



Pottery production, early urbanization and the Uruk phenomenon at Tell Brak in Upper Mesopotamia

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Abstract

Tell Brak is one of the largest sites in Upper Mesopotamia, where urbanism and social complexity already emerged in the late 5th and early 4th millennia BCE. This paper combines ceramic petrography and trace element analyses to examine how these changes impacted pottery production and regional trade. The results indicate that paste preparation modes, unlike shaping procedures, remained unaffected by urbanization, with paste recipes showing no link to variations in vessel function or technology. To meet the growing demands of an urbanizing society, production likely involved multiple units producing diverse vessels, whereby certain tasks such as the raw material procurement were coordinated collectively. The only notable change in paste recipes occurred during the final phase of the Late Chalcolithic (LC5, 3350–3100 BCE), possibly reflecting the full establishment of craftspeople from southern Mesopotamia. This period also saw the import of a few jars from the Upper and Lower Euphrates and Tigris regions, likely used to transport specific goods.

Keywords Early urbanism · Uruk phenomenon · Upper Mesopotamia · Pottery production · Petrography · Geochemistry

Introduction

During the Late Chalcolithic period (hereafter LC), Mesopotamia and its surrounding regions underwent significant structural transformations in their socio-economic and political landscapes. These changes led to the establishment of complex societies, characterized by political hierarchies, advanced administrative systems, centralized economies

and early urban centers (Wright 1984; Rothman and Stein 1994; Algaze 2001, 2008; Rothman 2001; Oates et al. 2007; Al Quntar et al. 2011; Frangipane 2016, 2022; Iamoni 2016; Baldi 2022).

In terms of pottery repertoire, the LC saw a shift from fine grit painted wares towards coarse chaff-faced undecorated wares. Production techniques adapted to prioritize efficiency, functionality, and speed (Fragnoli and Frangipane 2022). This is exemplified by the spread of open-shaped containers—such as the earliest Coba bowls, flower pots, and beveled-rim bowls—which were produced in large quantities using standardized procedures and models (Baldi 2012a; Al Quntar and Abu Jayyab 2014). This serial production of pottery mirrored a broader trend of increasingly repetitive and widely adopted social practices such as formalized food consumption practices and redistribution activities facilitated by hierarchical institutions in exchange for labor (Frangipane 1993, 2002, 2010, 2018, 2022; Oates et al. 2007; Baldi and Abu Jayyab 2012; Baldi 2014; Arroyo Barrantes 2016). The introduction of the wheel-coiling technique (Roux 1994; Roux and Courty 1998; Baldi and Roux 2016) implied the acquisition of specialized skills developed over extended periods of apprenticeship.

During the LC1-2 (approximately 4400–3900 BCE), distinct ceramic horizons emerged from the dissolution of

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the up-until-now-considered widespread and unified Ubaid “world” (but see Baldi 2022 for a critical interpretation of this uniformity). Three main macro-regions can be distinguished: one still poorly known in southern Mesopotamia (Early Uruk) and two in northern Mesopotamia, east and west of the Euphrates, respectively (Baldi 2016). In the LC3-4 (3900–3350 BCE), ceramic assemblages in northern Mesopotamia became more homogeneous, with widespread distribution of types like casseroles and hammerhead-rim bowls and the first appearance of southern Middle Uruk-style ceramics. Today, we know that contacts between the southern Mesopotamian Uruk culture and central Mesopotamia started as early as in the LC2 (Vallet et al. 2017). Nonetheless, it took until the LC5 (3350–3100 BCE), corresponding to the Late Uruk period in southern Mesopotamia, that southern Mesopotamian elements spread to different extents through the Euphrates River valley, Syrian Jazeera, southeastern Anatolia, and southwestern Iran, leading to a strongly debated “Urukized” Mesopotamia (Butterlin 2003; Matthews 2003; Stein and Özbal 2007; Frangipane 2009).

Since the late 1990s, archaeometric analyses of LC Mesopotamian pottery have focused on provenance determination through geochemical analyses to elucidate the so-called Uruk expansion phenomenon, which itself largely monopolized the scholarly debates following the “world system” model applied by Guillermo Algaze (Algaze 1986; Blackman 1999; Bolger and Stephen 1999; Stephen and Peltenburg 2002; Daszkiewicz et al. 2012; Sánchez and Montero Fenollós 2012; Minc 2014; Emberling and Minc 2016; Minc et al. 2019). The broad geographic scope adopted by some scholars revealed that most Uruk-style pottery was produced locally, with only limited movement of ceramics that primarily originated from southern Mesopotamia (Bolger and Stephen 1999; Stephen and Peltenburg 2002; Minc 2014; Emberling and Minc 2016). Some authors interpret these results as evidence of people moving from southern Mesopotamia to neighboring regions, where they might have used local clay sources to craft vessels in familiar shapes. The consistency of morphological types and decorative techniques suggests interactions that facilitated technology transfer and acculturation (Bolger and Stephen 1999).

This paper couples trace element analyses with ceramic petrography to yield a more detailed picture of ancient paste recipes. Our case study is the Late Chalcolithic pottery from Tell Brak, one of the largest sites in northern Mesopotamia. There, urbanism and evidence of strong and diversified social complexity can be traced back to the late 5th and early 4th millennium BCE (Ur et al. 2011; Ur 2014; McMahon 2015). Besides evaluating the incidence, variety and origin of imports, we explore how increasing craft specialization, alongside growing social complexity and urbanization,

impacted the local strategies for raw material acquisition and manipulation.

Geographic and geological settings

Tell Brak (36° 40' 00" N, 41° 03' 30" E) is situated in the upper Khabur Plain in northeastern Syria, at the confluence of the Jaghjagh and Radd wadis (Fig. 1). The Khabur River, which originates in the foothills of the Taurus Mountains along the Syro-Turkish border, is the principal left-bank tributary of the Euphrates. This river system has historically played a crucial role in shaping the settlement patterns and agricultural potential of the region (Wilkinson 1990: 89–90).

Geologically, the region lies on the northern Arabian Plate, within the Abd el Aziz-Sinjar tectonic zone (Barazangi et al. 1993; Brew et al. 2001). The tectonic setting is influenced by the convergence of the Arabian Plate with the Eurasian Plate, which led to the uplift and formation of the Zagros Mountains to the east (McClusky et al. 2000; Brew et al. 2001). The region is formed mainly of Tertiary sedimentary rocks locally overlaid by Quaternary alluvial gravel fans and basalt lava flows (Wilkinson 1990: 87; Ur and Wilkinson 2008). The most common soil type is calcic xerosol, which is typically associated with arid and semi-arid environments, characterized by limited organic matter and significant calcium carbonate content (Wilkinson 1990: 89–90). Tertiary sedimentary rocks here consist of Upper Miocene to Pliocene clays, marls, limestones, siltstones, sandstones, conglomerates, gypsum, and gravels (Ponikarov et al. 1963; Blackburn and Fortin 1994). These gravels reflect the extensive drainage basin of the local wadi system, incorporating a varied mixture of sedimentary, metamorphic, and igneous rocks. In particular, allogenic gravels are transported downstream into the Khabur Plain from the northern Anatolian highlands (Wilkinson 2002; Demir et al. 2007; Westaway et al. 2010). These highlands are predominantly composed of metamorphic lithologies—namely, the Carboniferous to Triassic Malatya Metamorphics in the west and the Precambrian to Paleozoic units of the Bitlis–Pütürge Massif in the east.

The Malatya Metamorphics consist of low-grade metamorphic rocks, not exceeding the greenschist facies, and include metacarbonates such as marbles along with metapelites such as slates and phyllites. In contrast, the Bitlis–Pütürge Massif comprises rocks ranging from a greenschist to amphibolite facies. Dominant lithologies include schists and gneisses, specifically (in ascending order of abundance) kyanite-mica schists, biotite-amphibolites, garnet-kyanite-muscovite mica schists, garnet-andalusite mica gneisses/

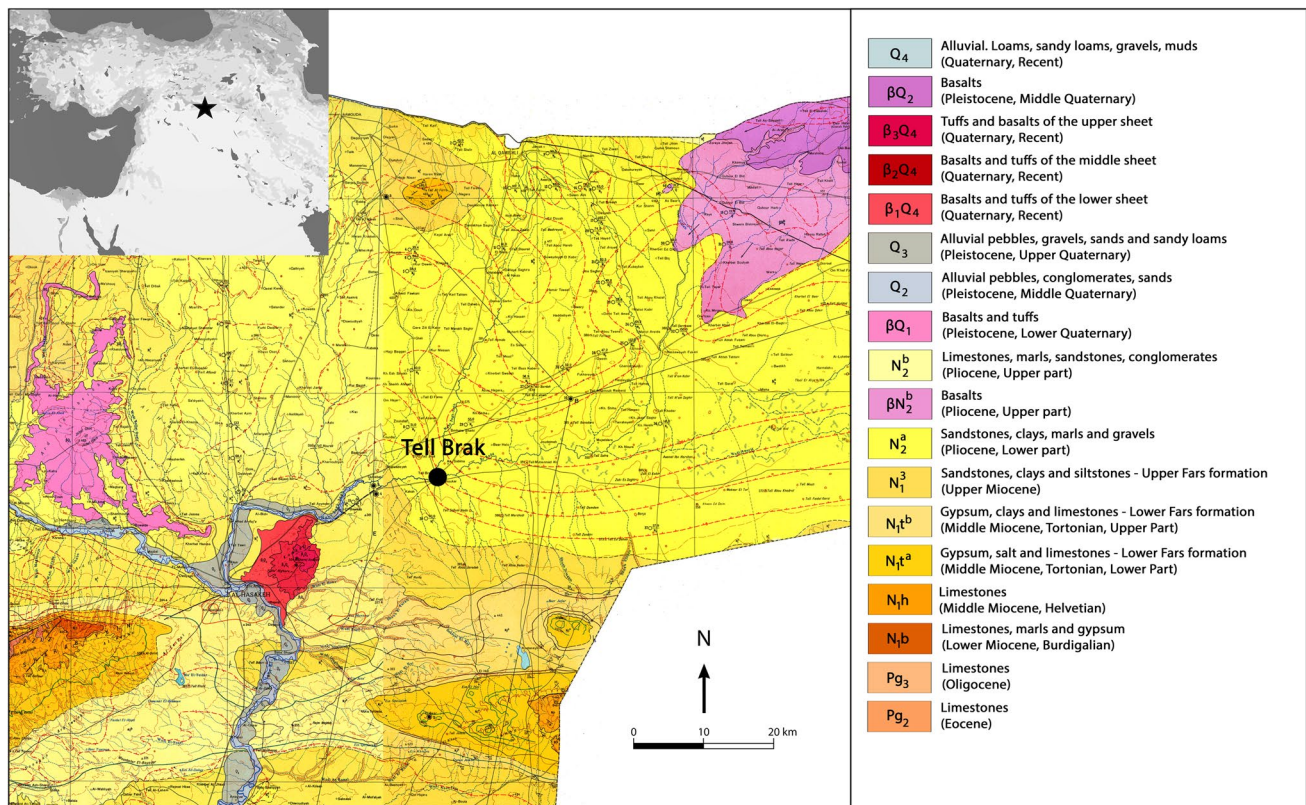


Fig. 1 Geological map illustrating a portion of the upper Khabur plain, including the location of Tell Brak, adapted from the “Geological Map of Syria (1:200,000)” from Ponikarov et al. (1963)

schists, albite-chlorite-muscovite schists, and calc-schists (Robertson et al. 2006).

The paleontological record in the area includes various bivalve genera from the Middle to Upper Miocene Fars Formation (marked as N1 on the geological map)—such as *Ostrea*, *Clausinella*, and *Anomia*—as well as benthic foraminifera from the Upper Pliocene (N2 on the map), including *Elphidium* (Ponikarov et al. 1963).

