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RESEARCH

Tracing household economies and food technologies in the Eastern Pyrenees: grinding at Late Iron Age of El Castellot de Bolvir (La Cerdanya, Spain)

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Abstract
This study presents a pilot systematic analysis of rotative grinding stones from the highland site of El Castellot de Bolvir (La Cerdanya, eastern Pyrenees), occupied continuously from the Late Bronze Age to the Roman Republican period. Focusing on the transitional phase between the Late Iron Age and early Roman influence (3rd–2nd centuries BCE), the research combines typological and microbotanical (phytolith) records to investigate domestic food production strategies and the role of grinding technologies. The assemblage reveals a standardized and specialized use of granite rotative grinding stones (namely *catilli* and *metae*), indicative of cereal processing practices. Phytolith results indicate the nature of the processed matter, including hulled barley, free-threshing wheat, and broomcorn millet, consistent with macrobotanical records at the site suggesting broader regional patterns of intensified agriculture and technological adaptation. This work fills a critical gap in Pyrenean archaeobotanical and technological studies and contributes to a more nuanced understanding of household economies and food technologies during a critical period of socio-political transformations driven by Romanization in northeastern Iberia.

Keywords Eastern Pyrenees · El Castellot de Bolvir · Late Iron Age · Grinding stones · Cereal processing · Phytoliths

Introduction

This paper focuses on food production strategies and grinding stone use at the Late Iron Age and Roman Republican site of El Castellot de Bolvir, located in the high mountain valley of La Cerdanya, in the eastern Pyrenees (Catalonia, northeastern Iberian Peninsula). According to stratigraphic, radiometric, and archaeological evidence, the settlement was continuously occupied by indigenous *Cerretani* communities at the Late Bronze Age through the Iberian period and into the Roman Republican era (Morera 2017); Morera et al. 2016, 2020; Olesti et al. 2023; Oller et al. 2018). El

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Castellot constitutes one of the most prominent *oppida* in the region, characterized by a long occupational sequence and its strategic topographical position on the top of a hill in the main terrestrial route crossing La Cerdanya valley and the river Segre (Fig. 1). Since 2006, archaeological investigations led by the Universitat Autònoma de Barcelona have uncovered a large, fortified settlement featuring complex defensive architecture, spatially organized domestic units, and activity areas related to food production, metallurgy, and storage.

The Iberian Iron Age occupational phase at the site, beginning in the first half of the 4th century BCE, shows a substantial reorganization of the settlement, including the construction of stone-built walls and radial domestic units (Fig. 2). During the middle 2nd century BCE, Roman influence introduced major transformations at the site, such as the development of monumental buildings and metallurgical installations (Morera 2017); Morera et al. 2016; Olesti et al. 2017). This transitional phase illustrates the coexistence of indigenous practices and Romanized architectural and productive models, reflecting broader socio-political dynamics in northeastern Iberia more widely. Economic strategies in this transitional occupation phase at the site were based on mixed agriculture and animal husbandry. Storage underground silos and rotative grinding stones, along with macrobotanical evidence from charred seeds, point to increased agricultural production. In particular, the macrobotanical records point towards a crop production based on hulled barley (*Hordeum vulgare*) and free-threshing cereals including wheat (*Triticum aestivum/durum/turgidum*), in addition to broomcorn millet (*Panicum miliaceum*) in the transitional period between the 3rd and 2nd centuries BCE, along with legumes such as peas and beans (Berrocal-Barberà 2021). The archaeofaunal records highlight an emphasis on cattle breeding, differing from ovicaprid-dominant regimes in the research region, thus suggesting adaptation to alpine

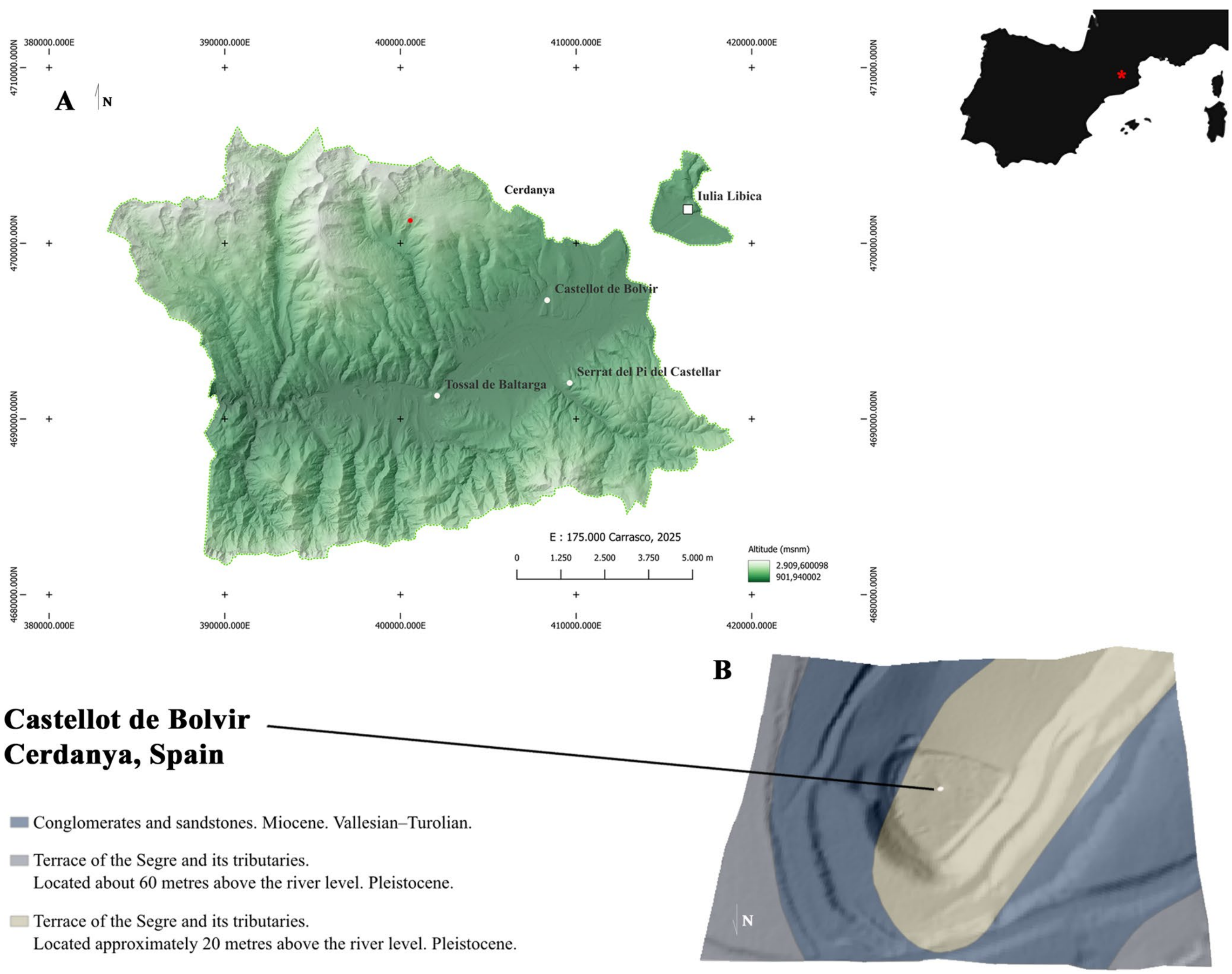

Fig. 1 (**A**) Location of El Castellot de Bolvir within La Cerdanya region (northeastern Spain); (**B**) Geological map of the site and its immediate surroundings (author: J.M. Carrasco)

