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The Biggest *Opus doliare* Production in Narbonese Gaul Revealed by Archaeometry (first to second centuries A.D.)*

*La plus grande production d'Opus doliare de Gaule Narbonnaise révélée
par l'archéométrie (I^{er}-II^e s. apr. J.-C.)*

Charlotte CARRATO^a, Verònica MARTÍNEZ FERRERAS^b, Jean-Marie DAUTRIA^c
and Michèle BOIS^d

Abstract: This article presents an overview of recent research on *dolia* (large storage jars) from the former province of Narbonese Gaul. It aims to bring to light a poorly known aspect of the Roman period, namely the production and diffusion of *dolia*, thought archaeological evidences. Thus, the largest workshop of *dolia* in Narbonese Gaul has been recognized by combining archaeological, geological and archaeological data.

Résumé : Cet article présente une synthèse des récentes recherches menées sur les *dolia* (grandes jarres de stockage) du territoire de l'ancienne province de Gaule narbonnaise. Il vise à mettre en lumière un phénomène méconnu, à savoir la production et la diffusion des *dolia* à l'époque romaine par le biais des données archéométriques. Cette étude démontre comment le croisement des données archéométriques, géologiques et archéologiques ont permis de révéler l'existence de l'une des plus grandes zones de production de *dolia* de Gaule Narbonnaise.

Keywords: Archaeometry, petrology, geochemist, geology, archaeology, Roman period, Narbonese Gaul, *dolium*.

Mots clés : Archéométrie, pétrologie, géochimie, géologie, archéologie, époque romaine, Gaule narbonnaise, *dolium*.

1. INTRODUCTION

The *dolium* is a ceramic storage jar of Greek and Etruscan origin, and is the largest container ever used in the ancient world. It appeared in Gaul during the fourth century B.C.,

became increasingly widespread until the first century B.C., and then flourished during the Early Empire. At that time, jars were installed in large storehouses and their capacity ranged from 600 to 2,500 l, ensuring the storage of significant quantities of wine and olive oil (Fig. 1).

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* This work is an extension of the PhD thesis published in 2017 in the collection Mémoire d'Ausonius-Bordeaux (Carrato 2017).

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Figure 1: (See colour plate IX) *Dolium* from the Bernardins villa in Montélier (Drôme) (capacity: 2,463 l) conserved in the Museum of art and archaeology of Valence (C. Carrato).

Figure 1 : (Voir planche couleur IX) *Dolium* provenant de la villa des Bernardins à Montélier (Drôme) (capacité : 2 463 l) conservé au musée d'art et d'archéologie de Valence (cl. C. Carrato).

Judging by early sources, the difficulty in manufacturing these large terracotta jars was proverbial¹. Contrary to long-standing common belief, each stage, from the preparation of the clay, to the difficult stage of manually mounting coils, to firing, required the savoir-faire of the most experienced potters, as suggested by ethnographic parallels (Checa, 1901; Romero Vidal and Cabasa Calpe, 1999; Giannopoulou, 2010; Vaz Pinto, 1997). A significant number of *dolia* were discovered at early agricultural sites from the Roman period in Narbonese Gaul, following the expansion of viticulture and olive growing during the course of the first century A.D. (Brun, 2005; Brun and Laubenheimer, 2001), indicating that the elders adapted the production of these containers to economic demands. Paradoxically, production sites and trade modes are still poorly known. For the whole

Mediterranean region, the only clearly evidenced production workshop is the Saint-Bézard villa in Aspiran (Hérault, France) (Mauné, *et al.*, 2006) and the Ermedàs workshop in Cornellà del Terri (Catalogna, Spain) (Tremoleda, *et al.*, 2018). Others production sites are only indirectly known through epigraphic stamps², which provide information concerning the status of those involved in this specialized production, but are of limited use in research on workshop localisation and production diffusion modes.

In order to address the paucity of archaeological data, the *dolia* from wine and oil exploitations in Narbonese Gaul were studied by one of the authors as part of a PhD thesis submitted in 2014 (Carrato, 2017, 158-164). The corpus of this study has a total of six hundred and fifty *dolia* from seventy three sites located in the coastal part of Narbonese Gaul, extending from the Pyrénées-Orientales to the Alpes-Maritimes, but also along the Rhône Valley to Lyon (Fig. 2). The macroscopic examination allowed classifying the specimens in different fabrics, which were more accurately defined through the archaeometric characterisation of a number of selected samples. The methodology adopted aimed to combine all of the available approaches, namely macroscopic classification, and the examination of the chemical, mineralogical and petrographic compositions in order to establish their provenance and the main technological processes of manufacture. Thus, the petrographic examination of one hundred and twenty-five samples selected from the initial corpus then led to distinguish forty-five regional paste types. The matching between regional groups required chemical analysis on thirty-six samples which appeared to be representative of four main petrographic fabrics. The results of this study allowed distinguishing the most common *dolia* pastes found in Narbonese Gaul dated between the first century and the middle of the second century A.D., to make inferences on their provenance and the location of the possible production centres, to evaluate their frequency and the main areas of distribution. The chronology and the extension of the area of influence of these workshops points to two main production and distribution systems. One includes thirty-eight workshops with micro-regional diffusion and the other refers to three workshops, or groups of workshops with regional, or even provincial diffusion.

