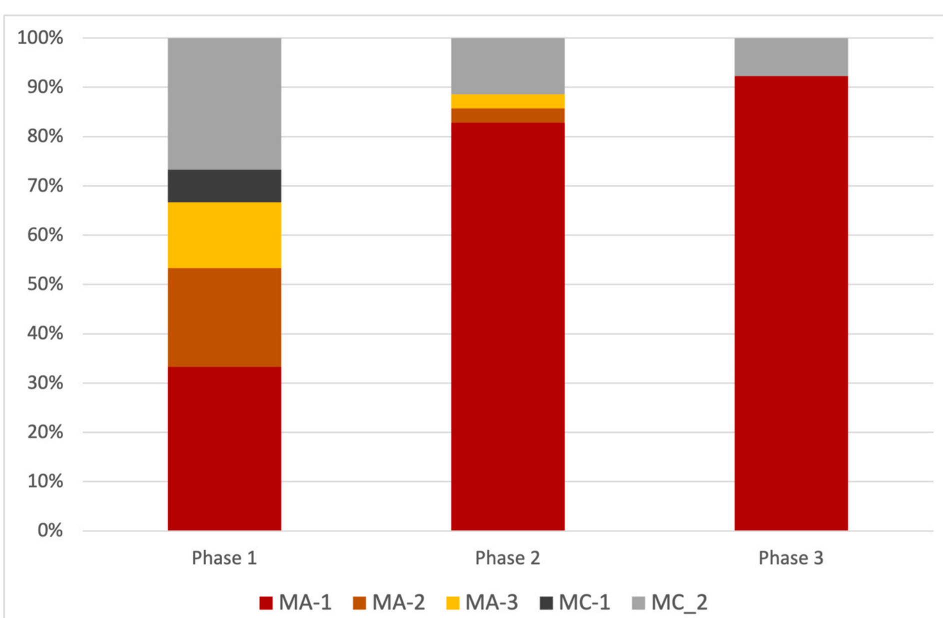

Fig. 8. Changing importance of the five petrofacies across the three El Argar phases. Only the results from 91 thin sections are considered, which slightly over-represent the MC petrofacies due to the applied sampling strategy (see above and Table 1).