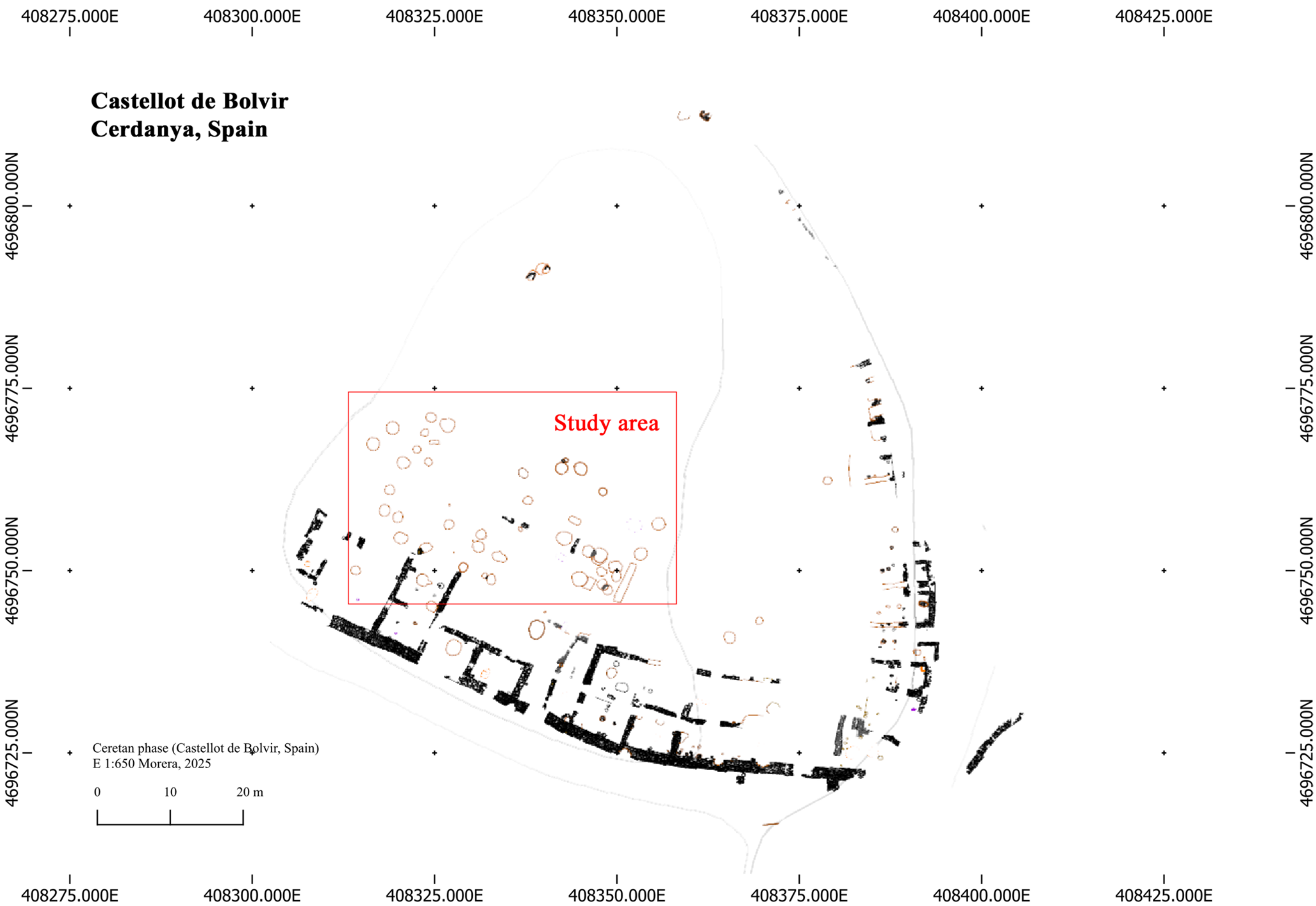

Fig. 2 Georeferenced plan of the Iberian Iron Age occupational phase (author: J. Morera)

pastures for traction and dairy production (Colominas 2017; Colominas et al. 2020).

The focus of the current study is the integrated typological and functional analyses of rotative grinding stones. It constitutes a pioneering case-study to the understanding of macrolithic tool function and plant processing practices within Pyrenean highland archaeological contexts. By combining macroscopic observations and phytolith evidence, this research aims to better understanding of food production technologies and assess the role of grindingstone tools within household productive activities. The research reported upon here is intended to provide new perspectives on technological organization of food production at the site.

Rotative grinding stone tools

Functional studies of grinding stone tools are fundamental for reconstructing food processing strategies and technological systems. Over the last decades, technological and use-wear analyses, have proved to be critical to identifying the specific uses of grinding tools and their role in food production and domestic organization (e.g. Adams 1989; Dubreuil 2004; Hamon 2022). Furthermore, traditional analyses based solely on macroscopic observations have evolved into more integrated approaches combining different scales and methodologies, including optical and confocal microscopy, texture analysis, 3D rugosimetry and GIS modeling, as well as microbotanical remains, primarily phytoliths and starch grains (e.g. Piperno et al. 2004; Cristiani and Zupancich 2021; Hamon et al. 2021; Paixão et al. 2021). Many of these studies build up on ethnoarchaeological or experimental records using replica querns (or grinding slabs) and handstones (or grinders) to better understand plant-processing activities in early agricultural systems and the developments of farming communities (e.g. Hamon 2008; Bofill et al. 2013, 2020; Portillo et al. 2013, 2017; Alonso 2014). However, limited attention has received in the literature rotative grinding stones, despite its critical importance representing a technological innovation widely attested in northeastern Iberia from the second half of the first millennium BCE onwards (Alonso 1999, 2002; Portillo 2006; Alonso et al. 2023).