Archaeological context and ceramic repertoire

Southern Mesopotamia has long been recognized as the homeland of urbanization during the 4th millennium BCE, with the world’s earliest city of Uruk in modern southern Iraq (Adams 1972, 1981; Adams and Nissen 1972; van de Mieroop 1997; Nissen 2002; Liverani 2006; Algaze 2008). Nonetheless, urban developments occurred in northern Mesopotamia at least as early as in the south (Emberling 2003; McMahon and Oates 2007; Oates et al. 2007; Ur et al. 2007, 2011; Stein 2012; McMahon and Stone 2013). At Tell Brak, for instance, nascent socio-economic complexity and

proto-urban growth appeared up to 1000 years earlier than what attested for the large urban centers in southern Mesopotamia (Gibson and Maktash 2000: 477; Ur et al. 2007, 2011; McMahon and Stone 2013; Ur 2014; McMahon 2020).

Tell Brak’s significance partly stems from its strategic location in an extensive fertile land, as well as on a major route connecting the Tigris Valley to metal-rich Anatolia in the north and extending westward to the Euphrates and the Mediterranean. The main tell at Brak is one of the largest in northern Mesopotamia, covering over 40 hectares and reaching a height of over 40 m. Despite its impressive size, the tell represents only 21 percent of the entire settlement complex, which also included an outer town surrounded by smaller mounds and evidence of extensive occupation spanning nearly 300 hectares (Ur et al. 2007).

The occupation of Tell Brak spans from the proto-Hasuna/pre-Halaf to the Parthian and Roman periods (6500 BCE to 224 AD), featuring alternating phases of population decline and resurgence (Ur et al. 2011). The site’s periodization is divided into 18 phases, designated by capital letters from A to T. The Late Chalcolithic includes phase D for LC1 (4400–4200 BCE), phase E for LC2 (4200–3900 BCE), phase F for LC3–4 (3900–3350 BCE), and phase G for LC5 (3350–3100 BCE). In southern Mesopotamian

chronology, LC1 aligns with the Terminal Ubaid, LC2 with the Early Uruk, LC3 and LC4 with the Middle Uruk, and LC5 with the Late Uruk. Current evidence suggests that the initial push towards urbanization began during the Ubaid period. However, it wasn't until the LC2 that the settlement saw rapid spatial and demographic expansion, with clusters of occupied spaces alternating with vacant zones (Ur et al. 2007, 2011). These separations have been interpreted as indicating social distinctions, with the empty spaces marking boundaries between different groups within the settlement. These household clusters are thought to represent distinct neighborhood communities, separated by enough social or political distance to require also physical segregation. Major changes also occurred in the ceramic repertoire, which now reflected contacts with the east—i.e., with Tepe Gawra and Tell Hamoukar—rather than with the west (Oates 2012). This major change in pottery assemblages at the beginning of the LC2 is evident today at several sites all over northern Mesopotamia (Baldi 2016, 2022). Throughout this period, the trend was towards increasing standardization and mass production (Al Quntar and Abu Jayyab 2014), exemplified by the proliferation of chaff-tempered flower pots. Concurrently, the variety of types and the use of surface treatments gradually decreased. Cooking vessels witnessed a similar evolution, with burnished-slipped hole-mouth pots being gradually replaced by chaffy carinated casseroles, which would then dominate in the subsequent LC3.

During the LC3-4, secular and ceremonial structures as well as an urban-scale settlement were present at Tell Brak (McMahon and Stone 2013). The space became more densely occupied, filling in the previously unsettled areas between the outer town and the inner clusters. The central mound housed large industrial structures and at least one elaborately decorated temple, with the total settled area growing to 130 hectares (Ur et al. 2007). The material evidence indicates systems of resource redistribution, centralized production, craft specialization, long-distance trade, and the rise of an elite material culture (McMahon and Oates 2007; Khalidi et al. 2009; McMahon 2009). The urban edge zone was used for “dirty” industrial activities and rubbish disposal as well as for burials resulting from violent conflict (McMahon 2009). Urbanism at Tell Brak occurred through inward expansion via the merging of distinct external settlements (Ur et al. 2007). This suggests that urban growth was driven by non-hierarchically ranked groups rather than by elite coercion. This phase marks a further homogenization in the ceramic assemblages, consisting almost exclusively of utilitarian plain pottery, such as large storage jars, hammer-head-rim bowls, casseroles, trays and flower pots (Al Quntar and Abu Jayyab 2014).

From ca. 3500 BCE, at Tell Brak as well as in the entire region, changes in the material assemblages, forms of

architecture, domestic settlements and administrative systems testify to the presence of people from southern Mesopotamia (Frangipane 2001: 317–318; Emberling 2002; Emberling and McDonald 2003). In the pottery repertoire, this is reflected by the dominance of Uruk-related types such as nose-lug jars—with typical incised hatched triangles, cross-hatching and parallel, combed, incised lines as well as fingernail impressions and reserved-slip decorations—, spouted jars, bottles with and without spout, and beveled-rim bowls (Emberling and McDonald 2003).

Materials and methods

Fifty pottery samples dating to the different LC phases were studied for this contribution. All were analyzed using ceramic petrography, 43 of these also by Neutron Activation Analysis. These samples cover the main categories of the ceramic repertoire in terms of typology, technology, style, and morphology (Table 1; Fig. 2). Samples include tableware, large storage containers, and cooking vessels. The surfaces display diverse treatments: some are enhanced with slip layers in various colors—occasionally using the reserved-slip technique—linear incisions, or fingernail impressions, while others are left plain with a chaffy appearance. The LC1-2 samples primarily include red-slipped bowls and jars, with only a very few mass-produced bowls from the LC2. The LC3-4 sampling reflects the typical repertoire of Upper Mesopotamia, including hammer-head-rim bowls, casseroles, trays, and flower pots. For the final LC period, samples relate instead to south Mesopotamia with beveled-rim bowls as well as nose-lug and spouted jars. Regarding the manufacturing technology, diachronic observations are based on the restricted assemblage kept at the University of Cambridge (Fig. 3). While sequential slab building predominates in the LC1, especially for open-shaped vessels, it decreases by the LC2, when combined shaping techniques, often involving coiling and molding, appear. In contrast, the use of rotating devices shows continuity until the LC3, when they are mostly used in the finishing stage of the sequence. This pattern changes by the LC4-5, especially in relation to flower pots, when rotational kinetic energy is introduced in the forming stage of coil-built roughouts.

For ceramic petrography, thin sections were examined using the polarizing microscope LEICA DM 2700P and grouped based on textural, mineralogical, and technological features. Comparative charts were utilized to quantify the main components (Rice 1987: 348). The petrographic associations were compared with the units reported on geological maps and in the literature to distinguish imports from local products. The distribution of petrographic groups, which reflects both production modes and raw material origins, was examined in relation to vessel types and shapes, as well

Table 1 List of analyzed ceramic samples with their respective phases, contexts, petro-groups, NAA groups, morphological and typological descriptions

Sample	Phase	Internal phases	Context	Petro-group	NAA group	Description	Uruk related	Typological comparisons and notes
TB1	LC1	D	CH656	B	V019	Pinkish Cobia-like scraped bowl	No	Baldi 2012b, type II
TB2	LC1	D	CH825	B	V019	Pinkish Cobia-like scraped bowl	No	Baldi 2012b, type II
TB3	LC1	D		B	V019	Bowl with inner cross-hatched incisions	No	Baldi 2012a, pl. 8.1
TB4	LC1	D	CH649	B	/	Bowl with inner cross-hatched incisions	No	Baldi 2012a, pl. 8.1
TB5	LC1	D	CH788	B	M01	Bowl with flattened rim and internal burnish/slip	No	Baldi and Abu Jayyab 2012, Fig. 6
TB6	LC1	D	CH794	D	V019	Flaring rim jar with burnish/slip	No	Balossi Restelli 2006, Fig. 10j, l
TB7	LC1	D	CH632	D	/	Simple rim bowl with external red slip	No	Balossi Restelli 2019, X.36.4
TB8	LC2	E	CH779	B	/	Cobia-like bowl	No	Baldi 2012b, type II
TB9	LC2	E	CH742	loner	/	Cobia-like bowl	No	Baldi 2012b, type II
TB10	LC2	E	CH792	B	V019	Reddish flaring rim jar	No	Baldi 2012a, Fig. 8.8
TB11	LC2	E	CH782	E	/	Small bowl with thick inner and external dark red slip	No	Peyronel and Vacca 2020, Fig. 14.19; Renette et al. 2021, Fig. 12.8 (the nearest comparisons are dated to LC2-3). The red slip does not appear to be diagnostic since it is present in the Northern Context, in the southern one and also in the Zagros
TB12	LC2	E	TW837	E	V019	Bowl with thick inner and external red slip and ridge under the rim	Uncertain	Baldi 2016, Fig. 5.11; Vallet et al. 2019, Fig. 7.12; but possibly also LC2 Zeidan from Fischer 2017, pg. 476 h, i
TB13	LC2	E	CH735	E	M01	Band rim bowl with red slip	Yes	Baldi 2016, Fig. 5.11; Balossi Restelli 2012, Fig. 10e
TB14	LC3	F	TW379	B	V019	Cobia-like bowl	No	Baldi 2012b, type II
TB15	LC3	F	CH705	B	/	Whitish Cobia-like bowl	No	Baldi 2012b, type II
TB16	LC3	F	TW346	B	M01	Thin coiled bowl with flaring profile	No	Baldi 2012a, Fig. 6.6
TB17	LC1-2	D-E	CH792	B	V019	Flaring rim jar	No	Baldi 2012a, Fig. 8.8
TB18	LC1-2	D-E		C	/	Flaring rim jar with burnish/slip	No	Balossi Restelli 2006, Fig. 10j, l
TB19	LC3-4	F	TW377	A	#42 pair (with TB21)	Hammerhead-rim bowl with red slip	No	Pearce 2000, Fig. 9b
TB20	LC3-4	F	TW346	B	V019	Hammerhead-rim bowl	No	Balossi Restelli 2006, Fig. 6j
TB21	LC3-4	F	TW410	A	#42 pair (with TB19)	Hammerhead-rim bowl with red slip	No	Pearce 2000, Fig. 9b
TB22	LC3-4	F		B	M01	Bowl with inverting profile and inner red slip	No	Balossi Restelli 2006, Fig. 5u
TB23	LC3-4	F		B	V019	Jar with vertical neck and exteriorly thickened rim as well as rice grain decoration on shoulder	Uncertain	Balossi Restelli 2006, Fig. 11d

Table 1 (continued)

