Shared technologies for pottery and acorns processing? Multidisciplinary and functional approach to modular kilns

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ABSTRACT

This paper deals with the so-called modular kilns, ceramic structures characteristic of the Bronze and Iron Age periods in various regions of Europe. Despite the interest shown in these material forms in recent years, their exact function is still unclear. However, the dominant interpretation within archaeological research has tended to associate them with pottery production. While this hypothesis has been based mainly on macro-observations derived from settlement surveys and excavations, our aim is to go further by exploring through a material-analytical approach. A set of samples from the sites of A Fontela and Castromao, in northwestern Iberia, have been analysed using a set of methods (mineralogical, geochemical, archaeobotanical and organic chemical) to evaluate the hypotheses on production and use. Although the samples share a similar morphology and technology, the analytical results reveal differences in the manufacturing processes between the two sites studied. Local clays, crop by-products and wild plants from the surrounding areas were used in the modelling, but with different purposes. In some cases, cereal chaff was added as a temper. Organic-chemical analysis revealed traces of oils of vegetal origin, with high levels of $C_{18:1}$ fatty acid (probably mostly oleic acid) and its degradation products, together with phytosterols, such as β-sitosterol, stigmasterol, campesterol, and δ-5-avenasterol. The organic compounds are compatible with the processing or culinary transformation of acorns, that appeared persistently in hearths, pots, and storage structures during Late Prehistory in the region.

1. Introduction

The archaeology of fire is probably-one of 'the most important branches of human sciences, as many traditional technologies have relied on the use of fire' (Gheorghiu 2021). The main capacity of fire is the transformation of inorganic and organic matter, as well as the creation of symbolism and ritual practices involved in technological processes. But if the use of fire itself was a great step on a practical and symbolic level, another achievement has been equally important: its encapsulation by material structures such as kilns. In order to enhance the firing cycles by providing better control of the temperature, the

development of furnaces was a breakthrough compared to open fires. Firing is a key and variable process in the manufacture of ceramics (Gliozzo 2020) and other materials, substances –e.g., tar –, and food processing.

In 1966, Mariano García Rollán carried out an archaeological excavation at the Castromao hillfort (García Rollán 1971), reporting a cylindrical ceramic with a perforated grill at the bottom, later referred to as a "Castromao oven". Although novel at the time, the following decades saw the appearance of modular kilns at many prehistoric sites in the Iberian Northwest (e.g. Álvarez González 2019; Álvarez Núñez 1992; Currás Refojos 2014; Rey Castiñeira et al. 2013) (Fig. 1), as well as

throughout the European continent (e.g. Bocquet and Couren 1974; Coulon 2021; Gaj et al. 2016; Lagrand 1959; Lauermann 2010; Venturino Gambari et al. 2017). The chronology of the majority of these kilns corresponds to a period ranging from the end of the 2nd millennium BCE and encompassing the entire 1st millennium BCE (i.e., Venturino Gambari et al. 2017). In NW Iberia (Fig. 1), the oldest archaeological context known comes from the Late Bronze Age site of A Fontela –10th-9th centuries BCE– (Teira Brión 2019). Although modular kilns were more frequent during the Iron Age (Rey Castiñeira et al. 2013), they were also found in some Roman rural settlements (Aboal Fernández and Cobas Fernández 1999). In this region, this type of furnace is composed of an upper firing chamber – whose diameters range from 45 to 68 cm – with a perforated grill, and a lower combustion chamber of which there is little material evidence. At some sites, the domestic stone hearths inside the dwellings are used as combustion chambers (see Fernández-Posse and Sánchez-Palencia 1988; Sánchez-Palencia and Fernández-Posse 1985). Although pieces that form a chimney have been found in some European archaeological sites (Coulon 2021; Lagrand 1959), only some fragments from the Castrovite hillfort can be interpreted as such (Rey Castiñeira et al. 2013).

Although the so-called modular kilns have formal similarities with those used for pottery production (e.g. Estrela et al. 2012; García Fernández and García Vargas 2012), they are instead small portable pieces that can be generally relocated after each use. Their functionality and manufacture remain controversial, and has given rise to various proposals for their interpretation: a) oven for an artisanal or domestic production of pottery (Álvarez Núñez 1992; Bocquet and Couren 1974; Coulon 2021; García Rollán 1971), b) kitchen (Sánchez-Palencia and Fernández-Posse 1985), c) food drying (Lagrand 1959; López Cuevillas and Lorenzo Fernández 1986), d) toaster or cereal drying structure (Venturino Gambari et al. 2017), or e) linked to metallurgical production (Berrocal-Rangel et al. 2002). These interpretations have been based largely on the archaeological context and, more specifically, on related structures and materials, providing essential information for their understanding. Only few exceptions have tended to explore more analytical approaches (e.g., Coulon et al. 2019).

Another approach to unravelling kiln function is experimental archaeology. In these studies, while their use as small ceramic ovens has often been considered to be viable (Andrieux 1976; Garidel 2011; Rey Castiñeira et al. 2013; Saint-Sever and Remicourt 2009, among others), other options such as food processing has also recently been suggested (Rey Castiñeira et al. in press; Teira-Brión et al. 2014). The presence of carbonised concretions in the internal surfaces of some examples may be related to food processing, arguing that the interior would not have been exposed to high temperatures that would be necessary for the firing of pottery (Teira-Brión et al. 2014). This diversity of information produced cannot be explained by a single interpretation and suggests a multifunctional type that could have been used for ceramic production or for cooking.

Considering the aforementioned issues, this study examined a number of samples from modular clay kilns documented in two archaeological sites of NW Iberia in order to determine their technology and functionality through a multi-disciplinary approach. The objectives were, firstly, to tackle the compositional variability of the ceramic pastes as a possible indicator of provenance of the raw materials, production units, workshops, etc., and likewise address elaboration aspects, use, or post-depositional information. Secondly, to explore the firing technology in the manufacture of these kilns, particularly by specially through the determination of the maximum temperature (Kaiser and Lucius

1989) through the detection of neoformed minerals (Navarrete et al. 1991), the cooking time (Olaetxea 2000), the variability of firing temperature (Tite 1999), and the oxidizing or reducing atmospheres. Thirdly, to identify through archaeobotanical analysis plant-based evidence in the manufacture of the kilns, as well as potential interactions with other socio-economic and craft activities such as farming processing or forest management. Fourthly, to detect the main insoluble or macromolecular constituents in kiln fabric, using pyrolysis techniques – more specifically, pyrolysis–gas chromatography-mass spectrometry (Py-GC–MS)–, which can yield information on manufacturing conditions. Furthermore, thermally assisted hydrolysis and methylation (THM-GC–MS) can sometimes be used to identify plant remains and fatty acid patterns even when present as only a small fraction of the organic matter (Kaal et al. 2021; Shoda et al. 2018). This information can then be used to predict which samples could yield relevant results for "residue analysis" with the more labour-intensive GC–MS studies of lipid extracts. And fifthly, to search for non-macromolecular biomarkers, which are compounds or groups of compounds that can be associated to specific animal, plant, or bacterial resources, using GC–MS (Oliveira 2017; Oliveira et al. 2019). By determining the composition of mixtures of lipids we can assign them to specific organic residues, offering direct archaeological evidence regarding their functionality. This analytical framework aims to define the manufacturing processes, establishes possible contexts and factors that determine use, and finally proposes hypotheses about the function of modular kilns in the northwest of the Iberian Peninsula during the 1st millennium BCE.

2. Materials and analytical methods

Kiln ceramic fragments from the archaeological sites of A Fontela –Palas de Rei, Lugo, Spain– and Castromao –Celanova, Ourense, Spain– have been analysed (Fig. 1, Fig. 2). From the 10 samples from these sites (Table 1), samples of the interior of the pottery have been collected as well as, in some of them, subsamples of organic concretions and ceramic coating to determine possible origins of plant-evidence or post-depositional evidence. The mineralogy has been analysed in all ceramic samples, including the organic subsample S9-2. Evidence of plant-based remains or imprints has been observed in all fragments. The pyrolysis analysis has included samples S4, S5, S7, S8, S9 and S10, while the organic residue analysis has been carried out on samples S4, S5, S8, S9 and S10.

In order to assess any post-depositional contamination phenomena known in Castromao samples (such as incorrect manipulation or sample consolidation operations) the registers of kilns were accessed, and the curators of the Museo Arqueolóxico Provincial de Ourense were consulted. Samples S7 and S8 have been consolidated using acrylic-based products (which has precluded radiocarbon dating of charred concretions), thus the organic chemical results should be treated with caution in both samples.