Although the limited availability of systematic technological and functional studies of grinding stones in the research region in northeastern Iberia, the co-existence of querns, handstones and grinders in addition to rotative cylindrical tools, as well as the co-existence of different motions (mainly reciprocal or back-and-forth, circular, full rotary motion or semi-rotational), has been widely attested through the first millennium BCE. Interestingly, manual cylindrical types consisting of active (*catillus*) and a passive (*meta*) grinding stones (Fig. 3), corresponding to Cato's *molas hispanienses* (De Agricultura 10.4) were common, while the *mola asinaria*, driven by animals or slaves, remain completely absent in transitional Late Iron Age (Iberian) and Republican contexts in northeastern Iberia (Alonso 1996a, 1999, 2002; Équipe d'Alorda Park 2002; Portillo 2006, 2008). The morphological features of these rotative stones may vary depending on several factors, such as the inclination of the grinding surface, the thickness and diameter of the tools, the morphology of their external faces, in addition to the handle system, which may determine the type of motion (Dembinska 1985; Alonso 1999). The still limited available microbotanical records from grinding stones from Iron Age contexts across the northeastern Iberian coast and the Balearic Islands point towards the grinding of cereals such as hulled barley (*Hordeum vulgare*) and free-threshing wheat (*Triticum aestivum/durum/turgidum*), which were the most common cereals grown during this period, independently of the implement's morphology (querns vs. rotative tools), although rotative tools were completely absent in the Balearic Islands (Portillo 2006, 2008; Portillo and Albert 2014; Portillo et al. 2014a).

In view of these earlier studies on grinding systems in the northeastern Iberian region, the current research at El Castellot de Bolvir expands the typological and functional records to grinding tools from a Pyrenean highland site. The focus is on rotative grinding systems at this key settlement site in the study area, in an effort to gain a better understanding of household economies and food technologies in transitional Late Iron Age–early Roman highland contexts.

Materials and methods

A selection of seventeen rotative grinding tools recovered from different archaeological excavation seasons at El Castellot de Bolvir, currently stored at the Espai Ceretània in Bolvir, were subjected to a combined typological and functional study. All the selected materials were recorded

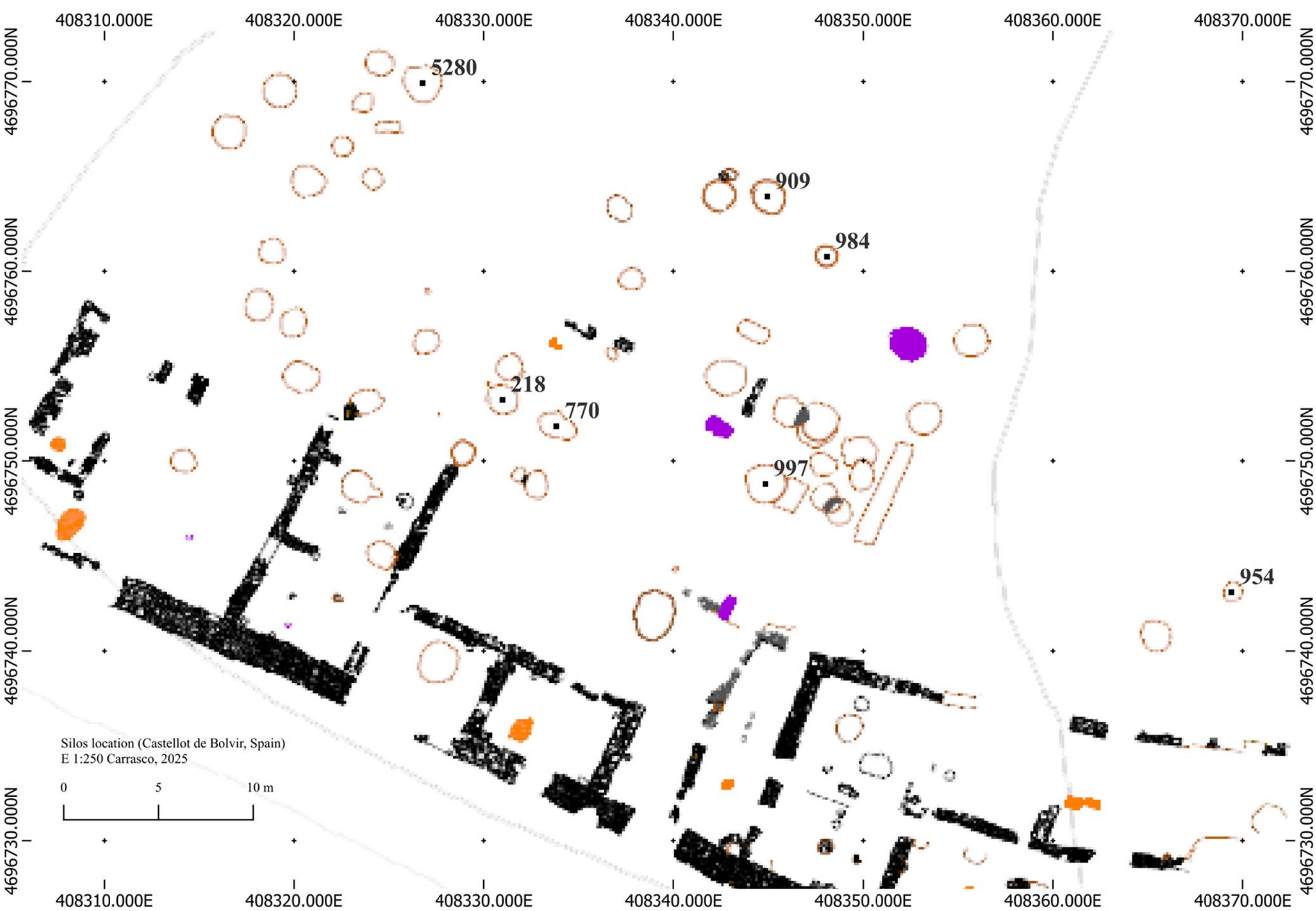

Fig. 3 Georeferenced distribution of the studied rotative grinding stones. The numbers refer to the stratigraphic units in which the grinding stones were found (author: Carrasco, based on data by J. Morera)

in secondary fillings from underground silos located in an open area at the site associated to domestic units, pointing to agricultural production in the transitional period between the 3rd and 2nd centuries BCE (Fig. 4). The main objectives of the current study were: (1) to characterize the recorded rotative grinding tools according to standard criteria of typological and technological analysis, such as morphology, dimensions shaping characteristics, and raw material; (2) to expand the phytolith record derived from rotative grinding stone use; and (3) to contribute to a broader understanding of food processing technologies during the Late Iberian Iron Age to early Roman transition at the site.

Firstly, rotative grinding stones were recorded through standard criteria of technological parameters, including morphology, metric and shaping attributes, and raw material (Portillo 2006). These macroscopic records were followed by typological analyses ($n=17$ grinding stones) based on the standard literature (Py 1992; Équipe d'Alorda Park 2002), previously applied in Iron Age sites across northeastern Iberia (Alonso 1999; Portillo 2006, 2008).