Sample	Phase	Internal phases	Context	Petro-group	NAA group	Description	Uruk related	Typological comparisons and notes
TB24	LC3-4	F	TW406	B	V019	Chaff-tempered tray	Uncertain	Renette et al. 2021 Fig. 6.2; Vallet et al. 2019, Fig. 7.13. Often reported as being Uruk types (Helwing 2000, Fig. 4; Trentin; Sürenhagen 1978), but present also in several northern regions earlier than Uruk contact (Renette et al. 2021, Fig. 6.2)
TB25	LC3-4	F	TW338	B	V019	Chaff-tempered tray	Uncertain	Renette et al. 2021 Fig. 6.2; Vallet et al. 2019, Fig. 7.13. Often reported as being Uruk types (Helwing 2000, Fig. 4; Trentin; Sürenhagen 1978), but present also in several northern regions earlier than Uruk contact (Renette et al. 2021, Fig. 6.2)
TB26	LC3-4	F	TW410	B	V019	Reddish casserole	Uncertain	Balossi Restelli 2006, Fig. 7a
TB27	LC3-4	F	TW227	B	V019	Burnished red-slipped casserole	Uncertain	Balossi Restelli 2006, Fig. 8b
TB28	LC3-4	F	TW412	B	V019	Casserole with lots of white large inclusions	Uncertain	Balossi Restelli 2006, Fig. 8h
TB29	LC4-5	F-G	CH705	B	M01	Thin Coba-like bowl	Uncertain	Baldi 2012b, type II
TB30	LC4-5	F-G	CH727	B	V019	Beveled-rim bowl	Yes but atypical	/
TB31	LC4-5	F-G	CH717	C	M01	Beveled-rim bowl	Yes	Sürenhagen 1978, tab.1: 19
TB32	LC4-5	F-G	CH698	B	V019	Coba-like bowl	No	Baldi 2012b, type II
TB33	LC4-5	F-G	CH699	C	M01	Coba-like bowl	No	Baldi 2012b, type II
TB34	LC5	G	TW125	Ioner	Ioner (no match with Minc 2014)	White nose-lug jar with plastic decorations	Yes	Iamoni and Sconzo 2022, Fig. 2.12: 24
TB35	LC5	G	TW297	E	V019	Nose-lug jar	Yes	Sürenhagen 1978, tab.8
TB36	LC5	G	TW209	E	V019	Nose-lug jar with relief horizontal cord bands	Yes	Baldi 2022, Fig. 7.9: 3
TB37	LC5	G	TW152	E	M01	Nose-lug jar with incised hatched decoration	Yes	Sürenhagen 1978, tab.6, 65
TB38	LC5	G	TW249	E	V019	Nose-lug jar with vertical and vertical relief bands	Yes	Iamoni and Sconzo 2022, Fig. 7.12: 24
TB39	LC5	G	TW306	E	V019	Nose-lug jar with incised hatched decoration	Yes	Sürenhagen 1978, tab.37
TB40	LC5	G	TW355	B	V019	Jar with simple reserved slip	Yes	Sürenhagen 1978, Tab. 5.61 (but only for the decoration)
TB41	LC5	G	TW349	E	M01	Jar with simple reserved slip	Yes	Sürenhagen 1978, Tab. 5.61 (but only for the decoration)
TB42	LC5	G	E	V019	V019	Jar with impressed dots around rim and reserved slip	Yes	Sürenhagen 1978, Tb.25: 31 with impressions on shoulder, like Sürenhagen Tab. 39, 75
TB43	LC5	G	TW338	E	V019	Jar with impressed dots around rim and reserved slip	Yes	Sürenhagen 1978, Tb.25: 31 with impressions on shoulder, like Sürenhagen Tab. 39, 61

Table 1 (continued)

Sample	Phase	Internal phases	Context	Petro-group	NAA group	Description	Uruk related	Typological comparisons and notes
TB44	LC5	G	TW209	Ioner	M02	Jar with jabbed impressions under the rim	Yes	Sürenhagen 1978, Tb.25. 38 with impressions on shoulder, like Sürenhagen Tab. 39, 60
TB45	LC5	G	TW349	E	V019	Bowl with inwardly protruding rim	Yes	Sürenhagen 1978, Tb.22. 85
TB46	LC5	G		E	V019	Sherd from bottom of jar (perforated, for pouring?)	Yes	/
TB47	LC5	G	TW337	E	M01	Small jar with everted short neck and simple rim	Yes	Sürenhagen 1978, Tb.25. 28
TB48	LC5	G	TW336	E	V019	Whitish fine bowl with inwardly beveled rim	Yes	Sürenhagen 1978, Tb.22. 83
TB49	LC5	G	TW333	E	V019	Spout from jar	Yes	Sürenhagen 1978, Tab. 33. 5
TB50	LC5	G	TW338	E	V019	Spout from jar	Yes	Sürenhagen 1978, Tab. 17. 101

as from a diachronic perspective. This yielded insights into specialization and standardization processes. These trends were compared with data from coeval sites in Upper Mesopotamia to construct a broader regional picture.

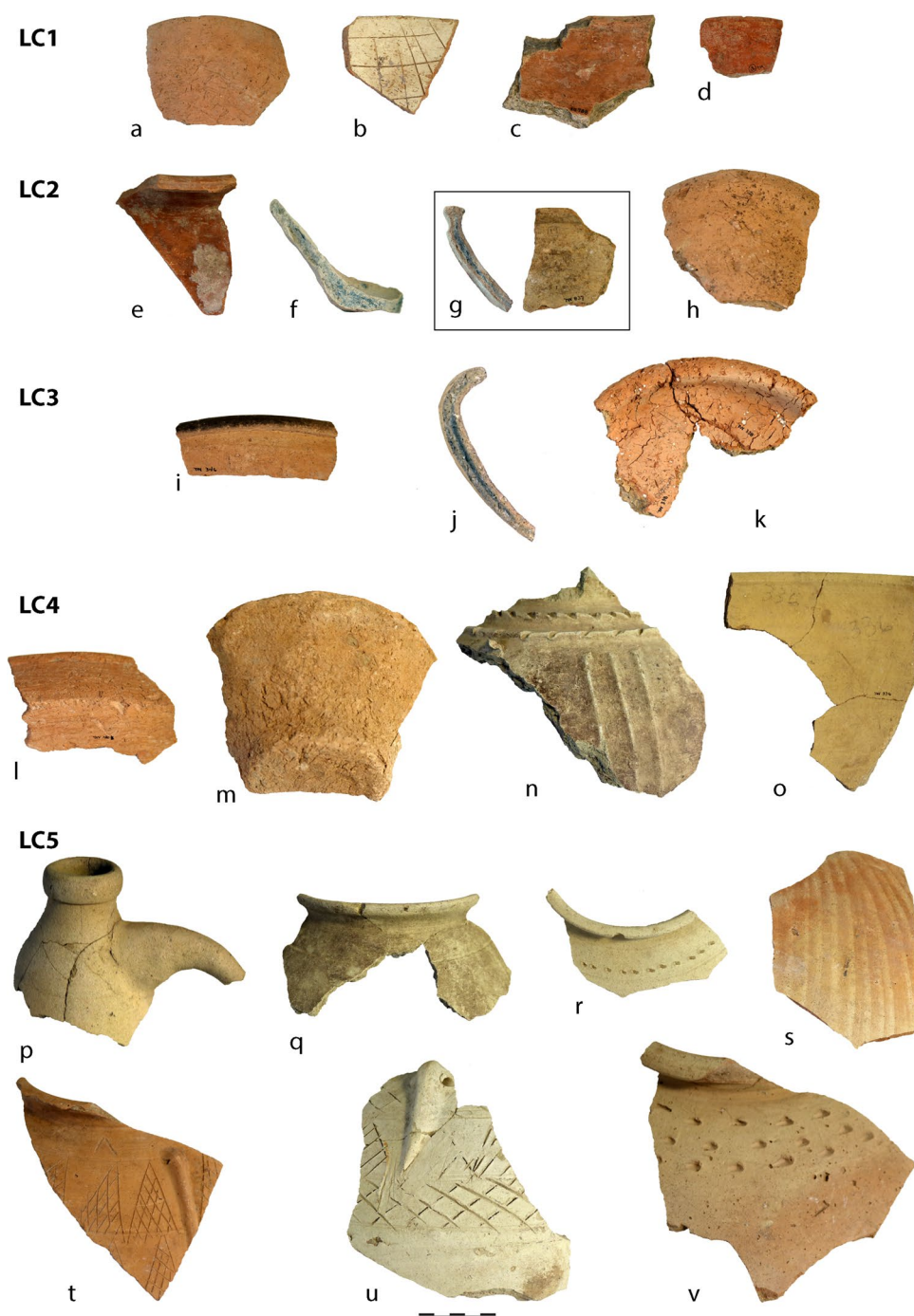
Neutron Activation Analysis was conducted according to established protocols for ceramics at the Center for Labeling and Isotope Production in Vienna (Sterba 2018). Each sample, weighing approximately 100 mg, underwent irradiation for 35 h at a neutron flux density of $1 \cdot 10^{13} \text{ cm}^{-2} \text{ s}^{-1}$. Quantification involved the irradiation and measurement of certified reference materials together with archaeological samples—CANMET reference soil SO1, NIST SRM 1633b Coal Fly Ash, Light Sandy Soil BCR No. 142, NIST SRM 2702 Inorganics in Marine Sediment—and comparison with the Bonn reference material (Mommsen and Sjöberg 2007) for compatibility with the combined Bonn/Vienna database. Data from two measurements, conducted after decay times of four weeks and four days, were used to calculate the concentrations of 28 elements. Statistical analysis of the raw data involved applying the best relative-fit factor calculations (i.e., dilution correction) as established in Bonn (Beier and Mommsen 1994), grouping the samples according to their modified Mahalanobis distance. All calculations were performed in the statistical software R (Team RC 2017), using functions that were programmed to implement the statistical approach as described in detail elsewhere (Mommsen et al. 1988; Beier 1993; Beier and Mommsen 1994; Mommsen and Sjöberg 2007; Sterba et al. 2009). In this process, a distance measure is calculated for each pair of samples, incorporating individual measurement errors as a scaling factor to the data. This distance is then minimized considering a possible dilution of the samples (Mommsen et al. 1988). This overcomes the potential statistical spread that results from the different content of water, silicon, or organic matter. Following this primary calculation, the distances are used in an iterative process to identify groups of samples. These groups are then compared with published Mesopotamian groups, obtained using similar methods and procedures, to pinpoint more precisely the provenance of non-local vessels (Minc 2014; Emberling and Minc 2016). Data comparability between this dataset and the combined Bonn/Vienna database is ensured by using the reference material NIST 1633a for quantification. This material, measured repeatedly in Vienna, provides a consistent basis for comparison across the datasets.

Results

Ceramic petrography

Five groups were distinguished—Group A, B, C, D, and E—based on the incidence and size of vegetal temper and mineral inclusions (Tables 1, and 2; Fig. 4). Most of the samples

Fig. 2 Selection of sampled vessels (scale 5 cm): **a)** TB1; **b)** TB4; **c)** TB5; **d)** TB7; **e)** TB18; **f)** TB8; **g)** TB12; **h)** TB16; **i)** TB20; **j)** TB22; **k)** TB25; **l)** TB26; **m)** TB31; **n)** TB34; **o)** TB48; **p)** TB50; **q)** TB47; **r)** TB42; **s)** TB40; **t)** TB39; **u)** TB37; **v)** TB44



fall into Group B ($n = 22$) and E ($n = 17$), while Groups A, C, and D each include only two samples. From Group A to Group E, vegetal temper tends to decrease both in frequency and size, while mineral inclusions show the opposite trend. Grouping criteria also consider the quartz-to-calcite ratio, the incidence of micas, and the presence and frequency of metamorphic rocks, K-feldspars, sandstones, limestones, and bioclasts. The specific characteristics of each group are summarized below, with extended descriptions provided in the supplementary materials (file 1).

In **Group A** (Fig. 4a), vegetal temper predominates across all fractions, from the coarsest to the finest ($3.6 \text{ mm} - < 0.25 \text{ mm}$), whereas mineral inclusions occur in very low amounts ($< 5\%$) and only in the fine fraction ($< 0.25 \text{ mm}$). Minerals consist mainly of quartz, with very few to very rare occurrences of muscovite, biotite, and calcite. The clay matrix is homogeneous, non-silty, reddish-brown, and optically partially active to inactive.