A Fontela is a Late Bronze Age archaeological site whose diverse negative structures are distributed around a ditch. The site lacks housing buildings and could have been a place of social aggregation and/or with religious functions. Its abandonment is discernible by the anthropogenic fill of its ditch, in whose upper levels several combustion events took place in the 10th-9th centuries BCE (Teira Brión 2019). In addition to charcoal, lithic and fire-affected bones, abundant fragments of walls and ceramic grills (more than 300) have been recovered from inside the ditch, which may correspond to one or more kilns. From A Fontela, 4 samples have been selected from a fragment of a perforated grill (S1), a
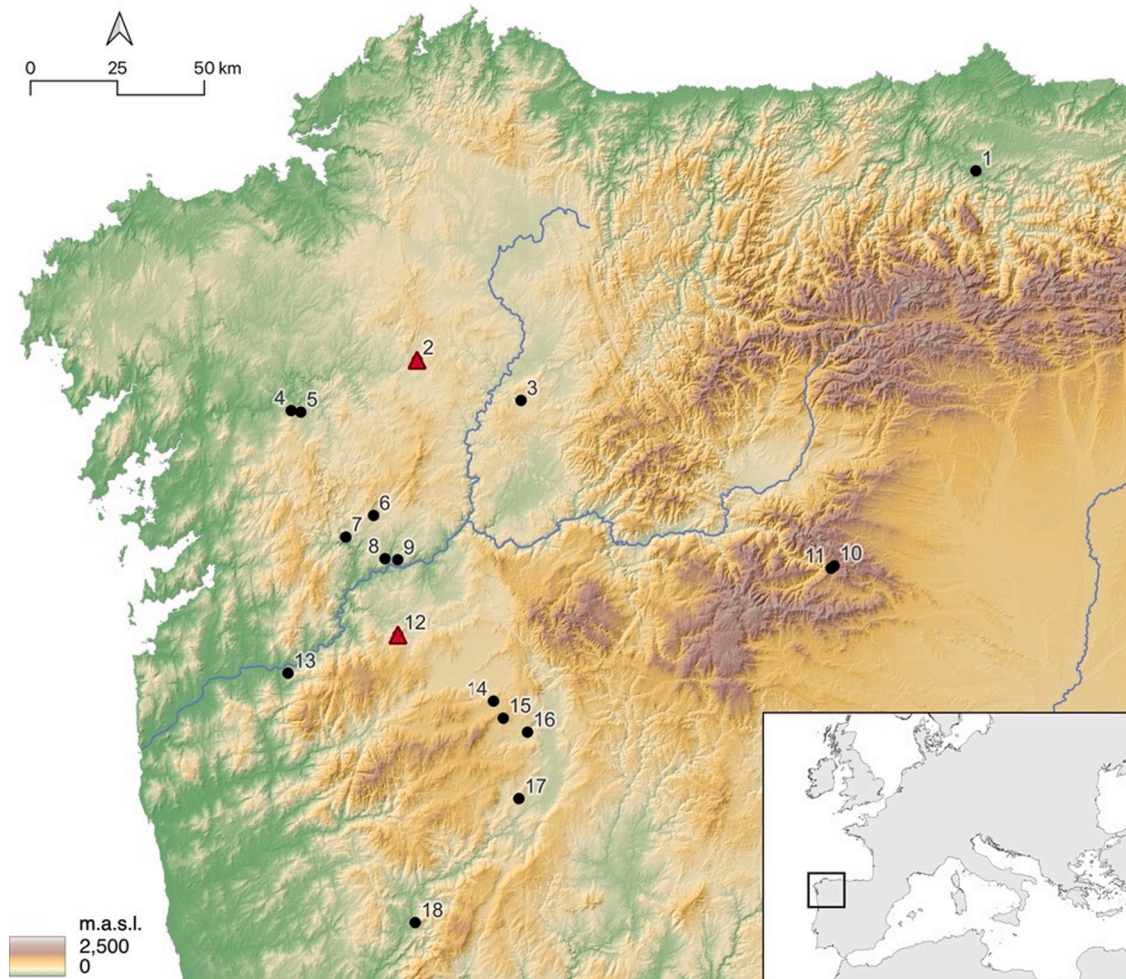
Fig. 1. Archaeological sites with modular kilns: 1) Llagú, 2) A Fontela, 3) Barán, 4) Castrovite, 5) Piñeiro, 6) Coto do Mosteiro, 7) Cameixa, 8) Ourantes, 9) As Pereiras, 10) Corona de Corporales, 11) Castro de Corporales, 12) Castromao, 13) Nosa Senhora da Graça, 14) Novás, 15) Santa Marta de Lucenza, 16) Medeiros, 17) Muro da Pastoria, 18) Crastoeiro.

fragment of the transition between the base and the wall (S3), and two wall fragments (S2 and S4) from kilns (Table 1, Fig. 3.1-4). Different subsamples have been taken from the samples S1, S2 and S4 to verify the existence of possible coatings made with clays of different composition or other residues.

Castromao is a hillfort with a long occupation history, whose origin possibly dates to the end of the Bronze Age given the existence of vessels of Alpiarça tradition (see Fariña Busto 1991). However, the orography of the settlement as seen today is mainly the result of the intense modification of the hill on which it was located during the Iron Age. In Roman times the site expanded outside its walled perimeter, creating a new outer suburb. Two samples were taken from the most complete kiln found inside a household (building II) (García Rollán 1971), registered as two pieces from the same firing chamber by the Museo Arqueolóxico Provincial de Ourense: the lid (S7) and the grill (S8). However, whether both modules belong to the same structure is questionable because the location of their fire imprints and charred residues are contradictory. The chronology of the better preserved Castromao kilns has been linked to the levels of the first wall of the lower platform, for which two dates

have been obtained: 751–364 cal BC (CSIC-638:2370 ± 50) and 722–206 cal BC (CSIC-639:2330 ± 50) (Fariña Busto 1991). The other samples (S5, S6, S9 and S10) belong to grill fragments found in other locations within the fortified settlement (Table 1, Fig. 3). Samples S6, S7, S8, S9 and S10 contain visible carbonised concretions on internal surfaces. A radiocarbon date from a carbonised concretion of the sample S9 has been obtained, i.e. 732–397 cal BC (Beta-614555: 2400 ± 30 BP).

2.1. Geochemical and mineralogical analysis

The geochemistry and mineralogy of the ceramic samples were analysed to study their technology and the origin of the raw material (clays). The elemental composition was analysed using X-ray fluorescence (XRF) in finely milled (grain size < 50 μm) and slightly compacted samples. Two energy-dispersive X-ray fluorescence spectrometers with a Si (Li) detector were used. The chemical elements that were detectable were Mg, Al, Si, P, S, Cl, K, Ca, Ti, V, Cr, Ba, Mn, Fe, Ni, Cu, Zn, Ga, As, Br, Rb, Sr, Y, Zr, Nb, Pb, Th and U. Quantification of element concentrations were calibrated using certified reference materials (NIST). The
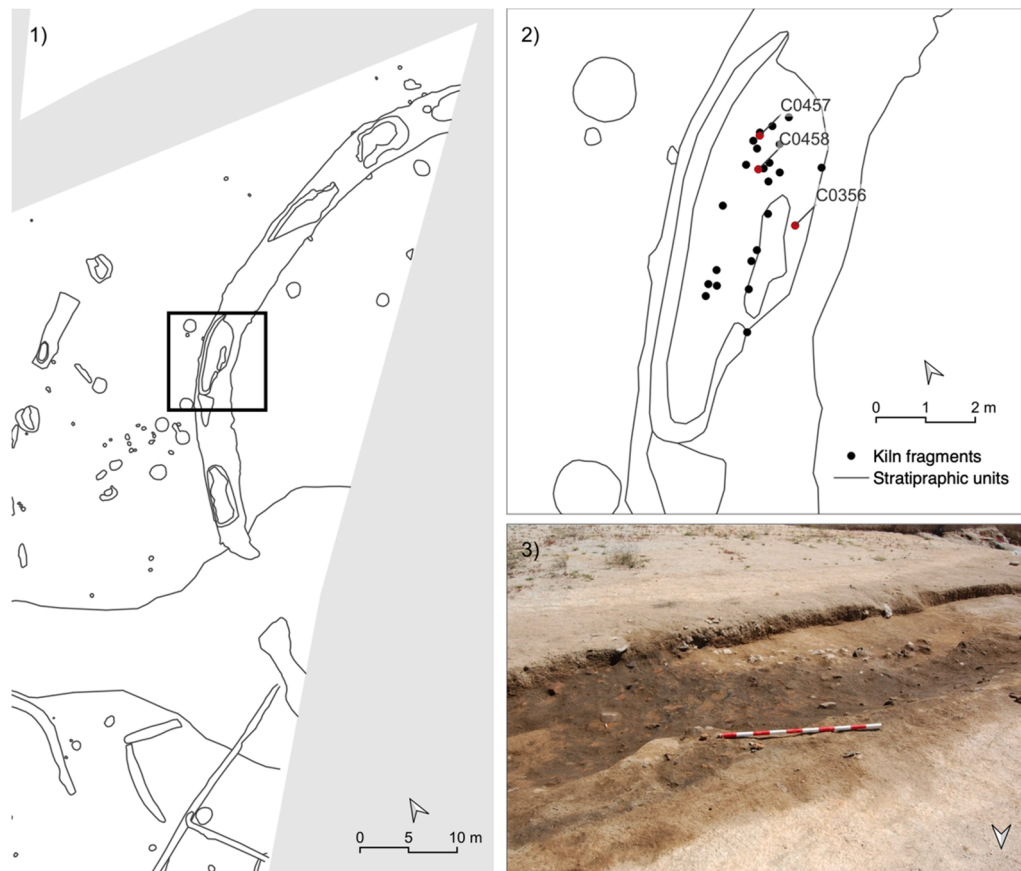
Fig. 2. The enclosure of A Fontela and the deposit where the kiln's fragments were found – analysed samples in red dots– (re-drawn from the survey plan and photos provided by Lorena Vidal Caeiro and Cristóbal Nodar Nodar). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
Samples selected and analysed from A Fontela and Castromao archaeological sites.

Sample	Archaeological site	Archaeological Reference	Part of the ceramic	Chronology	Subsample code	Subsample material	Colour
S1	A Fontela	C356	Grill	10-9th BCE	S1-1	Wide hole (down)	Brown
					S1-2	Narrow hole (up)	Brown
S2	A Fontela	C457	Wall	10-9th BCE	S2-1	Ceramic body	Brown
					S2-2	White scab	White-beige
					S2-3	Grey scab	Grey-beige
S3	A Fontela	C458-LAB01	Grill to wall	10-9th BCE	S3	Ceramic body	Brown
S4	A Fontela	C458	Wall	10-9th BCE	S4-1	Ceramic body	Black
					S4-2	Coating	Brown
S5	Castromao	CE004134-1	Grill	4th-2nd BCE	S5	Ceramic body	Black
S6	Castromao	CE004174-366	Grill	4th-2nd BCE	S6	Ceramic body	Grey-black
S7	Castromao	CE006266(A)	Grill (?) or lid (?)	4th-2nd BCE	S7	Ceramic body	Brown
S8	Castromao	CE006266(B)	Grill	4th-2nd BCE	S8-1	Ceramic body	Brown
					S8-2	Organic concretion	Black
S9	Castromao	DX0403-75(1)	Grill	4th-2nd BCE	S9-1	Ceramic body	Brown
					S9-2	Organic concretion	Black
S10	Castromao	DX0403-75(2)	Grill to wall	4th-2nd BCE	S10	Ceramic body	Grey

biophilic elements, C, N and H, were determined using a Leco TruSpec CHNS elemental macrosample (500 mg) analyser.

The mineralogy was identified using a standard crystalline powder X-ray diffractometer (XRD): a Philips PW1710 equipped with a vertical goniometer with Bragg-Brentano geometry θ/2θ, a generator with an anode Cu tube of 2.2 kW, and a graphite monochromator and proportional detector PW1711/10. Some milligrams of the sample were deposited on a zero-diffraction silicon plate (U-1.2rd, *Gem* Dugot: Dana Smith, Princeton) aiming for random orientation of crystal grains. The measurement time for each sample was 3 s/step, between 2° and 65° 2θ and a step size of 0.02°. The identification and semi-quantification were conducted on the DIFFRACplus EVA software (Bruker AXS), combined with the HighScore Plus Release: Version 3.0d (PANalytical B.V.). The Reference Intensity Ratio (RIR) was used for the semi-quantification.