Further, thirty-four sediment samples were selected for phytolith analyses. Phytolith samples were obtained by pipetting and brushing with distilled water the grinding stone active surfaces (grinding stone samples $n=17$), as well as either by brushing their non-active surfaces or by collecting sediments from filling pit deposits, serving both as reference or control samples (coded as C samples, $n=17$). Phytolith extraction and quantitative analyses followed the methods proposed by Katz et al. (2010). An aliquot of ~40 mg of sample was treated with 50 µl of 6 N HCl and 450 µl sodium polytungstate [$Na_6(H_2W_{12}O_{40})$]

Fig. 4 Rotative grinding stones from El Castellot de Bolvir stratigraphic units SU 218 (left: passive or *meta*) and SU 770/01 (right: active or *catillus* rotative tools)

at a 2.4 g/ml density, followed by dispersion with vortex, ultrasonic cleaner, and centrifugation at 5000 rpm during 5 min. A minimum of 200 phytoliths with diagnostic morphologies were examined under an Olympus BX43 optical microscope (200× and 400×). Both multicellular phytoliths (multi-celled, in anatomical connection), as well as percentages of weathered morphotypes (unidentifiable phytoliths because of pitting and etching), widely used as indicators of the state of preservation of phytolith assemblages, were also recorded (Portillo et al. 2021). The morphological study was based on modern plant reference collections (Tsartsidou et al. 2007; Albert et al. 2008, 2016; Portillo et al. 2014b) and standardized nomenclature (International Code for Phytolith Nomenclature– ICPN v. 2.0, ICPT 2019). Phytolith analyses were performed at the Institució Milà i Fontanals (IMF), Spanish National Research Council (CSIC) in Barcelona.

Results

Morphological and typological study

The rotative grinding stone *apparatus* from El Castellot de Bolvir belongs to different archaeological excavation seasons ($n=17$ grinding tools), including both active tools namely in ancient literary sources *catilli* ($n=13$) and passive or *metae* stones ($n=4$). The use of *meta* (for the passive voice) and *catillus* (for the active voice) is a convention, and the use of these terms, in Latin, does not in itself indicate a Roman chronology. According to the applied typological classification system (Équipe d'Alorda Park 2002, based in Py 1992) (Table 1), the majority of the *catilli* studied could not be securely classified as type C1 or C2 due to their fragmentary state of preservation, as seven of the total number of studied tools ($n=13$) fall into this indeterminate category (Table 2). Among these, four of the examined *catilli* exhibit a grinding surface with an inclination degree greater than 10°, corresponding to type C2, while only two present an inclination degree of less than 10°, consistent with type C1.

The second criterion applied in the typological classification is the grinding stone thickness, a parameter also considered by Py (1992), albeit with a more detailed formulation that enhances its applicability across archaeological assemblages (Table 1). This variable is calculated using the ratio of the maximum thickness (T) to the maximum diameter (D), multiplied by 10 (T/D×10). Based on this index, three robustness categories are defined, distinguishing between *metae* (thin ≤ 2.5 cm; medium between 2.5 and 3.5 cm, and thick ≥ 3.5 cm) and *Catilli* (thin < 3 cm; medium between 3 and 3.3 cm, and thick ≥ 3.3 cm) (Table 1). All the examined *metae* fall within the medium (M-b) and thick (M-c) subtypes, whereas the *Catilli*, were classified as subtype C-a

Table 1 Typological table of rotative grinding stones from El Castellot de Bolvir, adapted from Équipe d'Alorda Park 2002 (author: J.M. Carrasco)

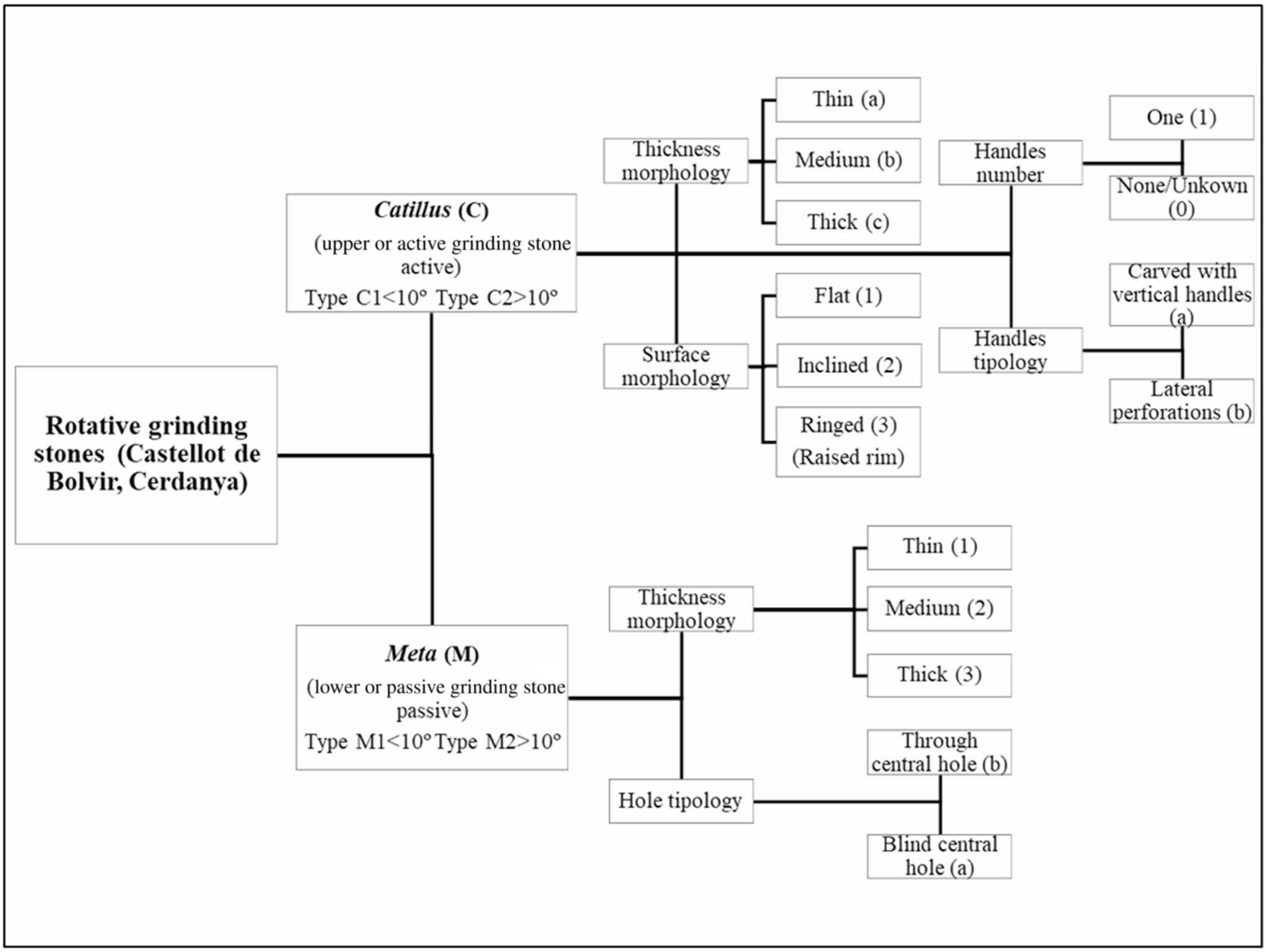

Table 2 Main morphological parameters and typology of rotative grinding stones from El Castellot de Bolvir. Passive or *metae* (M) active or *catilli* (C) rotative tools. Inclination degree (º), thickness (T, cm), maximun diameter (D, cm), radius (R, cm)