In **Group B** (Fig. 4b-d), vegetal temper and mineral inclusions are equal in incidence (10–15%). Compared to Group

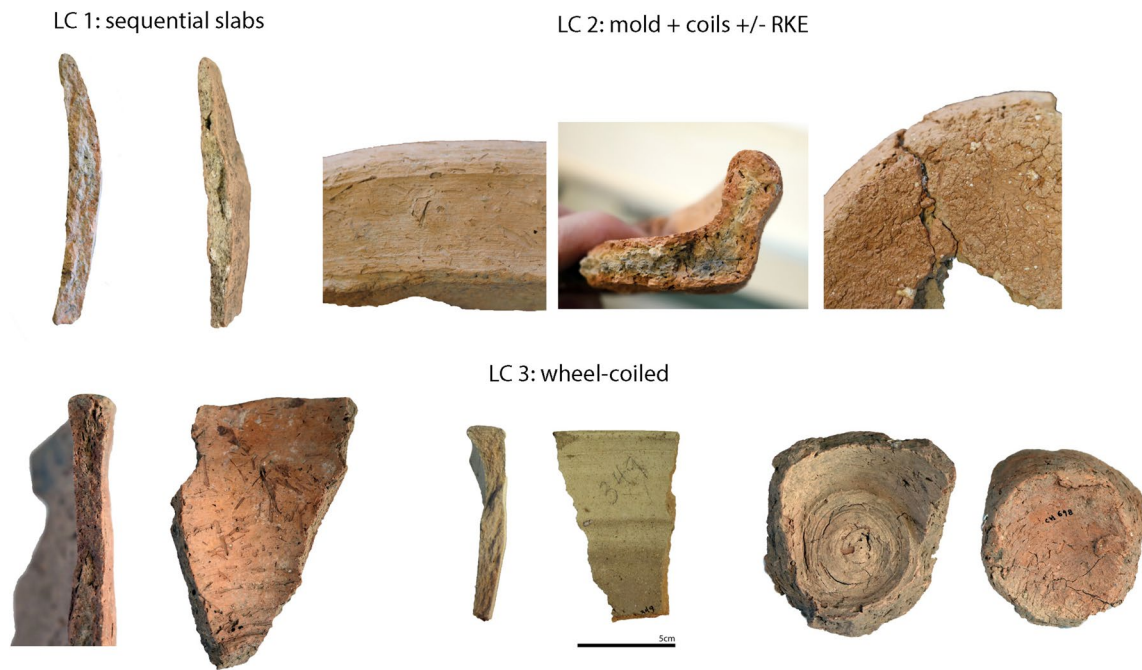


Fig. 3 Evolution of shaping procedures through the Late Chalcolithic period

A, mineral inclusions are both more abundant and coarser, appearing in both the medium (1.5–0.5 mm) and fine (<0.5 mm) fractions, while the coarse fraction (1.5–6 mm) remains composed solely of vegetal temper. Among the mineral inclusions, calcite dominates over quartz (Fig. 4b)—which can also appear as polycrystalline (Fig. 4c)—while muscovite and biotite continue to occur in very small amounts, as do newly-appeared K-feldspars. In general, Group B differs from Group A by the richer variety of minerals and rock types. Although not present in all samples and if present then only in very small amounts, there is evidence of sedimentary, metamorphic, and igneous rocks—e.g., chert, quartz schists, quartzite, basalt—as well as minerals such as plagioclase, epidote (Fig. 4d), hornblende, and fragments of bivalve shells. These latter components become especially prominent in two samples (TB22 and TB28). The matrix is mostly inactive, calcareous, silty, and heterogeneous, with a few clay pellets. Colors range from yellowish- to reddish-brown and dark red, with many samples displaying a dark core.

In **Group C** (Fig. 4e–g), the mineral fraction slightly dominates over vegetal temper (12% vs. 8%) and is represented across the different fractions, resulting in a slightly polymodal grain-size distribution. Contrary to Group B, quartz dominates over calcite, and there is an increased presence of plagioclase and K-feldspars, as well as metamorphic minerals and rocks (especially quartzite, lithic aggregates of quartz, epidote, muscovite, and K-feldspars). Group C also differs in the presence of very few to rare occurrences of iddingsite and kyanite in the fine fraction. The matrix is

inactive to slightly active, slightly silty, calcareous, yellowish- to reddish-brown, and moderately heterogeneous.

In **Group D** (Fig. 4h–j), the mineral fraction further increases relative to vegetal temper (12% vs. 3%), which also becomes finer, with maximum diameters below 1.7 mm. Calcite, including sparitic forms, dominates over quartz. In addition to the minerals and rocks already noted in Group C, Group D is distinguished by common bioclasts (bivalve shells and ooids) and organogenic limestone. Another distinguishing feature is the optical activity of the clay matrix, which is slightly silty, calcareous, heterogeneous, and orange- to yellowish-brown.

In **Group E** (Fig. 4k–o and Fig. 5a–f), the mineral fraction strongly dominates over vegetal temper (20% vs. 5%) and reaches coarser sizes (> 2 mm), resulting in a polymodal grain-size distribution. These textural features of the mineral inclusions, along with their angular shapes, indicate that they were probably deliberately added as crushed temper. The mineral fraction of Group E also reflects the richest geological variety, with inclusions of sedimentary, metamorphic, and igneous origins. For instance, quartzite, quartz and mica schists, as well as sandstones are represented across all the fractions. Most sandstones show distinctive characteristics: they are typically not grain-supported and contain both monomineralic and lithic detrital grains, often coated with iron oxide and cemented by post-depositional poikiloplastic calcite. Group E is also distinguished by dominant K-feldspars and rare to very rare occurrences of foraminifera, zoisite, and phyllite. The matrix exhibits the highest

Table 2 Main characteristics of each petrographic group and loner. The types of inclusions are listed in decreasing order of frequency and are italicized in case they are not present in each sample

Petro-group	Inclusions		Clay matrix			
	Types	%	Shape	Grain-size distribution	Maximum diameter	Orientation
A	Veg, Qz, Ms, Bt, Cal, <i>Ep</i>	25% min. (5%) veg. (20%)	Subangular to sub-rounded	Polymodal min. (unimodal) veg. (polymodal)	min. (0.4 mm) veg. (3.6 mm)	Horizontal to random
B	Veg, Cal, Qz, Kfs, Ms, Bt, <i>Chert</i> , <i>agg Qz</i> + Ms, <i>Qz</i> + Kfs, <i>Pl</i> , <i>Ep</i> , <i>Bcl</i> , <i>Hbl</i> , <i>Qz schist</i> , <i>Quartzite</i> , <i>Basalt</i> , <i>Dol</i> , <i>Gyp</i>	25–30% min. (10–15%) veg. (10–15%)	Subangular to sub-rounded	Polymodal min. (bimodal) veg. (polymodal)	min. (1.4 mm) veg. (6 mm)	Horizontal to random
C	Qz, Veg, Cal, Kfs, Pl, Ms, <i>agg. Ep</i> , <i>Ep</i> + Qz, <i>Qz</i> + Ms, <i>Qz</i> + Kfs, <i>Ep</i> , <i>Bt</i> , <i>Idd</i> , <i>Qz schist</i> , <i>Quartzite</i> , <i>Chert</i> , <i>Hbl</i> , <i>Basalt</i> , <i>Ky</i>	20% min. (12%) veg. (8%)	Subangular to sub-rounded	Polymodal min. (sl. polymodal) veg. (polymodal)	min. (0.8 mm) veg. (6.5 mm)	Horizontal to random
D	Cal, Qz, Kfs, Bcl, Veg, LMST, Ms, <i>agg Qz</i> + Ms, <i>Qz</i> + Bt + Sil + Ms, <i>Qz</i> + <i>Ep</i> , <i>agg Ep</i> , <i>Pl</i> , <i>Ep</i> , <i>Ky</i> , <i>Dol</i> , <i>Basalt</i> , <i>Chert</i> , <i>Hbl</i> , <i>Bt</i> , <i>Qz schist</i> , <i>agg Qz</i> + Kfs + <i>Hbl</i>	15% min. (12%) veg. (3%)	Subangular to well rounded	sl. Bimodal min. (uni-bimodal) veg. (bimodal)	min. (0.6 mm) veg. (1.7 mm)	Random
E	Qz, Kfs, Cal, Quartzite, Sandstone, <i>agg Qz</i> + Kfs (+ Ms/ <i>Ep</i> /Sil/ <i>Bt</i>), Veg, <i>Pl</i> , <i>Bt</i> , Mica/ <i>Qz schist</i> , Ms, <i>Basalt</i> , LMST, <i>Chert</i> , <i>Ep</i> , <i>agg Ep</i> , <i>Hbl</i> , <i>Ky</i> , <i>Phyllite</i> , <i>Gyp</i> , <i>Dol</i> , <i>Bcl</i> , <i>Zoi</i>	20–25% min. (20%) veg. (5%)	Subangular to sub-rounded	Polymodal min. (polymodal) veg. (polymodal)	min. (2.25 mm) veg. (1.6 mm)	Horizontal to random

Birefringence

Inactive to partially active

Mostly inactive, more rarely partially active

Inactive to sl. active

Active

Mostly inactive to sintered, more rarely sl. active

Table 2 (continued)

Petro-group	Inclusions	Clay matrix			
		Types	%	Shape	Birefringence
Loner TB9	Cal, LMST, Qz, Bcl, Veg, agg Qz + Kfs, Qz + Kfs + Chl + Sil + Grt + Hbl, Sandstone, Kfs, Dol, Basalt, Ms, Ep, Pl, Chert, Bt, Qz/Mica schist, Sil, Cpx, Hbl		30–35% min. (20%) veg. (10–15%)	Subangular to well rounded	sl. active
Loner TB34	Qz, Veg, Kfs, Pl, Chert, Quartzite, Basalt, Bcl, Ep		10% min. (6%) veg. (4%)	Subangular to sub-rounded	Sintered
Loner TB44	Veg, Qz, Kfs, Bt, Ms, Sandstone, Pl, Cal, Basalt, Quartzite, Qz/Mica schist, agg Qz + Ms, Qz + Kfs + Hbl, Qz + Sil, Ep + Qz, agg Ep, Hbl, Chert, Ol		25–30% min. (15%) veg. (15%)	Subangular to well rounded	Inactive to sintered

Abbreviations: *agg* aggregate, *Bcl* bioclast, *Bt* biotite, *Cal* calcite, *Cpx* clinopyroxene, *Dol* dolomite, *Ep* epidote, *Gyp* gypsum, *Hbl* hornblende, *Idd* iddingsite, *Kfs* k-feldspar, *Ky* kyanite, *LMST* limestone, *Ms* muscovite, *Ol* olivine, *Pl* plagioclase, *Qz* quartz, *Sil* sillimanite, *Veg* vegetal, *Zoi* zoisite