2.2. Archaeobotanical analysis

The external surface and fractures of the ceramics were examined to determine the presence of any plant matter. Macroscopic remains were identified by observing the decoration of the structures and plant taxonomy using a stereoscopic microscope (Olympus SZX7) and a reflected-light microscope (Olympus CX40) from x10 to x70 and x20 to x400
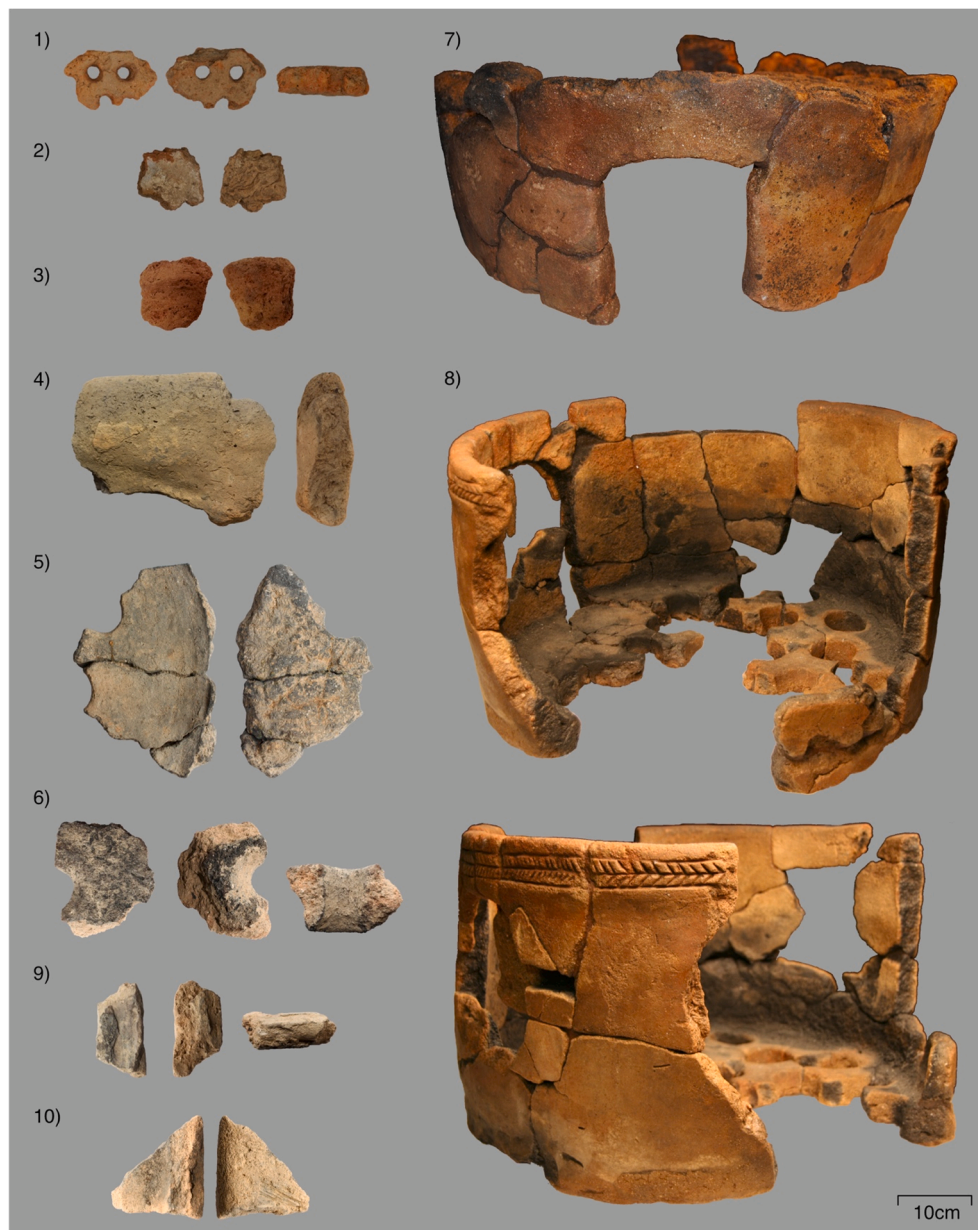
Fig. 3. Kilns analysed from A Fontela (1–4) and Castromao (5–10). The numbering corresponds to the identifier of each sample (see Table 1).

magnification respectively. Inflorescences and other plant parts were compared with specialised literature (Jacomet 2006; Neef et al. 2012; Sabato and Peña-Chocarro 2021) and with the modern and archaeological reference materials of the collection of the Archaeobotany Lab of the Universidade de Santiago de Compostela. The identification of the charred wood involved the observation of macro and micro-anatomical characteristics in the three anatomical sections of the wood (transverse, tangential and radial) (Cartwright 2015), and its comparison with reference anatomical atlases (Gale and Cutler 2000; Hather 2000; Schweingruber 1990). In parallel to the taxonomic identification of the wood, its dendrological attributes and taphonomy were also recorded (Marguerie and Hunot 2007; Théry-Parisot et al. 2010).

2.3. Py-GC–MS and THM-GC–MS

Selected samples were analysed by analytical pyrolysis techniques, i. e., pyrolysis–gas chromatography-mass spectrometry (Py-GC–MS) and thermally assisted hydrolysis and methylation-GC–MS (THM-GC–MS). The Py-GC–MS analyses aim to fingerprint all possible types of macro-molecular organic matter (OM) present in the samples. The THM-GC–MS involves the presence of a reactant (an aliquot of aqueous 25 % tetramethyl ammonium hydroxide, from Sigma) during the thermal step, which facilitates protection and detection of polar functional groups such as hydroxyls and carboxyls. The instrumentation used was a CDS Pyroprobe 5000 connected to a 5977 GC–MS system of Agilent Technologies. The pyrolysis temperature was 750 °C for Py-GC–MS and 650 °C for THM-GC–MS. This is the set-point temperature; the actual temperature is approximately 70 °C lower. The GC was equipped with a HP-5MS non-polar column and operated in 1:20 split ratio (helium carrier gas), and the MS operated in electron impact ionization mode (EI) scanning in the m/z 50–500 range. Further details are provided by Sanjurjo-Sánchez et al. (2018) for Py-GC–MS and Kaal et al. (2021) for THM-GC–MS.

Table 2
Geochemistry of the analysed ceramics of the A Fontela and Castromao archaeological sites (μg/g = ppm, d = detected, n.d. = not detected).

Sample	C	N	H	Na	Mg	Al	Si	P	S	Cl	K	Ca	Ti	V	Cr	Ba	Mn	Fe	Ni	Cu	Zn	Ga	As	Br	Rb	Sr	Y	Zr	Nb	Pb	Th	U
Units	%wt	%wt	%wt	area	%wt	%wt	%wt	μg/g	μg/g	μg/g	%wt	%wt	%wt	μg/g	μg/g	μg/g	μg/g	%wt	μg/g	μg/g	μg/g	μg/g	μg/g	μg/g	μg/g	μg/g	μg/g	μg/g	μg/g	μg/g	μg/g	μg/g
S1-1	0.29	n.d.	0.12	n.d.	1.31	9.09	20.77	60	459	n.d.	0.58	0.02	1.50	106	253	n.d.	908	6.19	116	20	84	58	17	7	118	76	31	303	16	24	31	27
S1-2	0.93	0.09	0.72	d	1.27	8.92	17.67	7998	1193	n.d.	1.84	0.71	0.67	n.d.	301	87	684	5.21	106	20	68	58	58	26	136	96	27	213	14	26	18	30
S2-1	0.43	0.04	0.65	n.d.	1.09	10.49	18.41	3397	2095	n.d.	3.68	0.13	0.14	24	31	627	826	5.47	67	16	63	55	43	14	122	106	31	243	12	22	17	28
S2-2	1.19	0.11	1.09	n.d.	0.48	12.75	16.15	12,059	2128	n.d.	1.98	1.06	0.63	15	288	313	1533	4.45	35	31	92	85	73	36	265	91	24	175	13	51	25	66
S2-3	0.98	0.09	0.92	n.d.	0.09	10.88	20.36	3639	1560	n.d.	2.57	0.40	0.34	n.d.	91	614	733	2.14	13	14	68	89	39	28	312	42	13	116	13	46	18	73
S3	0.30	0.08	0.55	n.d.	1.37	10.00	21.49	n.d.	274	n.d.	2.38	0.18	0.17	n.d.	28	213	794	4.99	95	28	85	45	35	3	169	91	26	201	15	25	19	33
S4-1	1.51	0.12	0.75	n.d.	1.02	10.07	21.07	765	1555	n.d.	1.92	0.81	0.60	98	246	625	947	4.78	98	25	97	41	34	8	150	91	23	190	14	24	17	30
S4-2	0.33	0.06	0.63	n.d.	1.21	9.83	19.13	1399	1276	n.d.	2.04	0.91	0.58	229	267	641	701	4.95	91	20	86	56	21	9	156	98	26	255	16	25	18	29
S5	1.11	0.16	0.52	n.d.	0.36	10.78	28.74	n.d.	636	n.d.	2.11	0.93	0.61	45	235	512	155	1.38	10	29	39	45	163	15	270	21	12	28	14	16	4	43
S6	1.96	0.58	0.55	n.d.	0.32	12.21	27.34	n.d.	1210	n.d.	2.97	0.11	0.03	9	n.d.	191	137	1.32	n.d.	1	47	50	6	3	275	42	16	79	13	35	8	50
S7	1.96	0.07	0.65	n.d.	0.00	10.28	32.51	n.d.	805	n.d.	3.72	0.05	0.13	12	3	288	164	1.62	n.d.	n.d.	25	53	54	5	272	56	13	72	15	34	24	51
S8	3.14	0.16	0.95	n.d.	0.35	11.62	30.57	n.d.	440	n.d.	3.20	0.21	0.10	40	22	461	171	2.25	17	111	27	46	71	4	249	35	16	89	13	35	18	42
S9-1	0.68	0.12	0.62	n.d.	0.66	11.55	24.41	n.d.	560	147	3.07	0.06	0.16	4	46	636	369	3.94	17	63	58	52	165	7	228	37	35	410	15	30	28	50
S9-2	2.02	0.29	0.64	n.d.	0.32	9.63	24.37	3838	774	31	3.14	0.05	0.41	70	28	698	426	3.50	14	49	56	42	224	7	206	35	36	204	15	23	11	51
S10	1.05	0.12	0.68	0.00	0.44	12.37	23.63	7860	607	n.d.	1.93	0.92	0.61	87	264	224	281	1.38	7	28	29	48	177	11	287	61	19	59	15	38	17	43

Table 3
Mineralogy of the analysed ceramics of the A Fontela (S1-S4) and Castromao (S5-S10) archaeological sites.