ID	SU	IND.	Datation	Typology	º	T (cm)	D (cm)	*R* (cm)
1	770	1	3rd century BCE	C1-a2	6	8	33,2	16,6
2	770	2	3rd century BCE	C2-a2	12	7,7	29	14,5
3	770	3	3rd century BCE	C-a2-1b	-	7,4	40,6	20,3
4	770	4	3rd century BCE	C-a2	-	10	38,6	19,3
5	770	5	3rd century BCE	C-2	-	6,7	-	-
6	770	6	3rd century BCE	C-2	-	10	-	-
7	909	1	4th –3rd centuries BCE	C1-a2-1a	9	5,3	45,6	22,8
8	909	2	4th –3rd centuries BCE	C	-	-	-	-
9	909	3	4th –3rd centuries BCE	C2-a2	12	6,1	38,4	19,2
10	954	1	2nd century BCE	C2-b2-1b	10	10	31,8	15,9
11	998	1	2nd century BCE	C-a1-1b	-	7	32	16
12	5280	1	2nd century BCE	C-1	-	5,9	-	-
13	5280	2	2nd century BCE	C2-c1	13	12,5	35	17,5
14	218	1	3rd century BCE	M2-3a	13	15,1	42,8	21,4
15	934	1	4th –3rd centuries BCE	M2-3a	14	18,3	43	21,5
16	998	2	2nd century BCE	M2-2a	13	15,6	49	24,5
17	998	3	2nd century BCE	M1-2a	7	14,1	43,4	21,7

(thin, $n=7$), C-b (medium, $n=1$), and C-c (thick, $n=1$) (Table 2). However, the absence of complete grinding stones at the site prevents the establishment of direct correlations between the subtypes of active and passive elements. Although this criterion has certain limitations, since dimensions may vary between sites, it remains a useful tool for formulating hypotheses about the functionality and mobility of grinding stones. In particular, the *metae* thickness may be related to the degree of fixation and whether the stone was integrated into a fixed installation or may suggest greater mobility in a less structured domestic environment (Alonso 1999).

The third criterion used to analyze *metae* is the characteristics of the central hole, which is classified as either non-perforating (subtype 1) or perforating (subtype 2, Table 1).

Table 3 Description of samples and main quantitative phytolith results obtained from rotative grinding stones (C = control samples)

Sample number	Phytoliths 1 g of sediment	Phytoliths weathering (%)	Multi-celled phytoliths (%)	Sample type/ Description
998-s1	170.000	12.5	0	C
998-s1	220.000	11.1	3.2	Grinding stone
998-s2	170.000	8.5	6.4	C
998-s2	300.000	6.4	3.2	Grinding stone
998-s3	170.000	4.9	0	C
998-s3	300.000	18.5	3.7	Grinding stone
954-s1	190.000	0	3.6	C
954-s1	200.000	5.7	13.2	Grinding stone
770-s1	250.000	8.9	0	C
770-s1	310.000	19.2	0	Grinding stone
770-s2	160.000	2.3	0	C
770-s2	160.000	16.3	4.1	Grinding stone
770-s3	160.000	2.2	0	C
770-s3	200.000	4	2	Grinding stone
770-s4	200.000	2	0	C
770-s4	240.000	13.6	5.1	Grinding stone
770-s5	210.000	8.2	0	C
770-s5	160.000	20.4	0	Grinding stone
770-s6	400.000	3	2	C
770-s6	670.000	5.4	1.6	Grinding stone
934-s1	220.000	0	1.8	C
934-s1	260.000	5.8	0	Grinding stone
909-s1	230.000	3.4	0	C
909-s1	320.000	17.5	0	Grinding stone
909-s2	280.000	1.2	1.2	C
909-s2	250.000	5.6	8.5	Grinding stone
909-s3	450.000	0.9	0.9	C
909-s3	480.000	2.1	3.5	Grinding stone
218-s1	320.000	21.1	0	C
218-s1	370.000	52.6	0	Grinding stone
5280-s1	230.000	8.6	3.5	C
5280-s1	730.000	6.8	9.3	Grinding stone
5280-s2	360.000	7.6	0	C
5280-2	760.000	7	6	Grinding stone

This feature may indicate whether the stone was fixed or not to the ground. Nevertheless, the potential reuse, modification, or adaptation of these stones for different purposes may caution further functional interpretations. In the present study, all *metae* present non-perforating (or blind) central holes (Fig. 3), similar to the pattern observed in costal Late Iberian Iron Age sites in northeastern Iberia (Portillo 2006).

Of particular note is the morphological analysis of the *catilli*, particularly relevant to understanding their functional design. Two of the most significant are the configuration of the upper surface and the handle system. The shape of the upper surface directly influences how grain was introduced through the central hole. In the current study, three subtypes were identified: (1) flat surface, (2) raised ring, and (3) sloping surface. In this assemblage, inclined upper surfaces were the most common ($n=9$), followed by flat surfaces ($n=3$) (Supplementary Material S1). Additionally, the handle system is crucial for inferring the type of motion. This criterion includes both the number of handles and their morphology. Handles were coded according to the number of recesses (0 = no handles, 1 = one handle). This classification may serve to assess whether the motion was fully rotative or semi-rotative. Handle morphology may be vertical or take the form of lateral perforations. Due to the fragmentary condition of the studied assemblage, it was not possible to identify handle characteristics in most of the studied tools. However, handle features were observed in four *catilli*, mainly corresponding to lateral perforations, while only one related to a vertical recess (Supplementary Material S1).

Lastly, the macroscopic observation of raw materials suggests a deliberate selection in the manufacture of these tools. In particular, granite was mostly chosen thus suggesting that raw material choice was not arbitrary, but therefore based on specific technical criteria and mechanical properties for grinding processing aimed at optimizing performance and durability. The origin of these raw materials is not known yet, although the local bedrock in the vicinity of the settlement consists primarily of sedimentary and conglomerate formations (Fig. 1-B). Overall, typological analysis of the rotative grinding stones at the site suggests a remarkable degree of standardization in both morphology and raw material selection.

Phytolith assemblages

In contrast to the relative lower phytolith amounts recorded in the control sediment samples, the active tool surfaces showed in general higher concentrations of phytoliths (Table 3). Phytolith concentrations from active grinding surfaces ranged from 160,000 to 760,000 phytoliths per 1 g of sediment (Table 3). The richest samples by far belong to the active surfaces from two *catilli* (sample n. 5280-s1 and

n. 5280-s2). Interestingly, the weathering index of phytoliths does not correlate with their concentrations, therefore suggesting that the phytolith assemblages do not seem to be highly affected by depositional or post-depositional processes (weathering average ca. 3%, Table 3). Conversely, certain samples yielded multicellular phytoliths (anatomically connected), although in relatively low proportions (up to 13% of the total of counted phytoliths, sample n. 954-s1), whereas these were completely absent in many samples. Here again, the concentrations of multicelled phytoliths does not correlate with their concentrations, and there do not seem to be a clear pattern according the weathering index of phytoliths or their location at the site either.