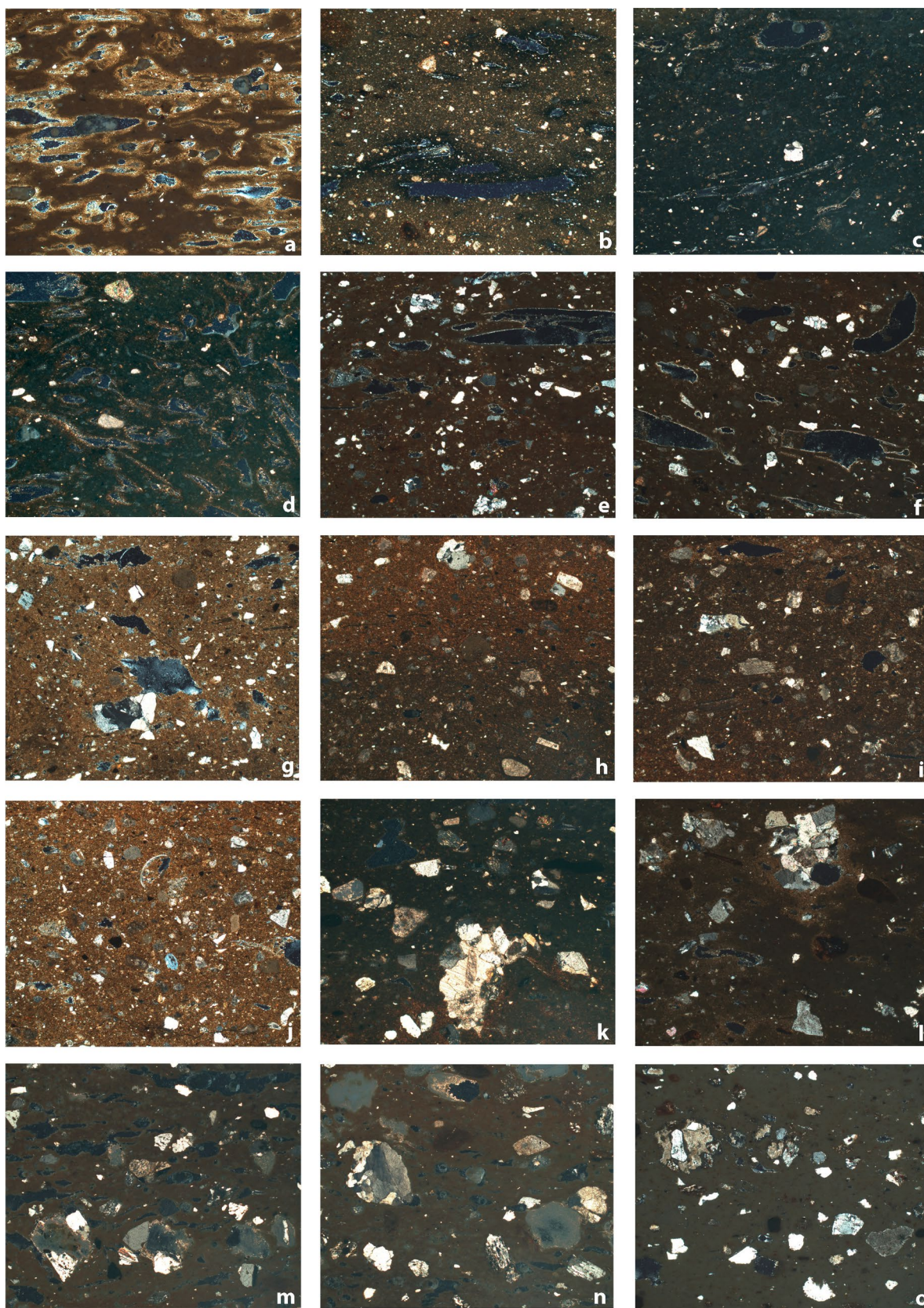


Fig. 4 Thin-section microphotographs under crossed-polarized light of petrographic groups A (a), B (b–d), C (e–g), D (h–j), and E (k–o). From Group A to Group E, vegetal temper decreases both in size and frequency, while mineral inclusions—comprising K-feldspars and metamorphic components—increase. Additional distinguishing features include variations in the quartz-to-calcite ratio and the presence of bioclasts and sandstones. Field of view = 3.35 mm

degree of optical inactivity, with frequent sintered areas. It is slightly silty, calcareous, heterogeneous with very few clay pellets, and dark orange to reddish-brown. Dark cores are present in four out of 17 samples (23.5%).

Among the analyzed samples, three do not fit into the petrographic groups described above and are therefore considered **petrographic loners** (Fig. 6a–f). **Sample TB9** (Fig. 6a–c) stands out for its coarse texture, with a maximum inclusion frequency and size of 35% and 5 mm, respectively. It is rich in limestone (including organogenic types), rhomb-shaped crystals of dolomite, and bioclasts such as bivalve shells, ooids, and foraminifera. The sample is also distinguished by the presence of sillimanite, clinopyroxene, and high-grade metamorphic rocks composed of quartz, K-feldspar, garnet, chlorite, sillimanite, and amphibole (gneiss). **Sample TB34** (Fig. 6d) differs by its low inclusion frequency and its greenish, heavily sintered marly fabric, which is rich in iron oxides. **Sample TB44** (Fig. 6e–f) stands out for its abundance of clay pellets and sandstones, an increased presence of micas and basalts, and the occurrence of olivine.

The mineralogical inclusions observed in most of the samples suggest that the primary materials were sourced from the local sedimentary landscape, with the nearby wadis likely contributing to the transport of materials from adjacent regions. The mineral-petrographic associations of Group A strongly reflect the geological setting of Tell Brak, which is primarily characterized by Tertiary sedimentary rocks. The increasing variety of minerals and rock types observed from Group B to Group E—particularly those of metamorphic origin—point to sediments from nearby wadis, which are rich in gravels of diverse geological origins transported downstream from the Taurus Mountains. This practice of using polymict sands from alluvial settings as temper has also been noted elsewhere in the Upper Euphrates, such as in the Early Bronze Age pottery assemblage of Tell el- ‘Abd (Russo et al. 2018; Carrión Anaya et al. 2024). Nonetheless, the presence of different metamorphic rocks in TB9 and TB44, combined with distinct petrographic features that set them apart as loners, suggests an allochthonous origin, which will be discussed further below.

Neutron activation analysis (NAA)

In a first step, the statistical methods described above were used to compare the 43 samples measured by NAA to all groups found in the combined Bonn/Vienna database. This initial comparison yielded no matches. The subsequent comparative analysis within the 43 samples dataset led to the identification of a chemical group containing 29 samples, which we labeled as V019 (Table 1). Two additional samples, TB19 and TB21, formed a distinct pair (termed #42), slightly differing from V019 through Hf, Rb, and Cs depletion (Fig. 7).

The next step involved comparing our samples to a published dataset of 97 samples from Tell Brak (Minc 2014). Of these, 29 samples align chemically with the V019 group. Most remaining samples, along with ten samples from our own dataset, formed a second chemical group, designated as M01 (Table 3).

To further characterize the chemical distinction between these two groups, we calculated element-by-element distances, normalized by the average spread for each element (Fig. 8). The most dominant differences emerged in Ca, Zr, Hf, Sm, and Th, with the first three elements higher in M01, and Th, and Sm more prominent in V019. Although the observed differences are moderate (1.5 to 2 times the average spread), they are large enough to distinguish the two groups, which is evident in their separability by the modified Mahalanobis distance. This separation is also apparent in a principal component analysis (PCA) of the dilution-corrected dataset (Fig. 9). The PCA is applied here only for visualization purposes; the grouping was performed by the modified Mahalanobis distance as explained above.

In the final comparison step, we analyzed our samples against Minc’s entire database, which comprises 1777 ceramic vessels from 24 key sites across modern Syria, Iraq, Iran, and western Pakistan, dating from the mid-4th millennium through the 3rd millennium BCE. This broader analysis revealed a third chemical group, M02, which includes sample TB44 from our dataset and several samples from Kunji Cave (KC_12, KC_17, KC_35, KC_57, KC_64), as well as Tell Hadidi (HDD_27) and Nineveh (NIN_13) (Tables 1, and 3). A distinguishing feature of TB44, compared to V019, is its strong depletion in Ta alongside enrichment in Sc and Fe (Fig. 10).

Of the 43 analyzed samples, only TB34 does not align with any identified group or other sample, making it also a chemical loner. TB34 is notably depleted in Rb and, to a lesser extent, in K (Fig. 11) when compared to the mean of chemical group V019. The raw data used for the statistical analysis of the Tell Brak samples is available in the supplementary materials (file 2).

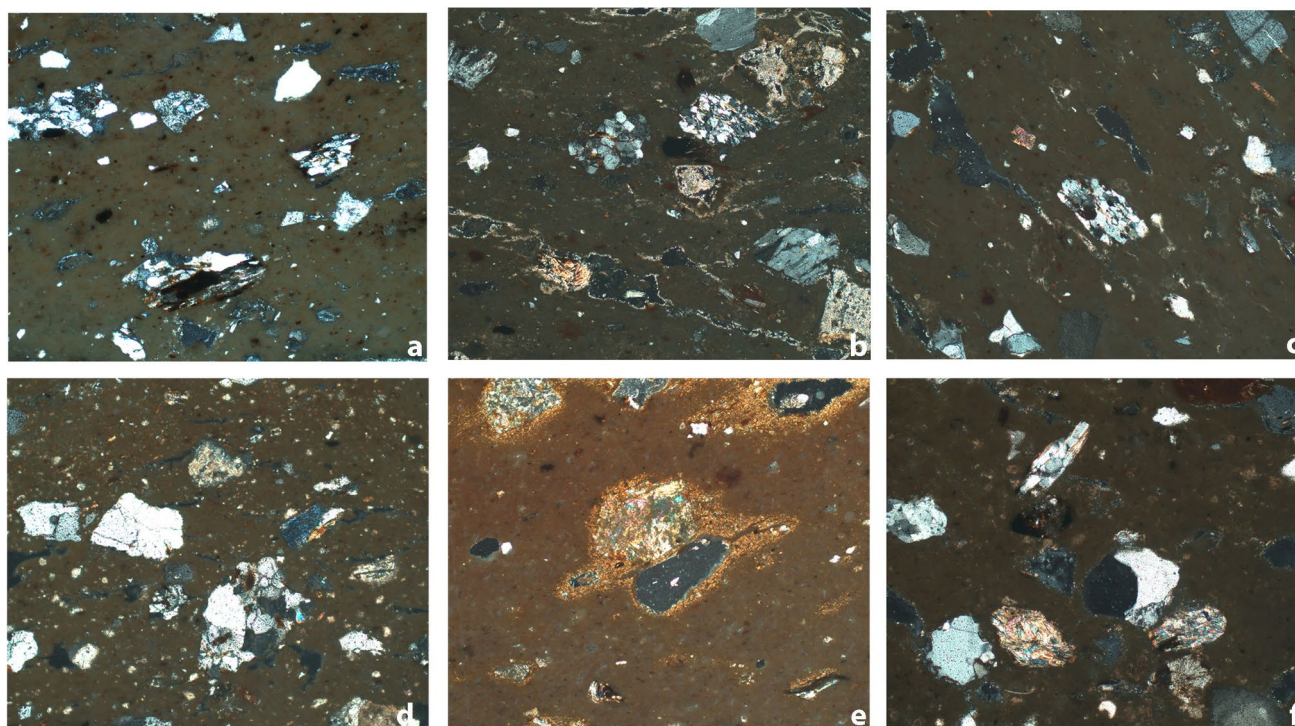


Fig. 5 Thin-section microphotographs under crossed-polarized light of Group E, showing the common occurrence of metamorphic rocks and minerals, including quartz schists (**a**, **f**), mica schists (**b**, **f**), quartzites (**b**, **d**), epidote (**c**, **e**), and zoisite (**d**). Field of view = 1.68 mm