Sample	Quartz	K feldspar (microcline)	Plagioclase (albite)	Mica (muscovite)	Chlorite	Vermiculite	Kaolinite	Amphibole (tremolite)	Serpentine (antigorite)	Talc	Spinel	Cristobalite	Mullite	Diopside	Sepiolite
S1-1	57	10	10	8				8		4	4	1	4	6	
S1-2	37	14	18	18		1		6		4					
S2-1	41	16	23	10				1		2					
S2-2	47	26	7	16		1				1					
S2-3	69	13	7	6											
S3	38	6	21	18	4			4		2				2	
4-1	31	11	25	18		1	5	7	3	3					1
S4-2	50	10	14	19		1		5		1					
S5	61	6	12	21											
S6	44	13	6	23			8							6	
S7	64	9	11	15			1								
S8	59	11	10	15			5								
S9-1	55	15	3	20			6								1
S9-2	62	15	2	13			6								2
S10	47	19	17	14										3	

2.4. Organic residue analysis

Selected samples were analysed by GC–MS. Briefly, approximately 0.5 g of ceramic powder was collected from the surface of each sample and the organic residues were extracted twice in mixtures of chloroform: methanol (v:v 2:1) in an ultrasonic device. The combined extracts were centrifuged, and the supernatants dried under a gentle N_2 flow. The total lipid extract was re-dissolved in *n*-hexane, derivatised with *N,O*-bis(trimethylsilyl)trifluoroacetamide containing 1 % of trimethylchlorosilane (BSTFA + 1 % TMCS) and analysed by GC–MS. The chromatographic analyses were performed with a Shimadzu GC2010 gas chromatograph equipped with a Zebron column ZB-5HT (15 m length, 0.25 mm I.D., 0.10 μm film thickness) that was coupled to a GCMS-QP2010 Plus mass spectrometer (Manhita et al. 2020). Compound identification was based on GC–MS spectra libraries NIST17 and Wiley8, co-injection with authentic standards and analysis of fragmentation patterns.

3. Results

3.1. Geochemistry and mineralogy

Of the chemical elements analysed with XRF (see Table 2), Si, Al, Fe, K and Mg have the highest concentrations, while the other elements are minor or trace. The most important elements are Al and Si. Other elements such as Fe, Mg, Mn, and Ni are relatively abundant in the A Fontela samples because they have a predominantly ultramafic composition (Table 3). Regarding samples in which several sub-samplings were carried out, S1-1 and S1-2 (top and bottom of one A Fontela grill) have similar composition with the only difference being a P, Ca, C, N and Br enrichment at the top, probably due to calcium phosphate deposits and organic contamination. Subsamples S2-1, S2-2, and S2-3 (A Fontela wall ceramic body, white scab, and grey scab from sample S2) have similar composition with the only difference being a P, C, Ti, Cr and Mn enrichment in the white scab probably due to some calcium phosphate deposits. Cr and Mn could be minor components originated by alteration and migration from the ceramic body. Subsamples S4-1 and S4-2 (body and coating from a wall-to-grill A Fontela ceramic) have similar composition which shows that S4-2 is not really a coating, and both have the same ceramic body. Castromao kiln has a typical felsic composition in all samples with low values of transition metals and high values of potassium. Subsamples S9-1 (ceramic body) and S9-2 (organic concretion) from sample S9 have the same composition, but a high organic content (C, N, P) has been identified in subsample S9-2.

The most abundant minerals identified with XRD were quartz, K feldspars (as microcline), plagioclases (as albite or anorthite), mica (as muscovite) and amphibole (as tremolite). Talc, vermiculite, and kaolinite were also detected and occasionally chlorite, vermiculite, serpentine, and sepiolite. Four high-temperature indicator minerals such as spinel, cristobalite, mullite and diopside (Heimann 1989) were identified in one sample (Table 3, Fig. 4).

The samples from A Fontela have an ultramafic composition (with amphibole, talc and eventually serpentine) with also a granitic contribution. In sample S1, subsample S1-1 has high temperature indicator minerals and lacks vermiculite, amphibole, and talc. These last minerals, present in S1-2, probably disappeared by fusion due to temperature. In sample S2, the subsamples S2-1, S2-2 and S2-3 have a similar composition. The white–grey colour of S2-2 and S2-3 could originate from microcrystalline calcium phosphates (Ca and P were detected), but unidentified by XRD. In sample S4, S4-1 and S4-2 have similar mineralogy. The ceramics from Castromao hillfort have a granitic composition (exclusively quartz, K feldspar, plagioclase and muscovite). In this last group, little kaolinite was detected. Within the sample S-9, both subsamples S9-1 and S9-2 have the same mineralogy, but S9-2 is distinguished by its organic content.

3.2. Plant-based evidence

Stereomicroscopic observations have identified diverse plant evidence from impressions and remains preserved in the ceramics, allowing the differentiation between those produced by materials in contact with the exterior surface of the kilns, and the remains integrated into the clay. Among the first, impressions of leaves of common bracken (*Pteridium aquilinum*) on the lower part of the exterior of the grill were observed in several examples from Castromao. These impressions formed when the clay was still wet (Table 4, Figure 5.1). Sample S10 also preserves the imprint of a slab or elongated wooden object with an irregular surface (Figure 5.5).

Some plant remains have been added to the clay during manufacture. This evidence is a distinctive feature in the A Fontela kilns, where abundant cereal straw has been identified (Table 4, Fig. 5). The negative imprints of paleas, lemmas and glumes correspond to parts of the inflorescences of the tribe Triticeae. At the macroscopic level, some remains of organic matter are observed on the surface of these imprints on the clay, possibly corresponding to cereals, but due to high degradation they could not be identified. The only determination at species level is the finding of a charred spelt glume base (*Triticum spelta*) in sample S3 (Figure 5.3).

The presence of plant materials mixed with the clay is more exceptional at the Castromao hillfort. At this settlement, two fragments of mineralised plant stems have been found within the clay of sample S10. The charcoal fragment incorporated in the clay of sample S9 has been identified as deciduous *Quercus* sp. Due to the fragment size of the *Quercus* sp. charcoal (1 cm) dendrological attributes, such as the growth ring distances and curvature, could not be registered. Regarding the taphonomic features, radial cracks and vitrification have been observed. These alterations which related to the combustion process, are the most frequent that can be observed in the group of deciduous *Quercus* sp. Vitrification implies a process of fusion and homogenization of the different wood anatomical features, which can impede the identification (Théry-Parisot et al. 2010). The two fragments of charcoal analysed from sample S6 could not be determined, as they did not preserve diagnostic features. The vitrification together with the small size of the charcoal fragments from sample S6 (0.5 and 0.6 cm) prevented their identification.

3.3. Macromolecular organic constituents (Py-GC–MS and THM-GC–MS)

Using Py-GC–MS, signal intensities of most samples were very low. The main type of organic matter (OM) identified is charred residues (pyrogenic OM), represented by compounds such as benzene, toluene, dimethylbenzenes, benzonitrile and polycyclic aromatic hydrocarbons (PAHs) such as naphthalenes and biphenyl (Fig. 6). Short-chain (C_9-C_{18}) *n*-alkanes, including branched alkanes, were identified in sample S9 from Castromao. Polysaccharide and protein products were not identified. None of the samples yielded compounds that could be ascribed unambiguously to preserved plant remains (e.g., lignin products), but obviously the pyrogenic OM may be largely plant-derived. Hence, S9 contains a mixture of pyrogenic and aliphatic OM, whereas S4, S5 and S10 only contain pyrogenic OM. For S4 (A Fontela), only benzene and toluene could be identified, co-eluting with a larger peak of sulphur (S2), which probably originates from inorganic S, and illustrates the low signals obtained for OM (not shown). The results for samples S7 and S8 are not presented because the Py-GC–MS chromatograms were dominated by products of an alkyl methacrylate (marked by e.g. ethyl methacrylate monomer and multiple dimer, trimer and tetramer fragments) formed during pyrolytic fragmentation of this synthetic (co–) polymer that added during consolidation. A separately analysed black "concretion" scraped from the surface of S8 gave the same results.

We calculated benzene/toluene (B/T) and naphthalene/methyl-naphthalenes (N/C_1N) ratios as proxies of charring impact to the
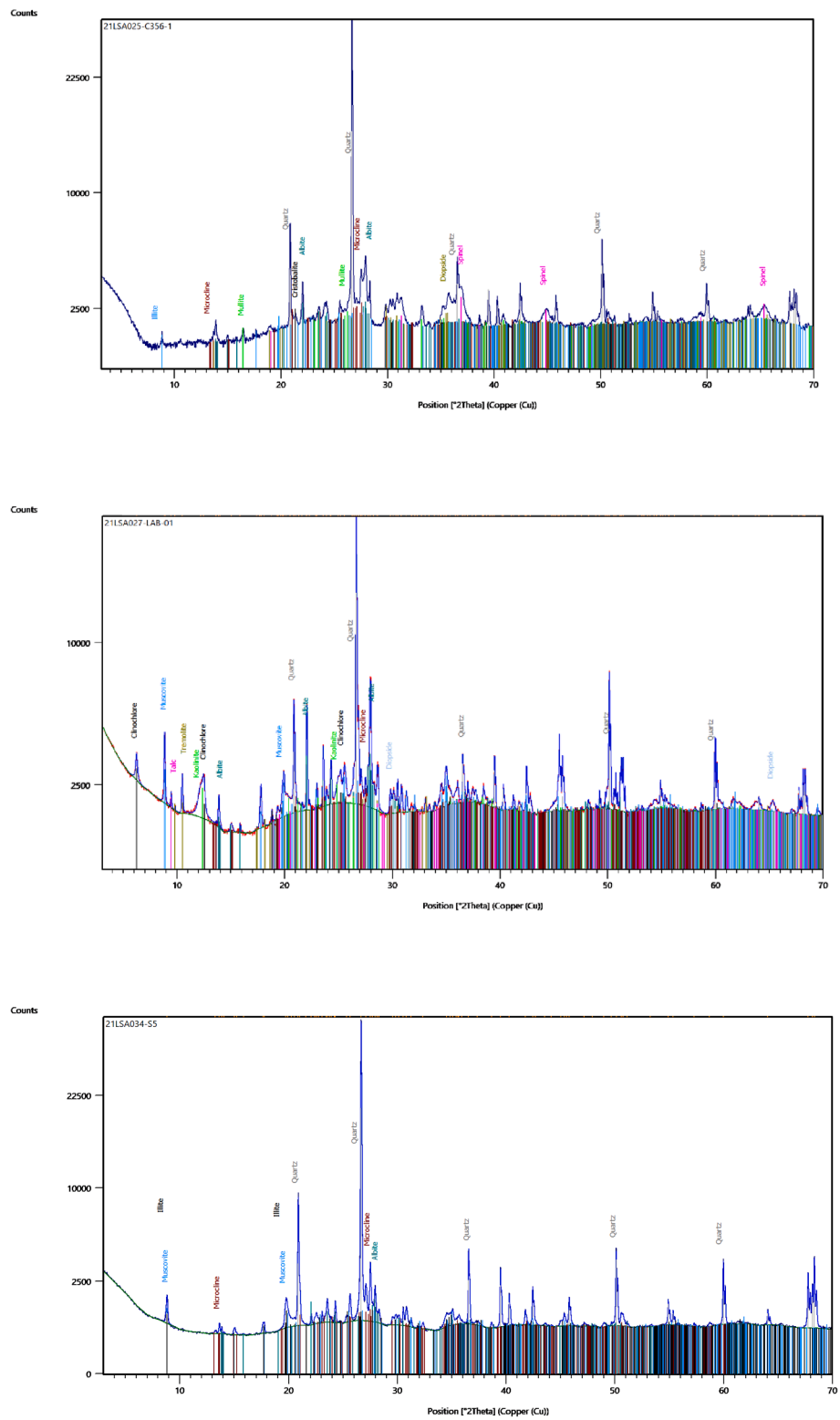
Fig. 4. Diffractograms from A Fontela subsample S1-1 (high temperature indicator minerals: spinel, mullite, cristobalite and diopside) and sample S3 (ultramafic composition: amphibole, serpentine, quartz); and from Castromao sample S5 (granitic composition: quartz, K feldspar, plagioclase, and mica).