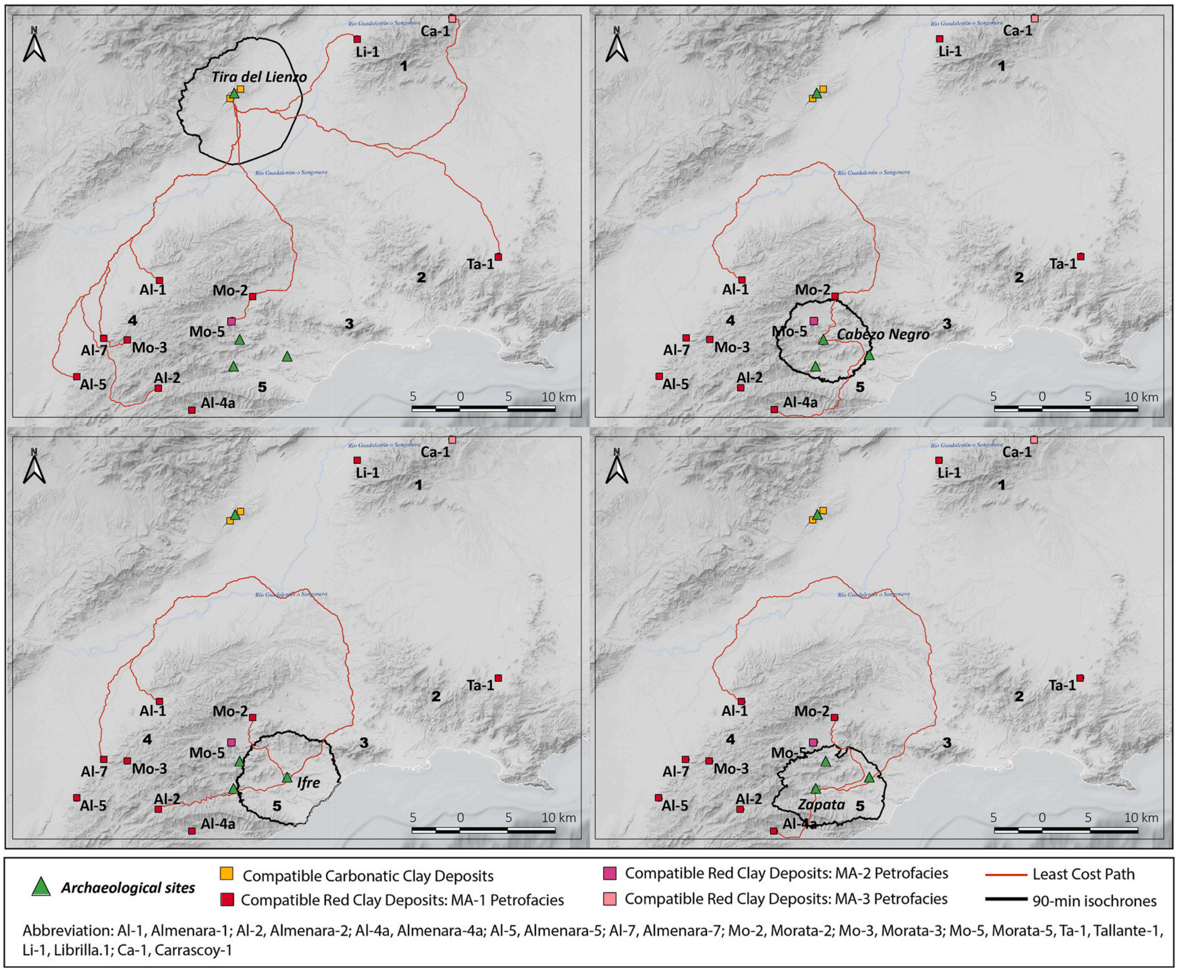

Fig. 9. Ninety-minute isochrones and Least Cost Paths (LCPs) calculated from each of the studied sites to the argillaceous clay deposits identified through petrographic correspondence. The spatial analysis illustrates potential access routes and catchment areas for raw material procurement. The mountain ranges are: (1) Sierra de Carrascoy, (2) Sierra del Algarrobo, (3) Sierra de las Moreras, (4) Sierra de Almenara, and (5) Loma de Bas.

explanation for the observed uniformity in raw materials and pottery shapes (Garrido-García et al., 2021), although such practices are rarely documented in the ethnographic record. A combination of strategies –such as the circulation of raw materials by itinerant potters alongside the distribution of finished vessels– depending on climatic and geographical factors, has been documented in the contemporary Andes (Ramón Joffré, 2020).

The level of specialization in a manufacturing process is often defined by its degree of *technical standardization* and *spatial concentration or exclusivity* (Costin, 1991; Blackman et al., 1993; Costin and Hagstrum, 1995; Risch, 2008). The high uniformity in vessel topology (van der Leeuw, 1993) and raw material composition in El Argar pottery, along with its geographically confined clay sources, strongly reflects both of these economic dimensions. A third parameter that needs to be equally assessed is the *intensity of production*. Based on the present results and the previous petrographic analyses of El Argar pottery the volume of production achieved by a limited number of production centers must have been substantial, considering the following.

- MA petrofacies have been confirmed through petrographic analyses in settlements in northern Murcia and Alicante, located over 50 km and up to 90 km, respectively, from the sources (Garrido-García et al., 2023; Moreno Gil et al., 2025; Seva Román, 2002).
- The Almenara deposits, along with the more limited Algarrobo and Carrascoy deposits, likely supplied hundreds of settlements known in the eastern El Argar territory, whose cultural attribution and dating are largely based on this characteristic pottery. Our extensive and intensive surveying of the region of Murcia, Alicante, and parts of Albacete has identified no other clay deposit compatible with the local El Argar pottery (Seva Román, 2002; Garrido-García et al., 2023; Moreno Gil et al., 2025).
- El Argar settlements typically contain large quantities of pottery, specially storage vessels, reflecting the scale of production and the relatively short lifespan of pots used in everyday tasks (Castro et al., 1998; Aranda, 2001; Schuhmacher and Schubart, 2003; Velasco, 2021).
- The most prominent El Argar settlements, such as Lorca or La Bastida, lacked equivalent clay sources in their surroundings. This suggests that they were supplied by non-local potters operating on a significant scale, likely based near the high-quality phyllosilicate clay deposits.

While a comprehensive petrographic analysis of all known Argaric sites has not yet been conducted, these findings support the hypothesis that supra-local supply systems operated in large parts of the El Argar territory. The available data point to an organisation involving independent specialists –not attached to elite institutions– operating within broader regional socio-political frameworks.