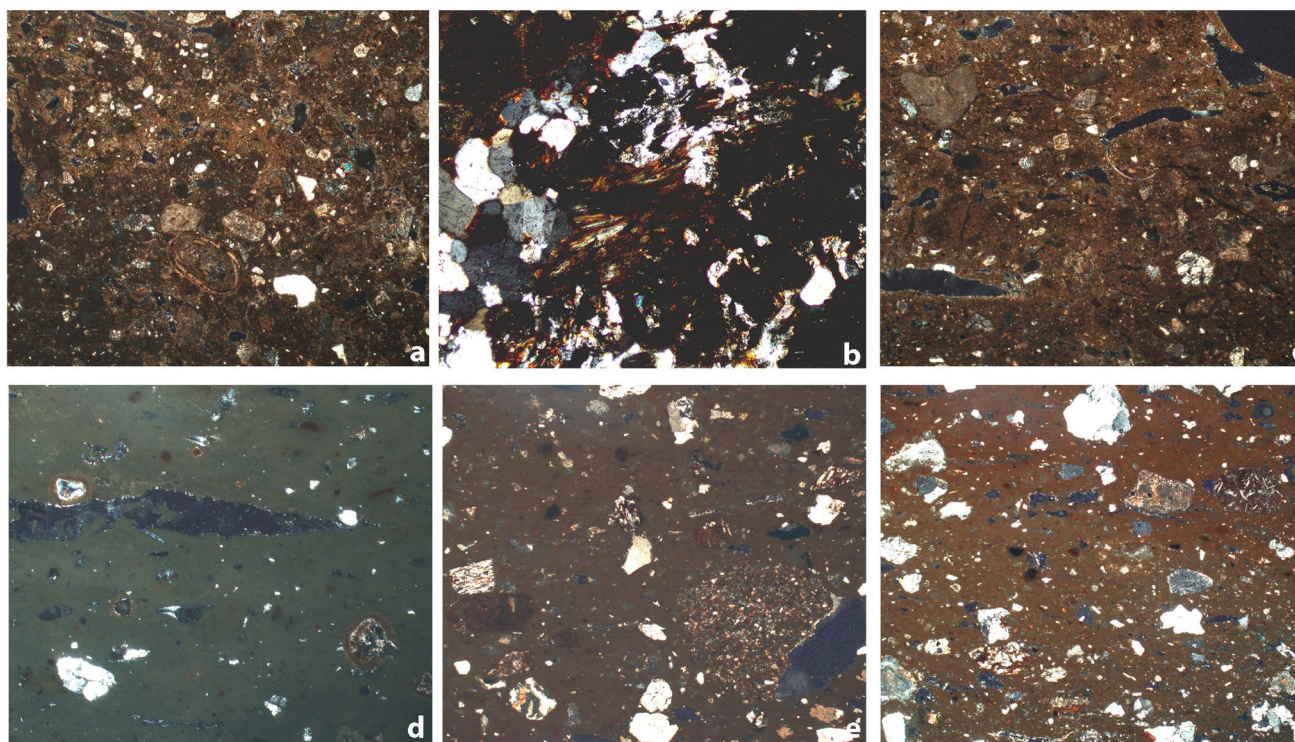
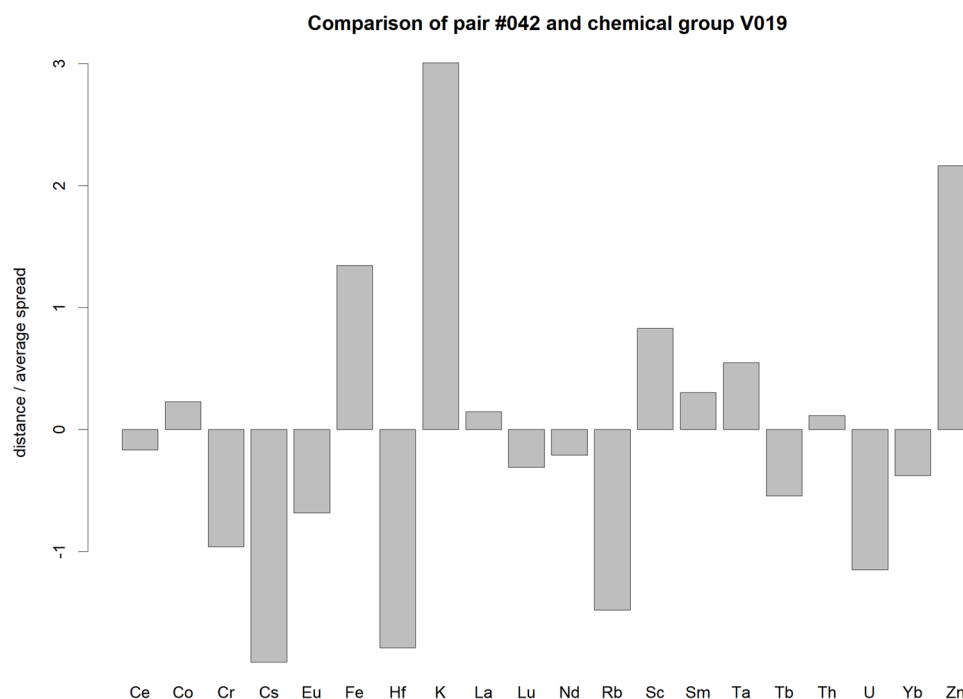


Fig. 6 Thin-section microphotographs under crossed-polarized light of the petrographic loners TB9 (**a-c**), TB34 (**d**), and TB44 (**e-f**). Field of view = 3.35 mm

Fig. 7 Normalized concentration differences in units of average spread between the chemical pair #042 and the chemical group V019. Hf, Rb and Cs are depleted in the pair in comparison to the group



Discussion

Based on the abundance criterion, overall chemical and mineralogical consistency, and compatibility with local geology, our results indicate that the LC vessels found at Tell Brak were primarily produced locally. This finding extends Minc's assumption regarding the locally-made Uruk repertoire to earlier LC phases. Nonetheless, local production at Tell Brak displays internal variation, reflected in distinct petrographic and geochemical groupings. Interestingly, the petrographic and geochemical groups mostly do not align (Fig. 12). Aside from methodological challenges in comparing the two approaches, this mismatch can also be understood in relation to the specific case-study.

Petrographic grouping at Tell Brak is primarily based on the amount and size of vegetal temper, visible as ghost voids under the microscope—features not detectable through geochemical analyses. Additionally, variations in the mineral composition of Groups B, C, D, and E—consistent with polymict sands derived from alluvial sediments—are not expected to significantly affect the geochemical fingerprint. In other words, the differences observed under the microscope largely reflect how mostly similar raw materials were processed during paste preparation. By contrast, NAA groups V019 and M01 differ mainly in their concentrations of Zr, Hf, and Th, likely reflecting varying amounts of heavy minerals within the clay matrix—features invisible in thin section. Altogether, the data suggest the use of at least two distinct clay sources, followed by multiple paste preparation modes.

In contrast, the petrographic and geochemical results converge (Fig. 12) in grouping TB19 and TB21—two LC3-4 red-slipped hammerhead-rim bowls belonging to petrographic group A and NAA pair #42—and in identifying TB34 and TB44 as outliers—a LC5 white nose-lug jar with plastic decoration and a LC5 red jar with jabbed impressions. The TB19-TB21 pair is depleted in Hf, Cs, and Rb, suggesting production from alluvial clays with reduced felsic affinities, likely subjected to prolonged weathering and sorting. This geochemical signature aligns with petrographic observations: the samples are dominated almost exclusively by vegetal temper, with rare, non-polymict mineral inclusions. Since the mineral inclusions match the local geology, however, it is unclear whether these vessels are imports or, most probably, local adaptations of paste recipes.

The LC5 nose-lug jar TB34 is a unique sample with no matches in either our or Minc's datasets. Its petrographic and geochemical characteristics suggest that it was crafted from fine-grained marly clay with minimal feldspar and mica content. This composition implies that the clay was formed in low-energy environments characterized by extensive sedimentary sorting and weathering. Given these distinctive petrographic and geochemical features, along with the very limited presence of volcanic or metamorphic materials, a southern origin from the lower reaches of the Euphrates and Tigris river systems is a plausible source for this jar. Although texturally different, the local fabrics from LC4 Gurga Chiya in Iraqi Kurdistan display similar mineralogical associations, as well as being vegetal-tempered (Lewis et al.

Table 3 Ceramic samples from Minc's database matching with the 50 new LC samples from Tell Brak analyzed in this paper

Sample	Phase	Context	Description	NAA group	Minc's interpretation
HDD_27	1900–1550 BCE (MBA)		Tabqa Dam/Lake Assad Syria vessel	M02	Unassigned
KC_12	Late 4th mill. BC		Luristan Iran Korammabad Valley	M02	core local
KC_17	Late 4th mill. BC		Luristan Iran Korammabad Valley	M02	core local
KC_35	Early 3rd mill. BC		Luristan Iran Korammabad Valley	M02	core local
KC_57	Early 3rd mill. BC		Luristan Iran Korammabad Valley	M02	core local
KC_64	Early 3rd mill. BC		Luristan Iran Korammabad Valley	M02	core local
NIN_13	Mid-4th mill. BC		Ninawa Governorate Iraq, Fine buff chaff bottle	M02	27-element prob. (import from TB?)
TBK_002	Late 4th mill. BC	TW2	Calcitic ware, Rim Uruk	V019	Brak core
TBK_005	Late 4th mill. BC	TW2	Calcitic ware, Jar shoulder with cross-hatched incisions	V019	Brak core
TBK_007	Late 4th mill. BC	TW2	Calcitic ware, Jar shoulder	M01	Brak core
TBK_008	Late 4th mill. BC	TW2	Calcitic ware, Jar	V019	Brak core
TBK_011	Late 4th mill. BC	TW2	Calcitic ware, Jar rim, red slip	V019	Brak core
TBK_012	Late 4th mill. BC	TW2	Calcitic ware, Beveled-rim bowl	V019	Brak core
TBK_013	Late 4th mill. BC	TW2	Calcitic ware, Beveled-rim bowl	V019	Brak core
TBK_014	Late 4th mill. BC	TW2	Calcitic ware, Beveled-rim bowl	V019	Brak core
TBK_016	Late 4th mill. BC	TW2	Calcitic ware, Beveled-rim bowl	M01	Brak core
TBK_019	Late 4th mill. BC	TW2	Calcitic ware, Beveled-rim bowl	V019	Brak core
TBK_020	Late 4th mill. BC	TW2	Calcitic ware, Beveled-rim bowl	V019	Brak core
TBK_021	Late 4th mill. BC	TW2	Calcitic ware, Jar	M01	Brak core
TBK_022	Late 4th mill. BC	TW2	Calcitic ware, Spout	V019	Brak core
TBK_024	Late 4th mill. BC	TW2	Calcitic ware, Droop spout	M01	Brak core
TBK_025	Late 4th mill. BC	TW2	Calcitic ware, Jar spout	M01	Brak core
TBK_026	Late 4th mill. BC	TW2	Calcitic ware, Handle	M01	Brak core
TBK_027	Late 4th mill. BC	TW2	Fine ware, Carinated bowl	M01	Brak non core
TBK_029	Late 4th mill. BC	TW2	Calcitic ware, Beaded-rim bowl	M01	Brak core
TBK_03	Late 4th mill. BC	TW2	Calcitic ware, Beveled-rim bowl	Loner?	Brak outlier assigned
TBK_030	Late 4th mill. BC	TW2	Calcitic ware, Beaded-rim bowl	M01	Brak core
TBK_031	Late 4th mill. BC	TW2	Calcitic ware, Beaded-rim bowl	M01	Brak core
TBK_033	Late 4th mill. BC	TW2	Calcitic ware, Beaded-rim bowl	M01	Brak core
TBK_034	Late 4th mill. BC	TW2	Fine ware, Carinated bowl	M01	Brak core
TBK_035	Late 4th mill. BC	TW2	Calcitic ware, Beaded-rim bowl	M01	Brak core
TBK_036	Late 4th mill. BC	TW2	Calcitic ware, Cup rim	V019	Brak core
TBK_039	Late 4th mill. BC	TW2	Calcitic ware, Cup rim	V019	Brak core
TBK_040	Late 4th mill. BC	TW2	Fine ware, Int. Ledge bowl	V019	Brak core
TBK_043	Late 4th mill. BC	TW2	Fine ware, Carinated bowl	V019	Brak core
TBK_044	Late 4th mill. BC	TW2	Fine ware, Carinated bowl	M01	Brak core
TBK_045	Late 4th mill. BC	TW2	Fine ware, Carinated bowl	M01	Brak core
TBK_046	Late 4th mill. BC	TW2	Fine ware, Carinated bowl	V019	Brak core
TBK_047	Late 4th mill. BC	TW2	Calcitic ware, Jar rim	V019	Brak core
TBK_048	Late 4th mill. BC	TW2	Calcitic ware, Jar shoulder with cross-hatch incision	Loner?	Other/unassigned (maybe Nineveh in Minc and Emberling 2016)
TBK_049	Late 4th mill. BC	TW2	Calcitic ware, Bowl rim	M01	Brak core
TBK_050	Late 4th mill. BC	TW2	Calcitic ware, Jar rim	V019	Brak core
TBK_051	Late 4th mill. BC	TW2	Calcitic ware, Jar rim	V019	Brak core
TBK_052	Late 4th mill. BC	TW2	Calcitic ware, Jar rim	V019	Brak core
TBK_053	Late 4th mill. BC	TW2	Calcitic ware, Jar rim	M01	Brak core
TBK_054	Late 4th mill. BC	TW2	Calcitic ware, Jar shoulder with reserved slip	M01	Brak core

Table 3 (continued)