Table 4
Results of the archaeobotanical analysis.

Sample	Site	Footprints	Charred remains	Mineralised
S1	A Fontela	Triticeae chaff		
S2	A Fontela	Triticeae chaff		
S3	A Fontela	Triticeae chaff	*Triticum spelta* (glume)	
S4	A Fontela	Triticeae chaff		
S5	Castromao	*Pteridium aquilinum* leaves		
S6	Castromao		Undetermined (2 charcoals)	Stem fragments
S7	Castromao	*Pteridium aquilinum* leaves		
S8	Castromao	*Pteridium aquilinum* leaves		
S9	Castromao		*Quercus* sp. deciduous (1 charcoal)	
S10	Castromao	Crafted wood		

pyrogenic OM (Kaal et al. 2014). Differences in the obtained values (Fig. 7) for samples S4, S5 and S9 were small, but the values for S10 are much higher. This suggests that the pyrogenic OM of sample S5 had formed at higher thermal impact conditions (i.e., higher temperature, duration or O_2 availability).

It is concluded that the Py-GC–MS results were of little value due to a combination of low OM content (all samples), a highly stable charred OM fraction that barely releases products upon pyrolysis (S10), and acrylic-based contamination (S7, S8).

Using THM-GC–MS, signals of polar moieties are more easily identified, and the pyrogenic OM is much less visible due to the solvent delay period and the absence of hydrolysable and derivatizable functional groups in polycondensed aromatic clusters.

Sample S5 gave a diverse chromatogram (Fig. 8), with a) PAHs (naphthalene, methylnaphthalenes, hydronaphthalenes, anthracene/phenanthrene) from pyrogenic OM, b) fatty acid methyl esters (FAMEs; F9, F14, F16, F18 chain length) from aliphatic OM (fatty acids), c) alkylpyrroles and alkylindoles possibly from microbial OM, d) benzenecarboxylic acid methyl esters with 2–4 carboxylic moieties probably from oxidized pyrogenic OM and e) 3,4-dimethoxybenzoic acid methyl ester (a.k.a. G6), possibly indicating lignin (plant) residues. This is the only evidence of plant lignin obtained using analytical pyrolysis. In sample S9, the signal is dominated by FAMEs (aliphatic OM),
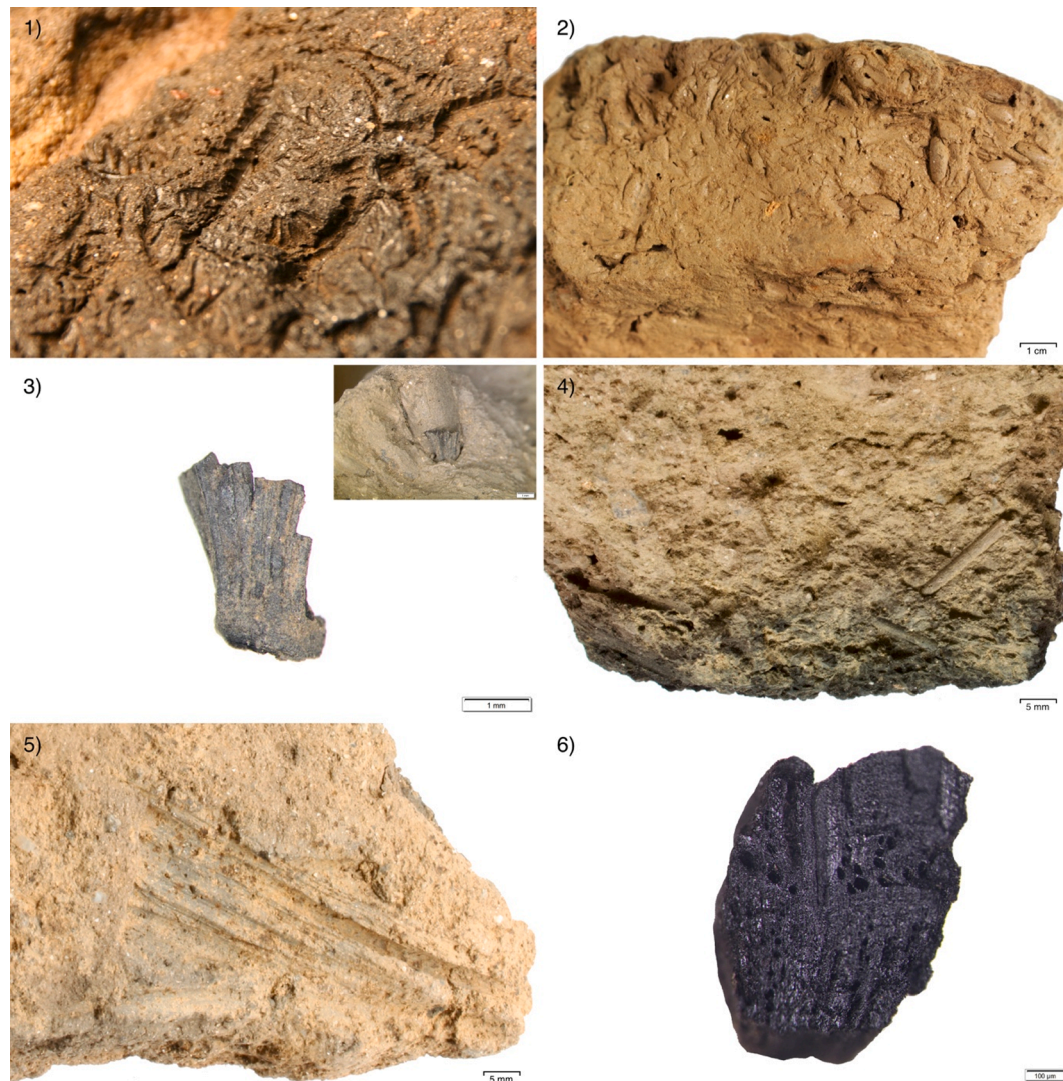

Fig. 5. Examples of evidence of plant-derived materials in the kilns), 5.1) *Pteridium aquilinum* imprints (S7), 5.2) Triticeae chaff (S3), 5.3) charred glume of *Triticum spelta* (S3), 5.4) mineralised stems (S6), 5.5) wooden slab impression, 5.6) transversal section of *Quercus* sp. deciduous charcoal (S9).
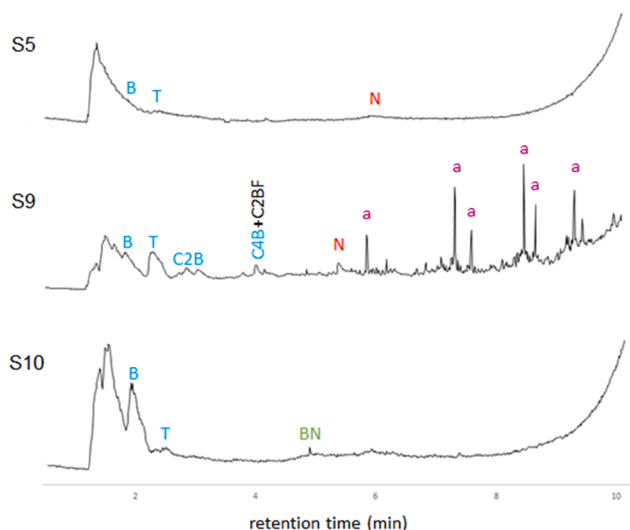
Fig. 6. Py-GC–MS total ion current chromatograms for samples from Castromao. Blue = monocyclic aromatic hydrocarbons (B = benzene, T = toluene, C2B = C_2-alkylbenzenes, C4B = C_4-alkylbenzenes). Red = polycyclic aromatic hydrocarbons (N = naphthalene). Green = nitrogen-containing compounds (BN = benzonitrile). Purple = *n*-alkane and branched alkane fragments. Black = other products (C2BF = C_2-alkylbenzofuran). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
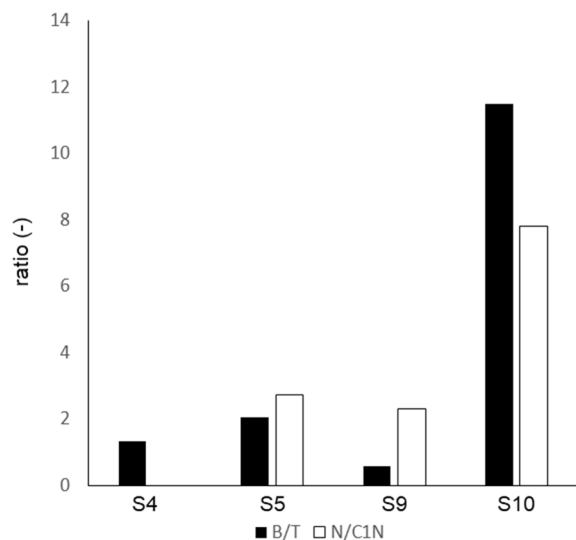
Fig. 7. Benzene to toluene ratio (B/T) and naphthalene to methylnapthalenes ratio (N/C_1N) from Py-GC–MS. For sample S4, intensities of naphthalenes (N/C_1N) could not be determined.

accompanied with some oxidized pyrogenic OM and PAHs, confirming the prevalence of aliphatic and pyrogenic OM. Sample S10 gave a very weak signal, with traces of FAMEs, but at such low yields many kinds of contamination can give rise to these peaks (instrument and operator oils and grease). Finally, sample S4 (not shown) did not produce a signal and samples S7 and S8 were not analysed because of the evidence of contamination already obtained by Py-GC–MS.