The phytolith morphological results showed a general similarity between all grinding stone samples, dominated by monocotyledonous plants, particularly by Pooideae grasses (with an average ca. 84% of all the counted morphotypes, Fig. 5). Furthermore, the morphological study of the grass phytoliths points to diagnostic morphotypes from the inflorescences (average ca. 28% of all the grass morphotypes, Fig. 6) including elongate dendritics and epidermal appendages such as papillate (Fig. 7b), as well as from the leaves and culms (mainly bulliform flabellates and epidermal appendages such as acute bulbosus, Fig. 7c), in addition to grass silica short cells produced in both plant parts, informative into grass subfamily level as the main dominant morphotypes (average ca. 36% of all the grass morphotypes, Fig. 6). The short cell morphotypes belong mainly to Pooideae grasses (rondels and polylobates, average ca. 25%, Fig. 7a), whereas Panicoideae grasses (bilobates and crosses) were recorded although into a lesser extent (average ca. 4.5%, Fig. 7d) (Supplementary Material S2). Phytolith results are consistent with the macrobotanical records from storage underground silos, including hulled barley (*Hordeum vulgare*) and free-threshing cereals such as naked wheat (*Triticum aestivum/durum/turgidum*), in addition to broomcorn millet (*Panicum miliaceum*) dating to the transitional phase between the 3rd and 2nd centuries BC at the site (Berrocal-Barberà 2021).

Discussion

This study provides a pioneering research on Iberian Iron Age rotative grinding systems in the Pyrenean region. The study addresses a significant geographical and chronological gap in current research and contributes to a more comprehensive understanding of grinding practices in northeastern Iberia. Moreover, it complements and extends the results of previous typological and archaeobotanical studies conducted in a number of coastal northeastern Iberian sites, as well as in the western hinterland (Alonso1999; Portillo 2006, 2008; Portillo and Albert 2014), thereby offering a broader regional framework for interpreting the development and variability of grinding use during this key transitional time period.

The emergence and spread of rotative grinding systems represents a remarkable technological advancement in food

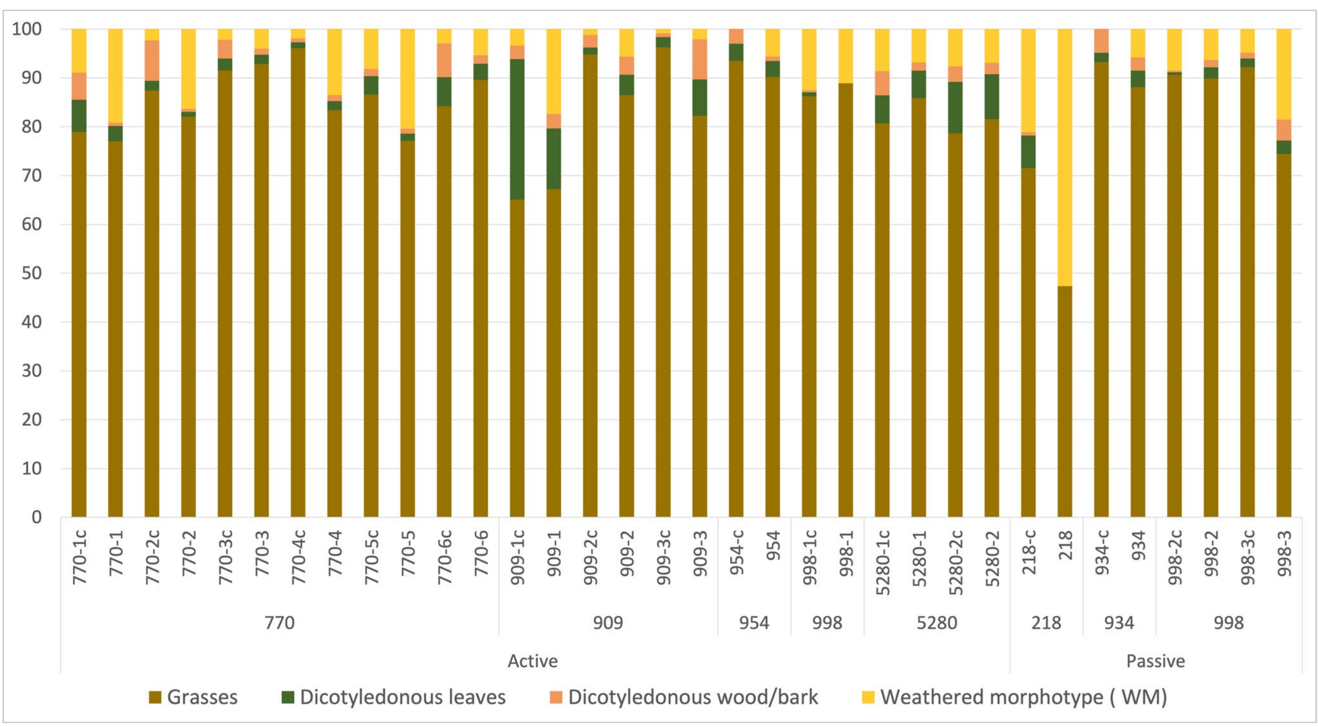

Fig. 5 Relative abundances of phytoliths obtained from the samples (%)