Taken together, the present results call into question the notion of a domestic mode of production for most of the ceramics examined. Distinct pottery production areas, pronounced material and stylistic uniformity, and over-regional exchange networks appear to align closely

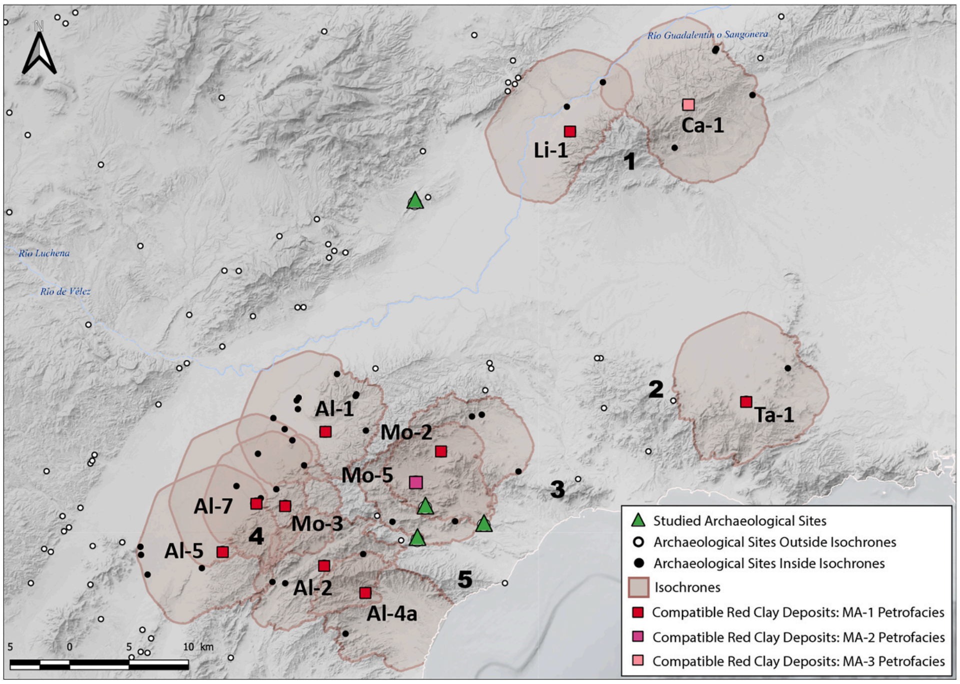

Fig. 10. Ninety-minute isochrone analysis around the optimum argillaceous clay deposits identified in the various mountain ranges. These areas represent the expected catchment zones for raw materials under a scenario of domestic pottery production. The mountain ranges are: (1) Sierra de Carrascoy, (2) Sierra del Algarrobo, (3) Sierra de las Moreras, (4) Sierra de Almenara, and (5) Loma de Bas. Sample abbreviations are: Al- for Almenara; Mo- for Morata; Ta- for Tallante, Ti- for Tira del Lienzo, Li- for Librilla and Ca-for Carrascoy.

with specialized productions in early state societies (Blackman et al., 1993; Costin and Hagstrum, 1995; Fragnoli, 2021). Unlike domestic modes, it entails centralised control of labour and resource allocation, the participation of non-consumer producers, and often standardisation in typology and paste composition. It is typically associated with supra-domestic planning and the existence of administrative structures. Ethnographic studies show that standardized ceramic forms can, in some contexts, also emerge from household-level production intended for exchange (Köhler, 2017). However, such practices typically lack the intensity and the geographically restricted raw material procurement observed in El Argar. Our findings align with previous research on El Argar lithic (Risch, 2002; Delgado-Raack, 2008; Delgado-Raack and Risch, 2016), metallurgical (Lull et al., 2010; Murillo Barroso et al., 2024; Escanilla et al., 2024), and possibly textile production (Basso Rial et al., 2023), demonstrating that ceramic production also reached a scale and level of specialization beyond domestic and local needs. Although further studies of additional archaeological sites are necessary, our results reveal production and distribution patterns characteristic of regional or supra-regional political systems, consistent with the proposed concept of an Argaric state (Lull and Risch, 1995; Risch, 1995, 2002; Lull et al., 2011b).

This study highlights the importance of establishing a consistent and well-founded methodological framework for rigorously determining the local or non-local origin of ceramics documented at archaeological sites. While petrographic analysis of ceramic paste components does not provide definitive information on production origins or organisational patterns, the proposed methodology overcomes this limitation by integrating detailed geoarchaeological prospection, sampling, and territorial analysis into our approach. The combination of these methodologies allowed us to accurately classify ceramic materials, establish their links to geological and archaeological contexts, and derive meaningful insights into production scales and patterns. Finally, the methodological approach applied here extends beyond the study of Argaric ceramics. It challenges the traditional assumption that the majority of ceramics within an archaeological context were locally produced, offering a broader perspective for future research.

CRediT authorship contribution statement

Carla Garrido-García: Writing – review & editing, Writing – original draft, Supervision, Software, Resources, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **David Gómez-Gras:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization, Validation, Visualization. **Marta Roigé:** Writing – review & editing, Supervision, Data curation, Formal analysis, Investigation, Validation, Visualization, Methodology, Writing – original draft. **Adrià Moreno Gil:** Writing – review & editing, Writing – original draft, Resources, Data curation, Formal analysis, Investigation, Validation, Visualization. **Roberto Risch:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Visualization, 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.

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Appendix A. Supplementary data

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