3.4. Organic residue analysis by GC–MS

The results of the organic residue analysis are included in Fig. 9. Sample S4 from A Fontela (Fig. 9.1) presents a chemical signature that is typical of highly degraded oils. Triacyclglycerols are chemical compounds that are abundant in oils from animal and vegetal sources (Evershed 1993; Evershed 2008) being usually detected in the archaeological record in the form of their degradation products, as diacylglycerols, monoacylglycerols, fatty acids and glycerol (Roffet-Salque et al. 2017; Romanus et al. 2007; Rosiak et al. 2020). This chromatogram clearly presents diacylglycerols as 1,2-dipalmitin, 1,3-dipalmitin and 1,2-distearin, intense peaks of the monoacylglycerols 1-monopalmitin and 1-monostearin, as well as the fatty acids palmitic (P) and stearic (S), in a chemical profile that is clearly indicative of the influence of degraded oils. The possible doubt about the animal or vegetal source was resolved by the detection of phytosterols, as stigmasterol, and especially the large peak of β-sitosterol, which suggests the prevalence of plant-derived lipids.

Cholesterol is a biomarker for animal fats, but its finding in conjunction with squalene could be attributed to a contamination with skin lipids (Evershed 1993; Heron et al. 2010; Vykukal et al. 2021; Whelton et al. 2021). Therefore, the small peaks of both cholesterol and squalene are typical of unprotected human contact with the sherds (manipulation without gloves has been confirmed) and their presence should not be valued. The detection of a small group of plasticisers related with cleaning, handling, and storage of the potsherds, does not interfere with the interpretation of the analytical data.

The palmitic (C16:0) to stearic (C18:0) fatty acid ratio obtained (P/S = 1.2) is lower than expected for vegetable oils, as plant oils tend to have higher P/S ratios than animal fats (as an example we can refer a ratio of about 4 for commercial olive oils). However, certain vegetal oils, such as sesame oil (P/S = 1.9) or walnut oil (P/S = 2.7), may have relatively low P/S values. Additionally, palmitic acid is twice as soluble in water than stearic acid, and therefore is more prone to leaching during burial, decreasing the original P/S ratio of the remains. Consequently, this diagnostic ratio could not be constant over archaeological time and should be interpreted with caution (Steele et al. 2010).

Besides the higher proportions of palmitic to stearic ratios, plant oils also have important contributions of unsaturated C18 fatty acids (Romanus et al., 2007). Unfortunately, the HP-5MS chromatographic column used does not allow the unequivocal separation and identification of different positional and geometrical double bond isomers. Even though the calibration of the GC–MS system with an analytical standard of oleic acid (among other fatty acids), the similarity between mass spectra of different unsaturated C18 fatty acids and the risk of coelution of isomers suggests the assignment of the monounsaturated C18 peak to C18:1 fatty acid (Whelton et al. 2021). Important peaks of unsaturated C18:1 and nonanoic acids were detected, suggesting traces of plant oils rich in unsaturated C18 fatty acids (note that the C9-diacid, azelaic acid methyl ester, were also detected alongside C18:1 of sample S4 using THM-GC–MS). This fact together with the finding of δ-5-avenasterol (another phytosterol) is compatible with traces of olive, wheat, acorn, or hazelnut oil (Al-Rousan et al. 2013; Debono Spiteri 2012; León-Camacho et al. 2004), but this compound is omnipresent in the plant kingdom. We elaborate on the plant materials based on available archaeological evidence in section 6.4.

Sample S5 (Fig. 9.2) presents traces of degraded oils and fats, that are visible by the presence of DAGs (1,2-dipalmitin; 1,3-dipalmitin; 1,2-diheptadecanoin; 1,3-diheptadecanoin), MAGs (1-monopalmitin; 1-monostearin) and linear fatty acids. The chemical signature of plant-derived oils is very clear, with an important group of phytosterols that includes a massive peak of β-sitosterol, smaller peaks of stigmasterol, campesterol, citrostadienol and δ-5-avenasterol, and a P/S ratio of about 1.5, slightly higher than sample S4. Besides C18:1 fatty acid, this sample also exhibits C18:2, reinforcing the hypothesis of containing traces of plant-derived oils. A clear peak of sulphur (S8) is also present, which was not detected in the other analysed samples.

Despite the absence of both DAGs and phytosterols, the chromatogram of Castromao S8 (Fig. 9.3) exhibits residues of MAGs, linear fatty acids (P/S = 1.8) and glycerol, characteristic of remnants of degraded
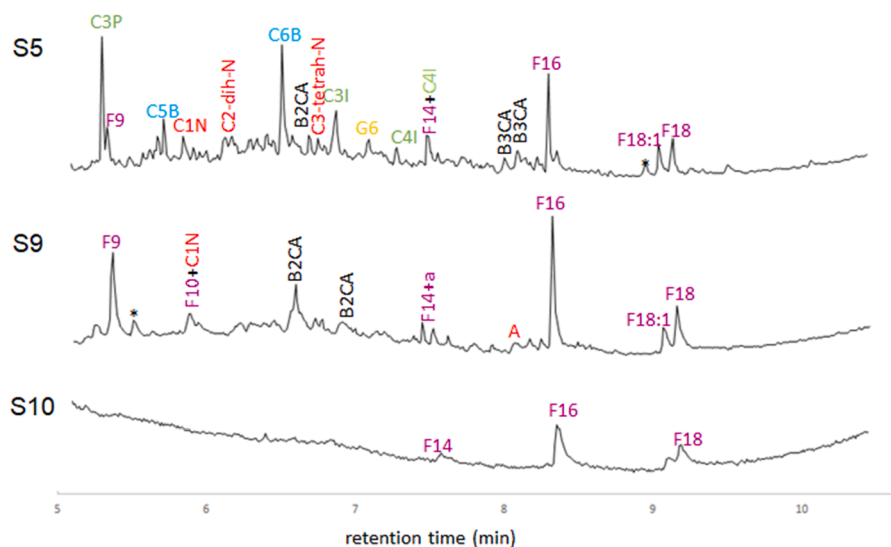
Fig. 8. THM-GC–MS total ion current chromatograms for samples from Castromao. Blue = monocyclic aromatic hydrocarbons (C5B = pentamethylbenzene, C6B = hexamethylbenzene). Red = polycyclic aromatic hydrocarbons (N = naphthalene, C1N = methylnaphthalene, *C*2-dih-N = dimethyl-dihydronapthalenes; C3-tetrah-N = trimethyl-tetra-hydronaphthalenes, A = anthracene/phenenthrene). Green = nitrogen-containing compounds (C3P = trimethylpyrrole, C2I-C4I = di-, tri- and tetramethyllindoles). Purple = fatty acid methyl esters Fx with × marking carbon number (F18:1 = monounsaturated C_{18} FAME, e.g.: the methyl ester of oleic acid). Black = benzenecarboxylic acids (B2CA and B3CA with 2 and 3 carboxylic moieties, respectively). Orange = lignin product (G6 = 3,4-dimethoxybenzoic acid methyl ester). *=Contamination. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

fat. It is important to point out a homologous series of even-numbered fatty acids (C8-C26), with a predominance order C16 > C18 > C9, and a homologous series of even-numbered alkanols (C11-C28), with a strong predominance of C18. Alkanols are long-chain alcohols that are often found in lipid residues. Even-chain alkanols are particularly prevalent in higher plant waxes (Tulloch 1976). C18:1 fatty acid and nonanoic acid were also detected, the last compound with a relatively intense peak, supporting the conclusion of plant-derived oils.

Castromao S9 and S10 samples (Figs. 9.4 and 9.5) present similar chemical signatures, with intense peaks of MAGs and smaller peaks of DAGs. S9 and S10 P/S ratios are 1.9 and 1.6, respectively, which is aligned with the previously analysed samples. S9 chromatogram also includes traces of phytosterols, with an intense peak of β-sitosterol and less intense peaks of stigmasterol and campesterol, confirming a plant origin for the degraded fats. Phytosterols are absent from sample S10.

4. Discussion and conclusions

4.1. Raw material procurement

The materials used in the manufacture of the modular kilns diverge between the two sites studied (Fig. 10). The A Fontela site is located in a region with granitic and granodioritic lithology, but it is nearby a basic and ultramafic area where the clay used has probably originated from (see geologic map of Figure 10.1). The composition (mineralogy and geochemistry) of the ceramic samples is ultramafic, which is coherent with a local production and a procurement of raw materials from 2.5 to 10 km away. Note that the ultrabasic areas in Galicia are scarce and an ultramafic composition in the proximity of a ceramic deposit is a clear marker of provenance. Likewise, this same conclusion was observed when the ceramic kilns of Castrovite, located over another ultramafic lithological area, were analysed (see data at Supplementary Material 1). The Castromao site just is located over a granitic (and schistose) lithology and their ceramics have compositions typically felsic, similar to available clays that come from the weathering of these rocks (Figure 10.2). Therefore, it seems logical to point to a local origin of the raw materials used for the kiln manufacture that had been suggested for the vessels. Studies of the provenance indicate that the majority of ceramic-made objects were made from local clays (Galván Martínez et al. 1993; Little 1990), although settlements have also been found that acquire most of their vessels (de Groot and González-Álvarez 2021). This could be understood as typical of Iron Age pottery production, which would have been largely made in domestic contexts, of a family or

artisanal nature, and with a largely regional or local distribution (Rey Castiñeira et al. in press).

4.2. The manufacture of kilns

Regarding the use of plant materials in the manufacture of the kilns, there are differences between the sites studied. At A Fontela, the kilns contain abundant cereal chaff for tempering the clay, which seems to have been selected since no remains of large stems and still-attached inflorescences were found. Evidence of the use of chaff in manufacture is also documented in other examples from the northwest, for example, barley (*Hordeum vulgare*) has been identified in the Castrovite hillfort (Teira Brión 2019). The use of a by-product of the cereal *chaîne opératoire* as a temper could have been functionally motivated to provide better shrinkage control, to reinforce shape during construction, to extend durability, or even a culturally meaningful choice (Dzhanfezova 2021).