Sample	Phase	Context	Description	NAA group	Minc's interpretation
TBK_055	Late 4th mill. BC	TW2	Calcitic ware, Flat base	V019	Brak core
TBK_056	Late 4th mill. BC	TW2	Calcitic ware, Jar shoulder with reserved slip	M01	Brak core
TBK_057A	Late 4th mill. BC	TW2	Calcitic ware, Jar	V019	Brak core
TBK_057B	Late 4th mill. BC	TW2	Calcitic ware, Jar shoulder	V019	Brak core
TBK_059	Late 4th mill. BC	TW2	Calcitic ware, Bottle rim	M01	Brak core
TBK_060	Late 4th mill. BC	TW2	Calcitic ware, Jar	M01	Brak core
TBK_061	Late 4th mill. BC	TW2	Calcitic ware, Jar rim	V019	Brak core
TBK_062	Late 4th mill. BC	TW2	Calcitic ware, Bottle shoulder	V019	Brak core
TBK_063	Late 4th mill. BC	TW2	Calcitic ware, Bottle rim	Loner?	unassigned (possibly Mesopotamia in Minc and Emberling 2016)
TBK_064	Late 4th mill. BC	TW2	Calcitic ware, Bottle rim	M01	Brak core
TBK_065	Late 4th mill. BC	TW2	Calcitic ware, Jar rim	M01	Brak core
TBK_067	Late 4th mill. BC	TW2	Calcitic ware, Jar with spout	Loner?	unassigned
TBK_069	Late 4th mill. BC	TW2	Calcitic ware, Bottle rim	M01	Brak core
TBK_070	Late 4th mill. BC	TW2	Calcitic ware, Bottle rim	V019	Brak core
TBK_071	Late 4th mill. BC	TW2	Calcitic ware, Base	M01	Brak core
TBK_072	Late 4th mill. BC	TW2	Calcitic ware, Base	M01	Brak core
TBK_073	Late 4th mill. BC	TW2	Calcitic ware, Bottle base	V019	Brak core
TBK_074	Late 4th mill. BC	TW2	Calcitic ware, Bottle rim	M01	Brak core
TBK_076	Late 4th mill. BC	TW2	Calcitic ware, Jar rim	M01	Brak core
TBK_077	Late 4th mill. BC	TW2	Chaff ware, Large round rim jar, internal groove	V019	Brak non core
TBK_079	Late 4th mill. BC	TW2	Chaff ware, Beaded-rim jar, internal groove	M01	Brak non core
TBK_080	Mid- 4th mill. BC	TW2	Chaff ware, Internally beveled-rim bowl	M01	Brak non core
TBK_082	Mid- 4th mill. BC	TW2	Chaff ware, Beaded-rim bowl	M01	Brak non core
TBK_083	Mid- 4th mill. BC	TW2	Fine small bowl, External groove	M01	Brak non core
TBK_084	Mid- 4th mill. BC	TW2	Gray ware, Internally beveled-rim bowl	M01	Brak non core
TBK_086	Mid- 4th mill. BC	TW2	Fine ware, Ledge rim jar	M01	Brak non core
TBK_087	Mid- 4th mill. BC	TW2	Chaff ware, Hammerhead-rim bowl	M01	Brak non core
TBK_088	Mid- 4th mill. BC	TW2	Calcitic ware, Beaded-rim casserole	M01	Brak non core
TBK_089	Mid- 4th mill. BC	TW2	Chaff ware, heavy ledge rim bowl	M01	Brak non core
TBK_091	Mid- 4th mill. BC	TW2	Chaff ware, Hammerhead-rim bowl	M01	Brak non core
TBK_092	Mid- 4th mill. BC	TW2	Chaff ware, Hammerhead-rim bowl	M01	Brak non core
TBK_094	Mid- 4th mill. BC	TW2	Chaff ware, Hammerhead-rim bowl	M01	Brak non core
TBK_095	Mid- 4th mill. BC	TW2	Chaff ware, large Round rim jar, internal groove	M01	Brak non core
TBK_096	Mid- 4th mill. BC	TW2	Calcitic ware, Beaded-rim casserole	V019	Brak non core

2020). Nonetheless, further investigation is needed to refine any provenance attribution.

The LC5 red jar with jabbed impressions is both a petrographic and geochemical loner within our dataset. In Minc's database, however, it groups (NAA group M02) with five samples from Kunij Cave in the Central Zagros region of western Iran, as well as with one sample each from Tell Haddidi in northern Syria (Upper Euphrates) and Nineveh in northern Iraq (Upper Tigris) (Table 3). Based on its petrographic features, Tell Brak—and more

broadly, the Upper Khabur region—can likely be excluded as provenance due to the increased presence of micas (Eiland 2003; Kibaroglu 2021). Minc (2014) attributes the Kunij Cave samples to a local production (Table 3). Although Kunij Cave lies within the sedimentary region of the Zagros Fold Belt (Barber et al. 2019), nearby rivers draining the Zagros Mountains probably introduce metamorphic and igneous materials into the region's clay deposits, which eventually reach the Tigris River system. Tell Haddidi, represented by a single later sample in Minc's

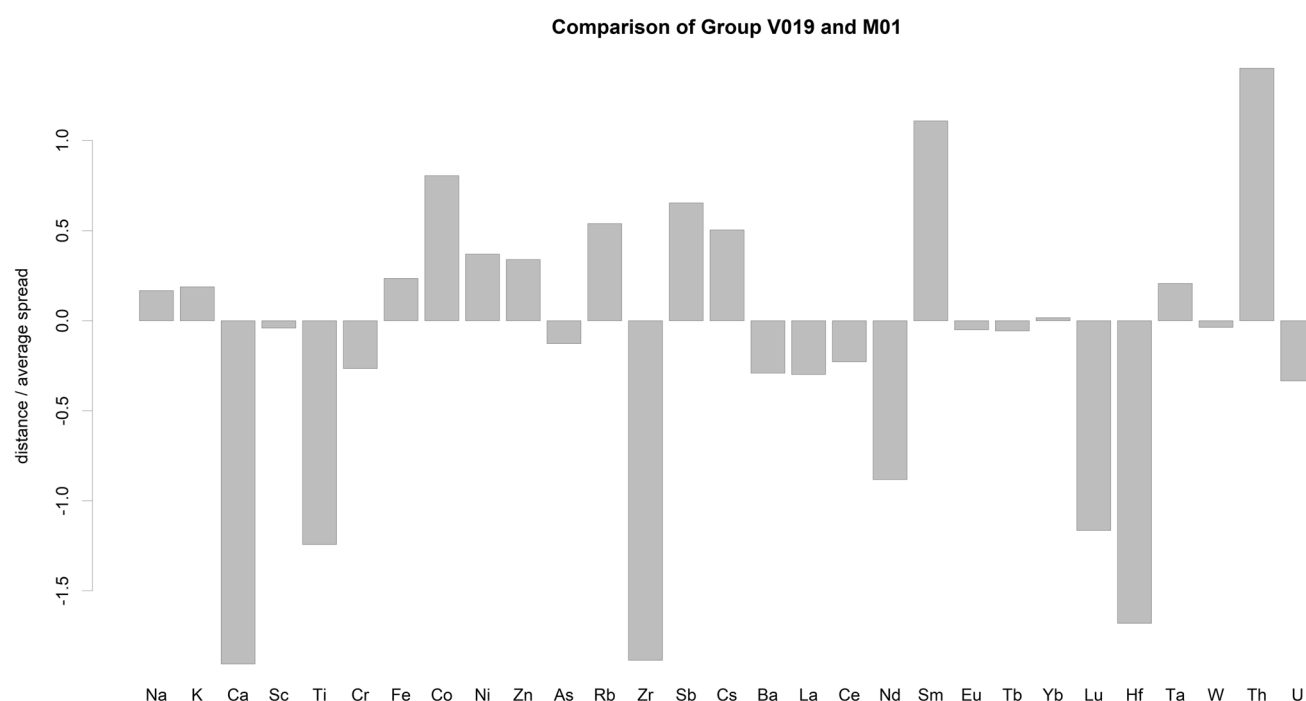


Fig. 8 Normalized concentration differences in units of average spread between the chemical groups V019 and M01

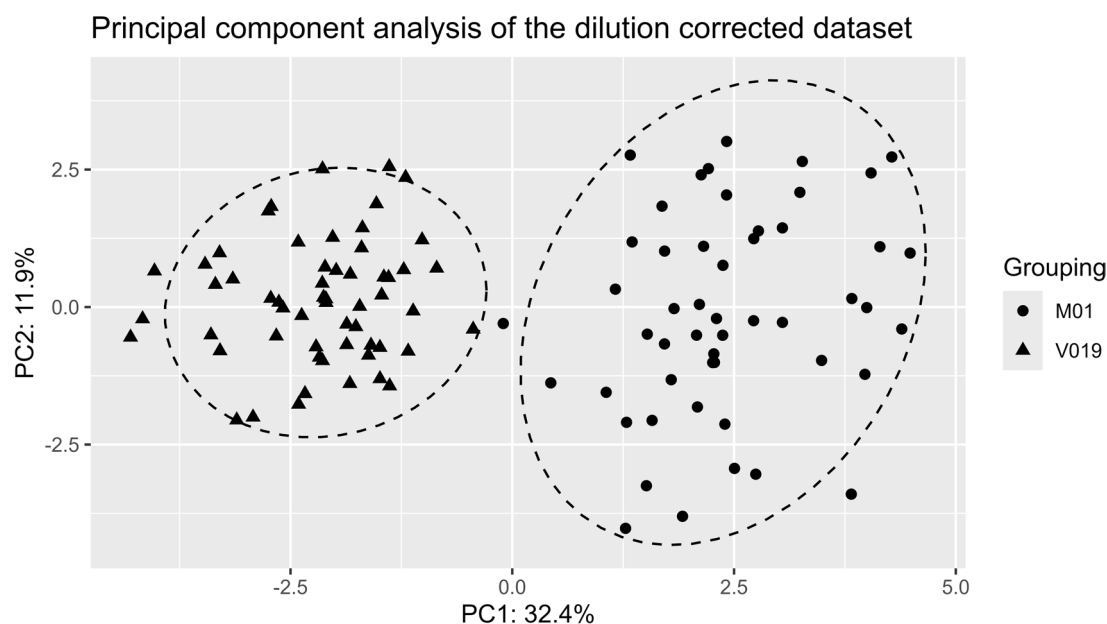


Fig. 9 Principal Component Analysis (PCA) of the dilution corrected data of the chemical groups V019 and M01. PCA is used here solely to visualize the differences that were found by application of the modified Mahalanobis distance approach

study, was left unassigned. Note, however, that the mineral-petrographic associations for Tell Hadidi vessels by Mason and Cooper (1999) closely resemble those observed in TB44. Additionally, the increased mafic affinities of TB44—indicated by Fe and Sc enrichment and a higher

frequency of basaltic inclusions—align with the geochemical signature of the Euphrates depression, as described by Minc (2016). The sample NIN_13 from Nineveh, a mid-4th millennium chaff-tempered bottle, was proposed as an import from Tell Brak due to its low Cr concentrations

Fig. 10 Normalized concentration differences in units of average spread between the chemical group V019 and the chemical loner TB44. The strong depletion in Ta is clearly visible, as is the enrichment in Sc and Fe