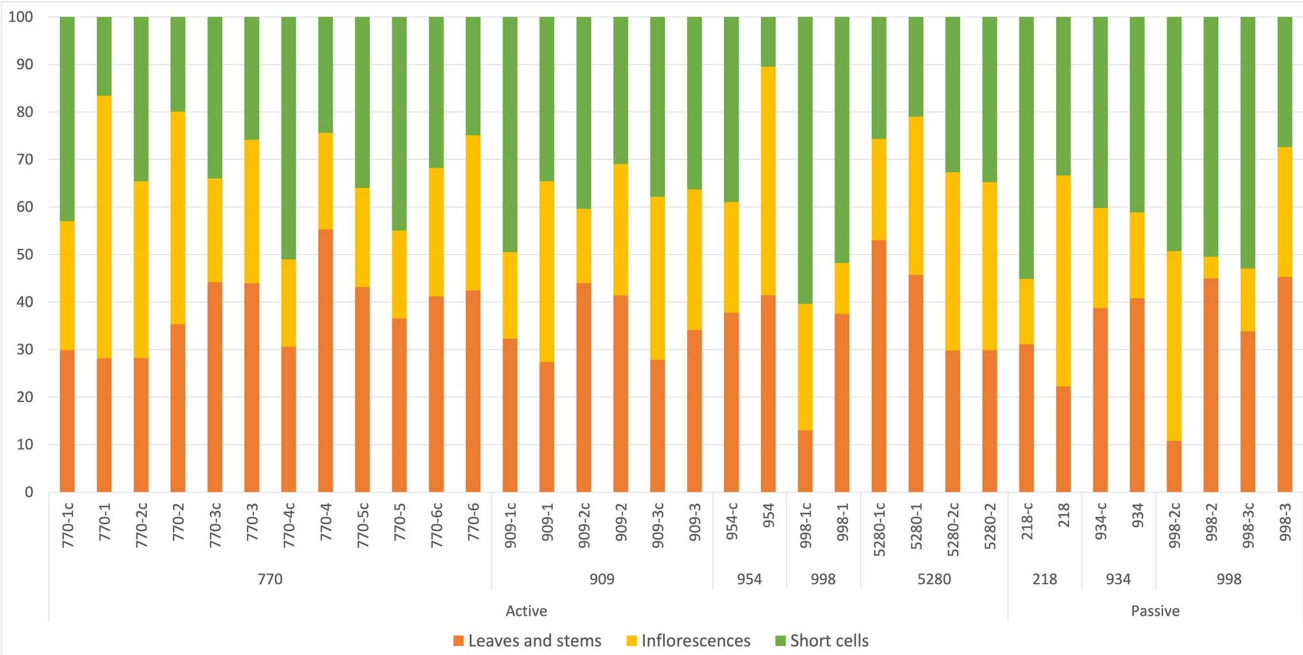

Fig. 6 Anatomical origin of grass phytoliths (%)

processing. The origins of rotative grinding tools has long been the subject of extensive research (Curwen 1937, 1941; Childe 1943; Moritz 1958); Borges 1978; Amouretti 1986, 1995; Py 1992; Morel 2001), along with comprehensive syntheses by Alonso (1996b, 1999, 2002). The earliest rotative grinding stone tools were recorded at Early Iberian settlements including Els Vilars (Arbeca, Lleida, Spain), Turó de Ca n'Oliver (Cerdanyola del Vallès, Barcelona, Spain), Alorda Park (Calafell, Tarragona, Spain) and Pech Maho (Sigean, Aude, France) (Alonso 1999; Équipe Alorda Park 2002; Portillo 2006; Longepierre 2014). Rotative grinding stones swiftly spread in the 5th-4th centuries BC across eastern Iberia and southeastern France to the Rhone Valley, further in the 3rd-2nd centuries BC throughout Iberia, northern and southern France up to the Rhone, and beyond the Alps to Central Europe (Wefers 2011; Longepierre 2014; Alonso and Pérez-Jordà 2014; Alonso et al. 2023; Vives-Ferrándiz et al. 2023). Despite a growing interest in the formal classification of these implements over the last decades, nevertheless, a standardized typology for describing these tools at a broader scale remains to be fully established.

Typological analysis of the rotative grinding stones at El Castellot de Bolvir reveals a remarkable degree of standardization in both form and raw material selection. The examined tools correspond to manual rotary grinding systems, composed of a passive (*meta*) and an active (*catillus*) elements, each exhibiting circular or slightly oval plans and showing minimal morphological variation. Particularly remmarkable is the exclusive use of granite in the manufacture of both elements—a material selected for its mechanical strength, coarse texture, and abrasive properties, which is also widespread in contemporaneous coastal Iberian sites (Portillo 2006). The choice of granite, likely sourced from local or regional outcrops, suggests an intentional exploitation of lithologies designed to enhance grinding efficiency and durability. Granite's resistance to wear and its ability to maintain a rough friction surface would have ensured the prolonged working life of these tools, making it an ideal material for intensive cereal processing. The visual and technological homogeneity observed across the assemblage reflects a deliberate technological strategy and a shared knowledge system among the inhabitants of El Castellot. Metric data reinforce this interpretation, revealing highly consistent dimensions among the grinding stones. This uniformity suggests the existence of a specialized production system, possibly embedded within broader processes of economic intensification and cereal production specialization in highland settlements of northeastern Iberia during the Late Iron Age and the early Roman Republican period. Therefore, this specialized production system based on grinding tools characterized by a clear uniformity in terms of typology and raw material provides further indication of fully established rotative grinding technology. This development represents a clear significant advance over earlier reciprocal and back-and-forth grinding systems, facilitating increased flour production efficiency and reflecting technological trends consistent with contemporaneous Late Iron Age sites across northeastern Iberia (Portillo 2006).

Beyond the morphological and typological characterization of rotative grinding systems, the current research