On the contrary, the clay prepared in the Castromao kilns has a low frequency of vegetal inclusions, which is insufficient to modify their properties. The organic remains may have been added unintentionally during the kneading of the clay or by contact with surfaces such as pavements or floors. There is no indication of the presence of cutin or suberin (bark, root, intact plant leaves), and intact polysaccharides and proteins were not detected. Organic chemical analysis only detects possible preserved plant remains in sample S5 (lignin products after THM-GC–MS, from woody debris including fuel, or fibres from straw or lignin-containing materials such as chaff). The most significant aspect of the modelling of the examples from Castromao is the choice of a base composed of common bracken leaves (*Pteridium aquilinum*), although examples are also preserved with impressions of branches or wooden objects. This type of imprinting of OM on clay during the 1st millennium BCE was shared among technologies using clay as a raw material (Pastor Quiles et al. 2022; Ruano 2021).

4.3. Firing

The firing of the modular kilns did not exceed the 900 °C at the time of manufacture (firing process) or at the time of use, since no minerals that indicate higher temperatures are detected, except the bottom of a grill from A Fontela, (S1-1, S1-2) which was subjected to high firing temperatures. The part in contact with the fire of the combustion chamber is the only one containing spinel, cristobalite, diopside and mullite, which indicates temperatures about 900–1000 °C. The spatial
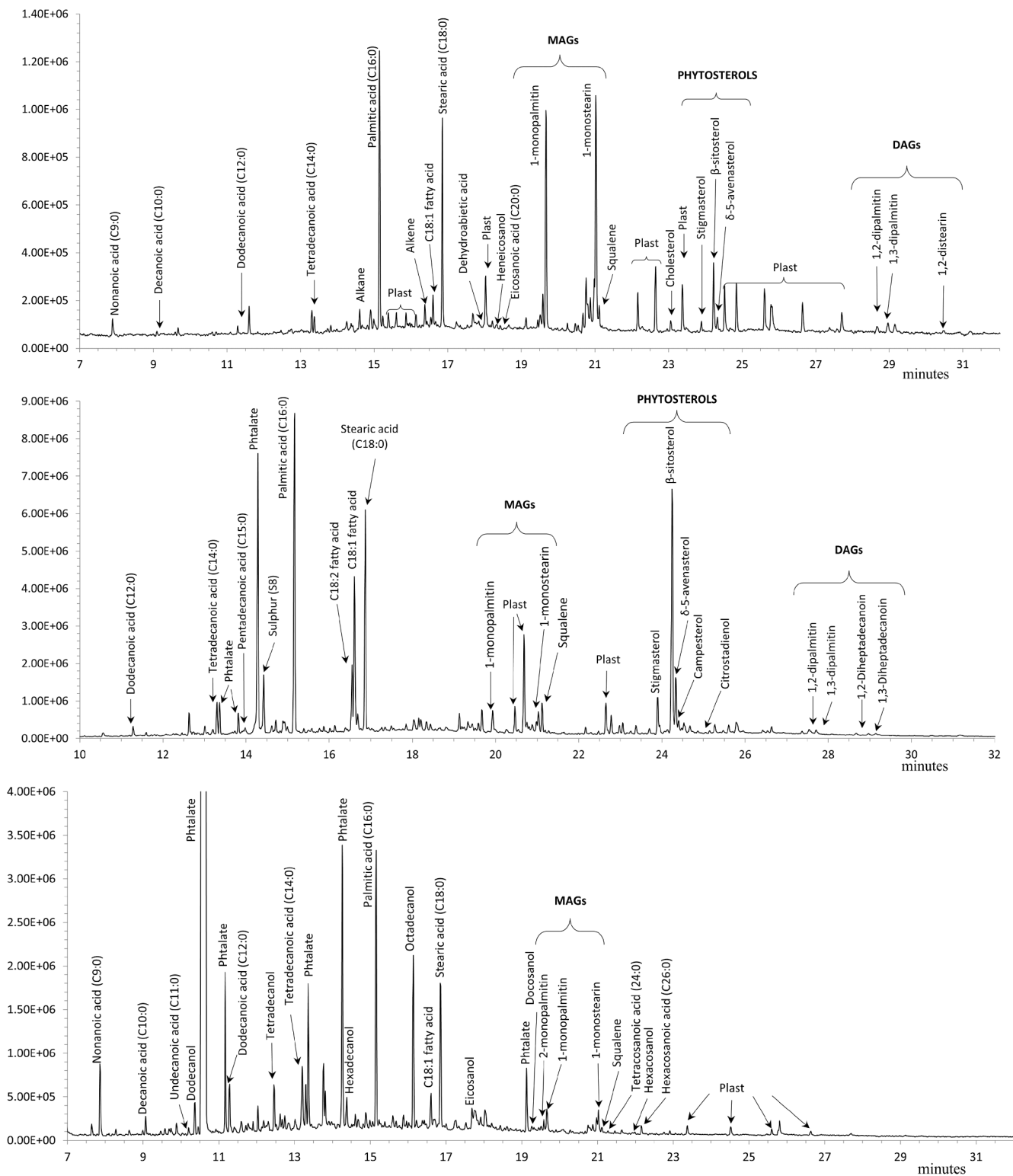
Fig. 9. GC–MS total ion current chromatograms for samples S4 (Fig. 9.1); S5 (Fig. 9.2); S8 (Fig. 9.3); S9 (Fig. 9.4); S10 (Fig. 9.5). MAGs = Monoacylglycerols; DAGs = Diacylglycerols; Plast = organic contaminants such as synthetic polymers from consolidation materials.
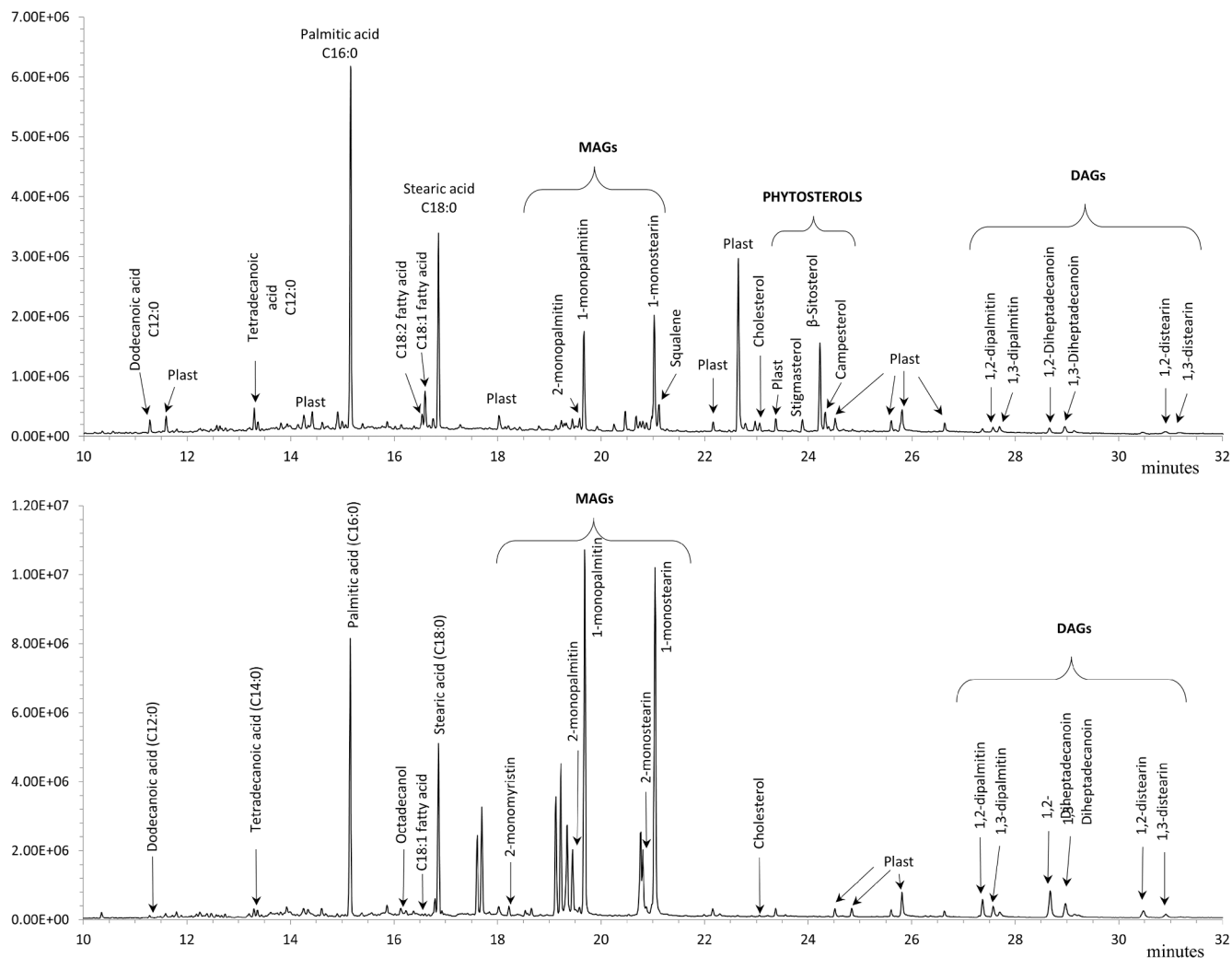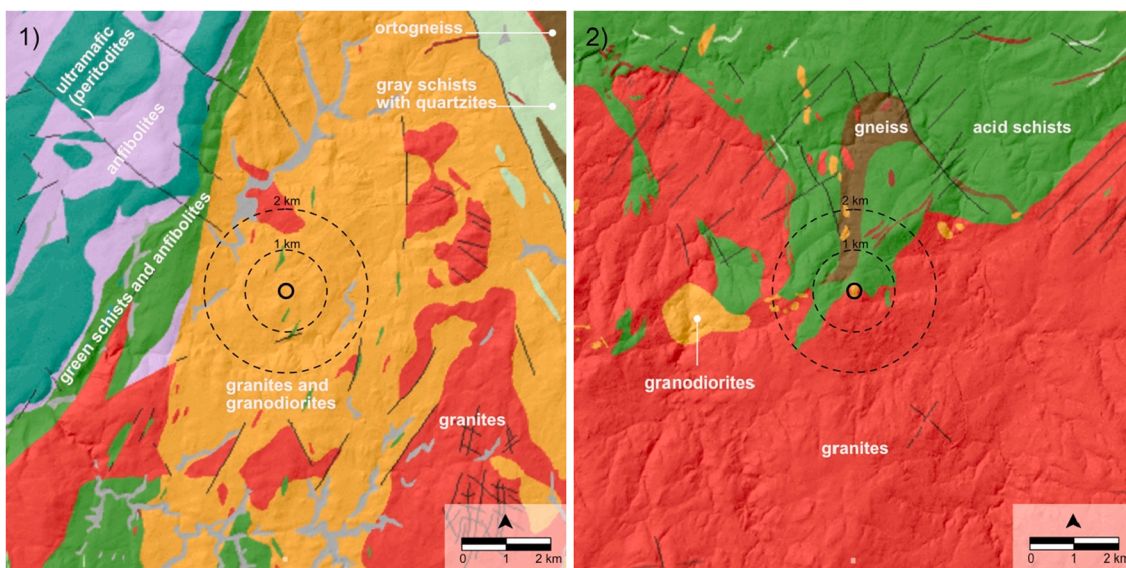
Fig. 9. (*continued*).