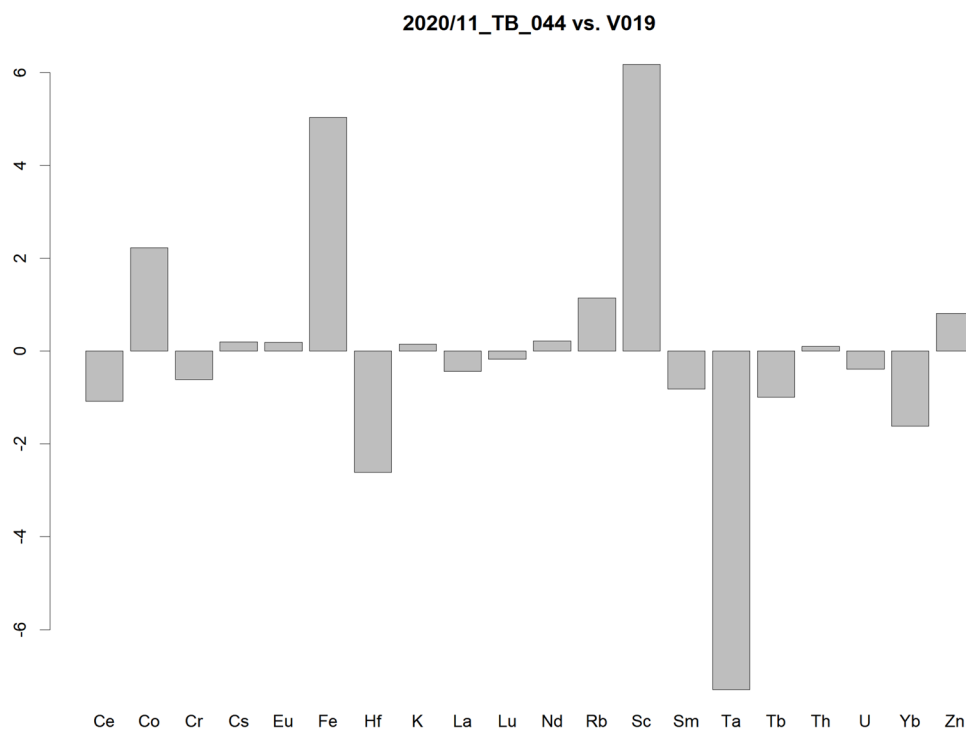
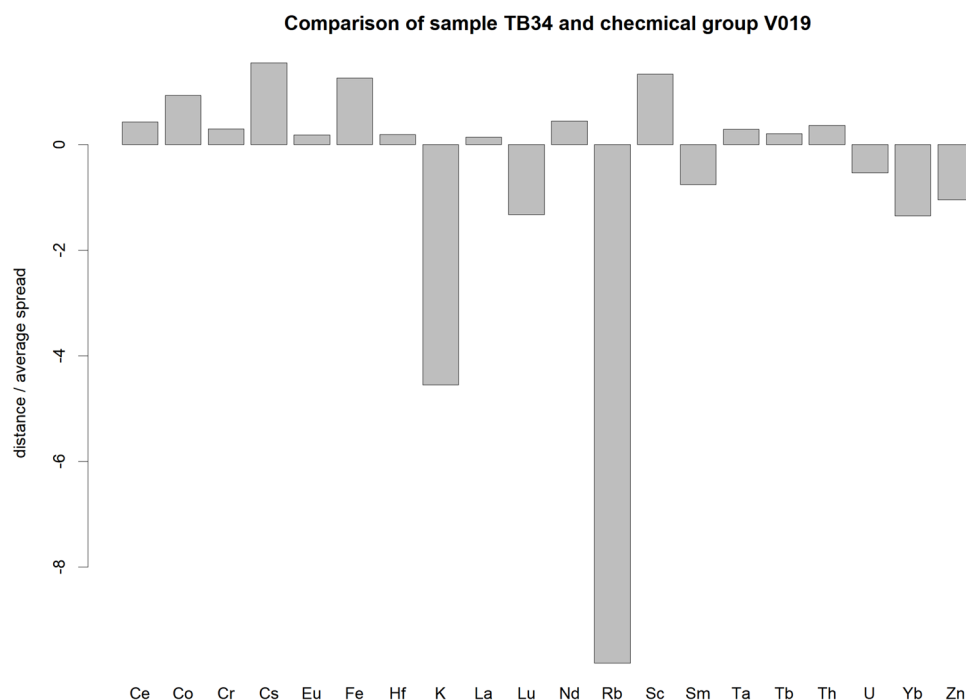


Fig. 11 Normalized concentration differences in units of average spread between the chemical group V019 and the chemical loner TB34. A strong depletion in Rb and somewhat more moderate depletion in K is visible in comparison to the group mean



(Emberling and Minc 2016). However, the Nineveh reference group shows significant internal variability and only partial overlap with Tell Brak. Overall, based on petrographic and elemental evidence, the most plausible provenances for TB44 are either the Upper Euphrates region (Tell Hadidi) or Luristan (Kunij Cave).

The remaining loner, a mass-produced bowl (TB9), dates to the earlier LC2 phase and was not analyzed chemically. TB9 contains high-grade metamorphic rocks, likely originating either in the Zagros Mountains to the east (particularly the Zagros imbricate zone) or in the Anti-Taurus Mountains to the north (notably the Malatya metamorphic massif)



Fig. 12 Histograms illustrating, from top to bottom, the relationships between petrographic and geochemical groups and their distribution throughout the LC sequence

(Alavi 1994, 2004, 2007; Robertson et al. 2006; Bozkaya et al. 2007; Ali 2012; Ali et al. 2013, 2014). The rocks from these sources could have been eroded and transported fluvially along the western bank of the Upper Euphrates and its upland tributaries or through eastern tributaries of the Tigris.

In general, petrographic and geochemical groups are distributed throughout the LC sequence independently of morpho-functional or technological characteristics (Fig. 12). Cooking, serving, and storage vessels—whether mass-produced, shaped by hand, or formed using varying degrees of rotational kinetic energy—may share the same paste recipe. Conversely, vessels similar in form and manufacture may

differ in raw materials and paste preparation. Although clay sources remained relatively consistent over time, paste preparation modes shifted by the LC5 period, as indicated by the predominance of Group E, associated with Uruk-style vessels. These vessels also differ in their firing conditions, as shown by their sintered clay matrix, suggesting their exposure to higher temperatures. The only three Uruk-style vessels predating LC5—the LC2 band-rim bowl TB13 and the LC4-5 beveled-rim bowls TB30 and TB31—all exhibit distinct recipes shared with the coeval non-Uruk repertoire.

Conclusion

Consistent with previous studies (Eiland 2003; Minc 2014; Emberling and Minc 2016), our results indicate that most vessels found in the Late Chalcolithic levels at Tell Brak were locally manufactured. Importantly, our integrated analytical approach reveals a more nuanced picture, particularly regarding the procurement and processing of raw materials. Interestingly, these aspects of production do not correspond to variations in vessel morphology, technology, or production rates. Moreover, they remain consistent throughout the Late Chalcolithic, suggesting a strong continuity in production practices. Given the socio-economic and cultural transformations during this period, the persistence of paste recipes—regardless of vessel type or forming technique—invites interpretation beyond a simple adherence to tradition.

Accordingly, by the LC3-4, Tell Brak had evolved into an urban-scale settlement with compelling evidence of specialized production (McMahon and Oates 2007; Khalidi et al. 2009; McMahon 2009; McMahon and Stone 2013). Based on our results, we hypothesize that multiple production units operated simultaneously, each producing a variety of vessel types to meet increasing demand.¹ Tasks such as raw material procurement may have instead occurred at a broader, possibly collective, level, involving unskilled laborers beyond individual workshops. This points to a layered production system—flexible yet coordinated—capable of sustaining large-scale ceramic output within a rapidly changing socio-economic environment.

In contrast, ceramic production at Arslantepe in south-eastern Anatolia followed a different trajectory. During the initial LC2 phase, ceramics recovered from domestic contexts were made using heterogeneous recipes. As social complexity increased in subsequent phases, more standardized recipes emerged, showing a clear correlation with vessel attributes—whether morpho-functional or technological (Fragnoletti and Palmieri 2017; Fragnoli 2021). Unlike the

¹ Previous studies have highlighted the role of Tell Brak as exporter within Upper Mesopotamia (Minc 2014; Emberling and Minc 2016).

urbanizing Tell Brak, where ceramic production appears to have been more centralized, Arslantepe ceramics might have been produced through more fragmented and less coordinated systems, potentially tailored to meet diverse social or economic demands.

At Tell Brak, the LC5 or Late Uruk period marks the only notable shift in ceramic production, specifically for vessels of Uruk typology. These were predominantly produced locally using distinct recipes and firing temperatures, with only a very limited number imported over long distances. Although rejecting a simplistic and dichotomous model of the Uruk phenomenon, we assume that Uruk ceramics were not imitated by local communities but were more likely produced by groups of southern origin (Baldi 2022). Despite being differently involved in the Uruk phenomenon, similar patterns have been observed at Arslantepe and in the Qara Dagħ region of Iraqi Kurdistan, where Uruk-type pottery was also produced using distinct materials and techniques (Baldi 2022; Fragnoli and Frangipane 2022). In contrast, at the small and rather peripheral settlement of Gurga Chya in Iraqi Kurdistan, Uruk-type pottery was crafted with materials and techniques firmly rooted in earlier local traditions (Lewis et al. 2020). Recent FTIR analyses of LC assemblages from the same sites, however, reveal shifts in firing practices associated with the emergence of the Uruk phenomenon—specifically, the use of slow and relatively low-temperature firings (Lewis 2025). Meanwhile, in the Upper Mesopotamian context of Tell Brak, this phenomenon appears tied to short-duration, high-temperature firings. This is suggested by the occurrence of dark cores and sintered matrices, though further analysis is needed to confirm this pattern. The introduction of new production practices associated with the Uruk phenomenon reflects different scales of migration and integration into local production systems (Lightfoot and Martinez 1995; Graves-Brown et al. 1996). A larger presence of southern communities, as at Tell Brak, may have led to the establishment of autonomous pottery-working groups retaining their own technological traditions throughout the *chaîne opératoire*. In contrast, where these communities were smaller, as at sites like Gurga Chya, integration was more pronounced, with core practices showing continuity with earlier local traditions.

The appearance of imported vessels by the LC5, though limited, underscores increasing integration into broader trade networks of the Tell Brak community. These imports are linked to several locations along the Upper and Lower Euphrates and Tigris, though not the Upper Khabor. As previously suggested (Minc 2014; Emberling and Minc 2016), the imported vessels were predominantly jars, which may have been used to transport specific contents.

Our diachronic analysis at Tell Brak reveals that shaping techniques shifted more drastically with urbanization,

while paste recipes were primarily influenced by the arrival of new groups from the south. During the LC2 period, associated with urbanization, paste recipes remained unchanged, but shaping techniques evolved with the introduction of molding. This likely reflects efforts to meet the increased demands of a growing population. In contrast, during the LC5 period, which coincides with a possible full establishment of Uruk-related groups or at least with the presence of a totally Uruk-style ceramic repertoire, new paste recipes were introduced. Forming techniques, conversely, showed continuity with earlier practices, remaining dominated by wheel-coiling. These findings align with Gosselain's assumptions (2000) that those technical procedures that leave no visible traces on finished artifacts—such as paste preparation—tend to be more resistant to change and reflect enduring aspects of social identity and technological style. Among these “invisible” practices, the exploitation of clay sources appears to be particularly stable at Tell Brak, as evidenced by the consistent presence of the two NAA groups throughout the LC sequence. Conversely, shaping and decorating techniques—being more visible and contextually adaptive—proved more susceptible to shifts in response to changing social and economic conditions. These patterns at Tell Brak suggest that technological choices were deeply embedded in cultural traditions, while also responding to external pressures and innovations brought by urban growth and human mobility.

Finally, our study also underscores the importance of integrating chemical and petrographic data for defining ceramic reference groups in Upper and Lower Mesopotamia. The region's extent and complex hydrology distribute diverse geological materials over large distances, complicating provenance research. Limited geological research outside petroleum exploration adds to this challenge. Nonetheless, our combined approach identified key trace elements and minerals that distinguish local from non-local products. Ceramic petrography also revealed shifts in local practices associated with the Uruk phenomenon—changes that may be invisible in other steps of the *chaîne opératoire*.

In summary, our findings are an important step forward in understanding early urbanism and craft organization. The case of Tell Brak demonstrates that urbanization did not necessarily require the standardization of production practices. Instead, technological traditions could persist across millennia, while production systems adapt structurally to meet the growing demands of a large population. Urban complexity, in this context, was not built on uniformity, but on the flexible integration of diverse practices. Migration events, depending on their scale, shaped production practices to varying degrees, from subtle adjustments to fundamental changes across the *chaîne opératoire*.

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Authors contributions P.F. was responsible for funding acquisition, conceptualization, sampling, formal analysis (ceramic technology and petrography), analysis interpretation, and writing the original draft. J.H.S. performed trace element analyses and elaborated trace element data. R.C. contributed to ceramic petrography work under the guidance of P.F., as part of her training. F.B.R. assisted in sample selection and provided archaeological insights on the contexts, materials, and results. All authors reviewed and edited both the original and final drafts.

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Code availability Not applicable.

Declarations

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Consent to participate All the authors read, reviewed, edited, and approved the manuscript.

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