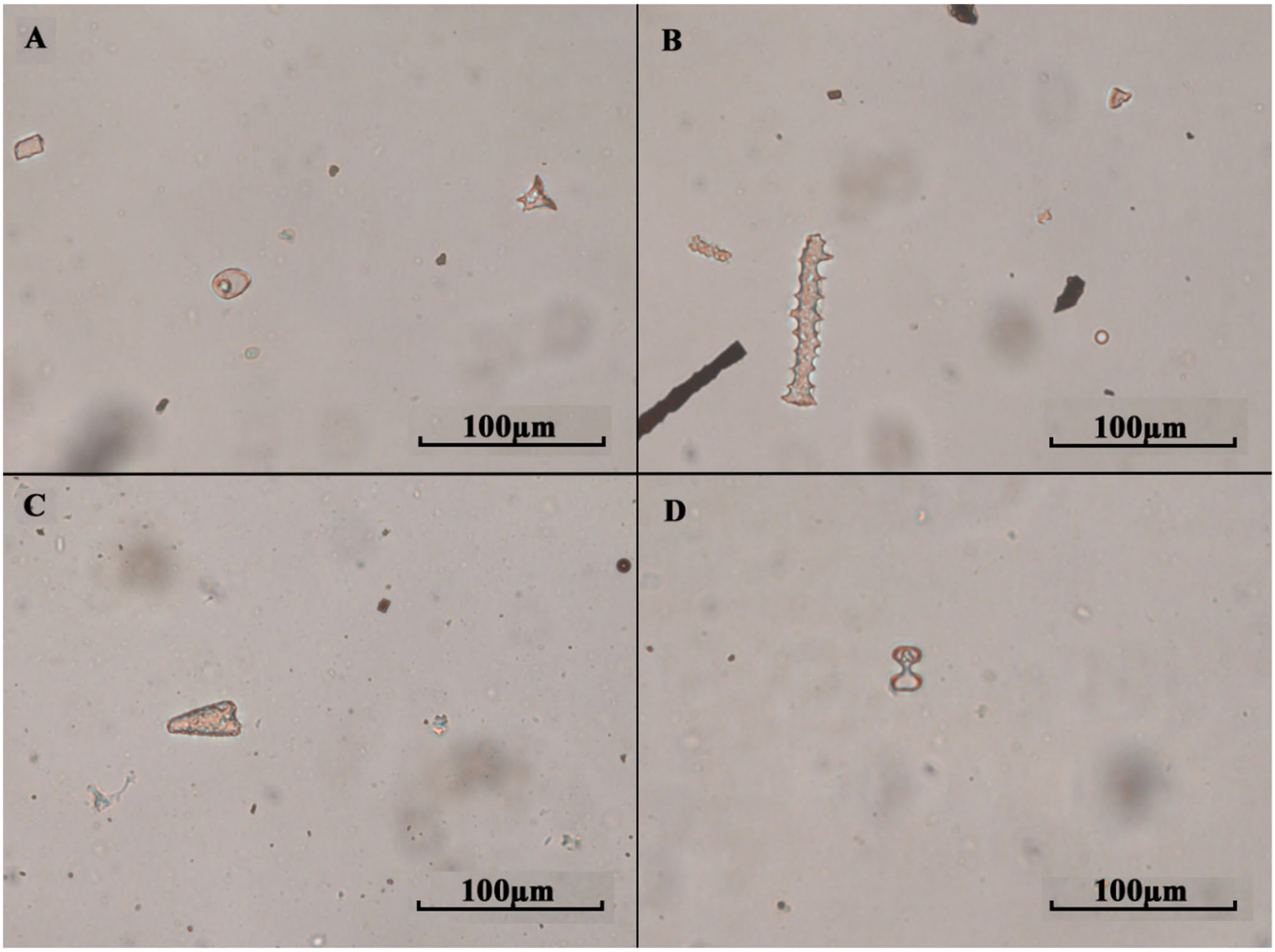

Fig. 7 Photomicrographs of phytoliths identified in the samples (200×). (**a**) grass silica short cell rondels from Pooideae grasses; (**b**) elongate dendritic from grass inflorescences; (**c**) acute bulbosus from leaves and stems of grasses; (**d**) grass silica short cell bilobate from Panicoideae grasses

integrates new direct microfossil evidence for cereal processing from a highland site in the study region. As previously argued, the weathering index of phytoliths does not overlap with their concentrations in the grinding stone samples, and the assemblages do not seem to be highly affected by post-depositional processes, pointing towards an overall good state of preservation of the phytolith records. Furthermore, the concentrations of multicellular phytoliths (anatomically connected) does not correlate with their concentrations, and there do not seem to be a clear pattern according the weathering index of phytoliths or their location at the site either, suggesting that this scarcity (and even completely absence in certain grinding stones) may relate to the rotative grinding system. A similar pattern was previously reported on contemporaneous Late Iron Age grinding stones from several sites across north-eastern Iberia (Portillo 2006). Experimental studies on the dehusking and grinding of hulled cereals (*Hordeum vulgare* and *Triticum monococcum*) obtained on replica sandstone querns and handstones (operated by reciprocal or back-and-forth motion) demonstrated that the size of multicellular or anatomically connected phytoliths decreases as a result of mechanical degradation suffered through all the processing stages (Portillo et al. 2013, 2017). Yet, one question is whether this scarcity or complete absence may relate to the rotative grinding system, as quantitative experimental research with rotative grinding stone replicas are still lacking. Despite the scarcity of multicellular forms, the presence of anatomically connected elongate dendritics from the husks and culms of Pooids, including primarily barley (*Hordeum* sp.) and wheat (*Triticum* sp.), along with the dominant grass silica short cells (mainly rondels and polylobates) from the Pooideae subfamily, in addition to bilobates from panicoids into a lesser extent (Supplementary Material S2), the overall morphological results of the current study point towards the processing of cereals. These results are consistent with macrobotanical assemblages from charred seeds at the site indicative of cereal crop production, including hulled barley (*Hordeum vulgare*)(and free-threshing cereals such as naked wheat (*Triticum aestivum/durum/turgidum*), in addition to broomcorn millet (*Panicum miliaceum*) during the transitional period between the 3rd and 2nd centuries BCE (Berrocal-Barberà 2021). This occupational phase at the site is defined by intensified agricultural practices and cereal specialization, the expansion of storage underground silos, and a remarkable degree of standardization of rotative grinding stones, in the dawn of the profound socio-political transformations associated with the progressive Romanisation of the region.

The grinding of at the site, particularly *Panicum miliaceum*, reflects broader patterns observed across the Iberian Peninsula, where millet cultivation expanded significantly during the Iron Age. Recent studies emphasize how broomcorn millet (*Panicum miliaceum*) became a major component of Iberian agricultural systems, its diffusion linked to indigenous agricultural innovation and external Mediterranean influences (Alonso and Pérez-Jordà 2023). The agronomic advantages of millet—its adaptability to poor soils, low water requirements, and rapid growth cycles—rendered it particularly suitable for diversified subsistence and intensified cereal production. Its widespread adoption at El Castellot therefore relates to a strategic response to both growing conditions and socio-political change. Further macrobotanical and phytolith evidence from broomcorn millet is also attested at nearby contemporaneous Late Iron Age Tossal de Baltarga. Particularly significant is the presence of millet (*Panicum miliaceum*) from *in situ* penning deposits associated with the articulated skeleton of a horse within a building (Colominas et al. 2023; Portillo et al. 2023; Olesti et al. 2024). The identification of diagnostic panicoid phytoliths through high-resolution micro-contextual analyses pointed towards a horse-foddering regime that was either based on or included millet as a dietary supplement. This evidence points to deliberate human intervention in animal feeding regimes, reflecting complex livestock management strategies during the Late Iron Age occupation of the site. Furthermore, the present study it highlights the contemporaneous millet's dual role as a human food crop and as a component of animal fodder.

Overall, the typological and functional study of rotative grinding tools from El Castellot demonstrate the adoption of an effective and standardized grinding technology, adapted to local geological conditions and designed to meet the demands of intensified cereal production. The current study underscores the role of technological specialization and resource optimization in the evolution of household economies in highland environments during a critical period of long-term socio-economic transformations.

Conclusions

This study provides the first integrated functional and typological analyses of rotative grinding stones from a highland Iron Age context in the eastern Pyrenees. The standardized morphology, tipology and raw material selection, primarily granite, reflect a specialized and efficient grinding technology embedded within broader domestic food economies. Phytolith evidence from grinding tool surfaces, including both active (*catilli*) and passive (*metae*) stones, point to the processing of the main cereal crops, such as hulled barley (*Hordeum vulgare*) and naked wheat (*Triticum aestivum/durum/turgidum*), in addition to broomcorn millet (*Panicum miliaceum*), which are consistent with macrobotanical assemblages at the site. Overall, rotative grinding stones and storage underground silos, together with archaeobotanical evidence from charred seeds and phytolith records, point towards increased agricultural production in the transitional period between the 3rd and 2nd centuries BCE. The shift to fully rotative grinding systems and the role of technological specialization and resource optimization in the evolution of household economies signal both innovation in highland household subsistence strategies during the Late Iron Age–early Roman transition in northeastern Iberia.

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Author contributions AG was responsible for writing – review and editing, visualization, validation, methodology, investigation, formal analysis, and data curation. MP contributed to writing – review and editing, writing – original draft, visualization, validation, supervision, software, methodology, investigation, funding acquisition, formal analysis, data curation, and conceptualization. JMC contributed to writing – review and editing, visualization, validation, typological study, investigation, formal analysis, and data curation. JM contributed to review and editing, and data curation. JO and MMP participated in data curation. OO contributed to review and editing, and data curation. All authors read and approved the final manuscript.

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Data availability All data generated or analysed during this study are included in this article. Primary and secondary sources and data supporting the findings are publicly available at the time of submission.

Code Availability Not applicable.

Declarations

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