Fig. 10. 1) Geological environment of A Fontela archaeological site (green label: X: 590101.41, Y: 4747555.09; Lat.: 42.87528, Long.: −7.89681), and 10.2) Geological environment of Castromao (green label: X: 584494.85, Y: 4668267.02; Lat.: 42.16198, Long.: −7.97716). Base maps from http://mapas.xunta.gal/visore s/basico/. U.T.M projection, zone 29, ellipsoid GRS80, Datum ETR89. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

pattern of temperatures suggests that this temperature was reached in a use phase and not when the kiln was built. The remaining of samples have been subjected to minor temperatures because no high temperature indicator mineral was detected. The ranges of temperatures in the kilns is coherent with the maximum values that have been documented for ceramic production during the 1st millennium BCE in NW Iberia (Little 1990; Rey Castiñeira and Soto Arias 2002). Kaolinite undergoes a transformation process when heated to approximately 550°Celsius (Heimann 1989), so its presence in all the Castromao samples means that they would not have exceeded this temperature during firing or during subsequent use of the kilns. Pyrolysis-GC–MS indicates that the impact of the heating on the OM was strongest for sample S10.

4.4. Functionality

The samples from Castromao would not have reached the temperatures estimated for Iron Age pottery production (i.e., Little 1990; Rey Castiñeira and Soto Arias 2002). These temperatures were indeed reached in the A Fontela grill, as evidenced by the presence of minerals such as appearance of spinel, cristobalite, diopside and mullite, but they have not been identified in the samples from the walls. Although we cannot rule out its use as a ceramic kiln, the continuous heating of the grill base for other uses (such as cooking) could also explain the presence of neoformation minerals. In conclusion, these results do not support clearly the use of the modular kilns analysed for firing pottery, although it has been suggested as one of their main probable functions (e.g., Rey Castiñeira et al. 2013). However, the organic residue analyses allowed the detection of lipids from vegetable oils, evidencing traces of an organic matrix with a similar chemical profile among all the samples. Likewise, mineralogical analyses identified levels of carbon, nitrogen and phosphorous in black crusts on ceramic S9-2, indicating organic contents associated to the kiln (e.g., food cooking residues).

The presence of high levels of unsaturated C18 fatty acids (probably mostly oleic acid, as detected by pyrolysis), together with phytosterols, as β-sitosterol, stigmasterol, campesterol and δ-5-avenasterol could be related to nuts with a high oleic acid content that are produced by different species existing in the natural environment, such as hazelnuts (*Corylus avellana*), wild olives (*Olea europaea*), acorns (*Quercus* spp.), chestnuts (*Castanea sativa*), or walnuts (*Juglans regia*), among others. The above species grew wild in the forests of the Iberian Northwest (López-Merino et al. 2010; Martín Seijo 2013; Ramil-Rego et al. 1998; Silva-Sánchez et al. 2014) and could have been sources of these compounds. However, the use of their fruits was very uneven during the Prehistoric period, either they do not appear (chestnuts, walnuts), or they are very scarce (hazelnuts, olives), or they are very abundant (acorns) in archaeological sites (Teira Brión 2019; Tereso et al. 2016; Tereso et al. 2013a).

Although it is impossible to determine the origin of the vegetable oils due to the wide variety of plants that contain them, we can nevertheless hypothesise about their provenance from other archaeobotanical evidence and the context of the kilns. The most common interpretation of the presence of oleic acid in ceramic vessels is olive oil (Kimpe et al. 2001; Koh and Birney 2019; Romanus et al. 2009; Sacchi et al. 2020); however, during the 1st millennium BCE, oil production was limited to the Mediterranean and southern areas of Iberia (Pérez-Jordà et al. 2021). Only from the Roman period onwards did it frequently reach the northern regions and local production is likely (Teira-Brión 2022). We have documented pollen in a few archaeological sites (Martín-Seijo et al. 2020) and natural deposits (Silva-Sánchez et al. 2014), and the use of its wood and charred endocarps is, in the current state of art, limited to settlements located in the Sabor river basin (Portugal) from the 2nd century BCE onwards (Seabra et al. 2020; Tereso et al. 2018; Vaz et al. 2016). The processing of olives (or any other fruit) together with a heat source such as ovens would have allowed the preservation of remains resulting from accidental charring or as part of waste disposal, as has been found in other sites in the Iberian Peninsula (e.g., Voropaeva and Stika 2018). While oil production cannot be proven during the Iron Age in the NW region, the trade arrival of oil also presents problems. Although a Phoenician glass bead has been found in A Fontela (Teira Brión 2019), and an Attic pottery in Castromao (Carballo Arceo 1987) informs on existing Mediterranean trade routes, Punic amphorae used as oil containers (among other products) would not become common until the 5th/4th centuries BCE in the coastal area (Sáez Romero et al. 2019), far from the sites of the ovens analysed.

Most wild fruits are very rare in archaeobotanical samples as mentioned above. In comparison, acorns were widely and massively consumed in the NW of the Iberian Peninsula during prehistoric times (Amado Rodríguez 2013; Teira Brión 2019; Tereso et al. 2016). The fruits of the different species of *Quercus* sp. are found in more than 25 % of the carpological samples from the 1st millennium BCE, being the third most frequent taxa after wheat (*Triticum* spp.) and broomcorn millet (*Panicum miliaceum*) (Teira Brión 2019). Acorns appear insistently in the hearths of domestic constructions (Carballo Arceo 2002; Peña Santos 1992), accidentally charred during their culinary preparation or intentionally thrown into the fire; in the interior of some ceramics that may have been used for storage or cooking (Silva 2008); or inside storage structures such as granaries or silos, being an essential part of community food supply (Teira Brión 2019; Tereso et al. 2013b). In Castromao, García Rollán (1971) reports fragments of a kiln grill found together with abundant acorns and pottery in building XI that may suggest a close relationship between these nuts, the fire and the oven. Furthermore, acorns are mentioned in written sources as a key food resource among the Iberian communities, consumed both roasted in the ashes and in the form of bread according to the information provided by the Greco-Latin authors (Strabo, *Geografía*, 3,3, 7–8; Pliny the Elder, *Naturalis Historia* 16, 15).

Nevertheless, the majority of *Quercus* species produced fruits which have a high concentration of tannins, therefore different processing is necessary to make them edible, such as roasting, boiling, leaching, alkaline treatment (e.g., addition of ashes/clay), or lactic fermentation (e.g. buried or submerged in water) (Anderson 2007; Ayerdi et al. 2016; Hanson et al. 2019; Mason 1992; Mason and Nesbitt 2009; Šálková et al. 2011; Wang and Jiang 2021). Acorn oil comprises a wide range of phytosterols, including β-sitosterol, which constitutes 80 % of the total sterol fraction, campesterol, stigmasterol, Δ5-avenasterol and Δ7-stigmastenol, in addition to some minor components (León-Camacho et al., 2004). The plant oils contained in modular kilns may have seeped into the ceramic as a remnant of food processing (e.g. roasting, baking), or even the acorns may have been cooked to obtain oil (Hanson et al. 2019). Drying or roasting could be related to the preservation of the fruits. Examples such as the corndryers of the British Isles (Lodwick 2017) are essentially kilns very similar to those used for pottery, with the same two-chamber firing and cooking scheme as the modular kilns. Roasting could also facilitate debittering, which could be followed by further steps such as poured with hot or cold water (e.g., Hanson et al. 2019; Mason and Nesbitt 2009). Plant oils could also have been integrated into the pottery from the food preparation, either by bread making as 'tannur'-type ovens as found in several regions of Europe (Monteix and Noûs 2021) or as stoves, channelling the heat towards food or vessels; although possibly in the latter case it would be expected that the residues also include compounds of animal origin. However, despite all these options, specific processing or food use of acorns remains a puzzle to be addressed in future research.

Not only is the importance of the *Quercus* fruits reflected in prehistoric diet, but they also perform as part of commensality rituals (Tereso and Silva 2014), or as funeral offerings accompanying the deceased (Basso Rial et al. 2022), perhaps as food in the afterlife. As iconographic elements, the representations of acorns on earrings, necklaces, and pendants of Mediterranean influence made in gold and silver are full of symbolism (Perea et al. 2010). In the diadem from La Puebla de los Infantes (Sevilla, Spain), acorns face each of fifteen goddesses with their wings folded expressing the idea of female fertility (Perea 2006). Their

participation in life and beliefs, and the symbolism of the incised herringbone decoration on the rim of the Castromao oven (one of the scarce known cases of decorated pieces) could extend the meaning of the kilns of NW Iberia beyond a mere utilitarian object. Following this, the modular kilns could be understood in terms of social practices in which acorns (associated to fertility or abundance) may also form part of a ritualised sphere of domestic life.

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CRediT authorship contribution statement

Andrés Teira-Brión: Conceptualization, Investigation, Resources, Writing – original draft, Visualization, Supervision. **Joeri Kaal:** Investigation, Writing – original draft, Visualization. **Óscar Lantes-Suárez:** Investigation, Writing – original draft, Visualization. **César Oliveira:** Investigation, Writing – original draft, Visualization. **Javier Rodríguez-Corral:** Investigation, Writing – original draft, Writing – review & editing. **Nuria Romero-Vidal:** Investigation, Visualization, Writing – original draft. **Josefa Rey-Castiñeira:** Project administration, Funding acquisition.

Declaration of Competing Interest

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

Data availability

All data are contained in the article

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Appendix A. Supplementary material

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