Among the latter, a group of pastes (called group 1), with predominant calcite inclusions is widespread in Narbonese Gaul. During the period under study (first-second centuries A.D.), these pastes were used for one *dolium* out of three in certain regions. This group also presents the most

1. Known as *In dolia fugalarem artem discere* by Plato, *Gorgias*, 514^e and *Lachès*, 187b, or Erasmus, *Les Adages*, 515.1.6.15.

2. See in particular Descemet, 1880; Steinby, 1993; Gasperoni, 2003; 2005; Lazzeretti and Palleschi, 2005; Palleschi, 2012; Carrato, 2017, pp. 164-174.

extensive diffusion zone, extending over nearly 400 km, from Lyon to Narbonne, through Arles and the outskirts of Marseille, corresponding to almost the whole Narbonese province. Due to the abundance of this fabric in Roman sites, its homogeneity and the extent of its diffusion zone, it seems to reflect an unusual and unprecedented production system in the province. The present study focuses on the complete archaeometric characterisation of the *dolia* from different consumption centres attributed to group 1. The aim of the present study is to thoroughly evaluate the degree of homogeneity in the composition of these vessels, to determine the technological processes involved in their manufacture and to identify their provenance (the location of the production area).

2. SAMPLING AND METHODS

Macroscopic characterization

The macroscopic examination was carried out with the naked eye or with a magnifying glass on fresh breaks

Considering the size of the inclusions in the *dolia* pastes, the macroscopic examination is a useful technique for an initial classification of the specimens under study. They consist of coarse to very coarse fabrics, although they differ in the composition and characteristics of the clayey matrix and the non-plastic inclusions. Indeed, the corpus of *dolia* studied by the main author (Carrato, 2017) includes specimens manu-

factured using both, Ca-rich clays or Fe-rich clays. The observation of the matrix colour mainly reveals oxidizing firing. Nevertheless, the central area of the thick walls of some individuals is brown because it was less affected by the firing temperature than the internal and external surfaces of the jars. In other cases, the core of the ceramic walls is greyish, suggesting changes in the atmosphere of the kiln during the firing process. In addition, the examination of complete specimens indicates that a single *dolium* can present different surface colours. This different colouring is generally linked to the position of the container in the kiln and cannot consequently be taken into consideration for macroscopic identification. The examination of the non-plastic inclusions was a more convincing discriminating marker. In general, they consist of coarse to very coarse grains of different nature that were added as temper to the clayey raw material. Most of the individuals of the corpus appear to have been tempered with crushed calcite, while coarse to very coarse sand grains from a plutonic and or volcanic geological complexes were added to the rest of the fabrics.

The macroscopic group 1 comprises around two hundred *dolia* from the main corpus. All of them exhibit a dark-orange to dark-red matrix, rarely grey-black. The non-plastic material is very abundant and poorly sorted. It is mainly composed of fine, coarse and very coarse white inclusions, usually quadrangular and angular, consisting of monocrystalline or polycrystalline crushed calcite. They appear associated with rarer rounded wine-coloured or black grains which probably correspond to ferruginous nodules (Fig. 3).

Figure 3: (See colour plate XI) Macroscopic views of fragments of group 1 paste (1,5×). The numbers refer to the sites listed in Fig. 2.

Figure 3 : (Voir planche couleur XI) Vues macroscopiques de fragments de pâte du groupe (1,5×). Les numéros renvoient aux sites répertoriés dans la Fig. 2. (Cl. C. Carrato).

Archaeometric characterization

Complementary analyses were made on twelve samples attributed to group 1 in order to confirm and refine the macroscopic determination. Those specimens were coded DOL1 to DOL12 (Carrato, 2017, 223, fig.114)³. They come from nine wine exploitations located in the Hérault, Aude and Drôme areas, and they are dated between the first century and the middle of the second century A.D. The investigation included the petrographic composition of the selected samples and the chemical and mineralogical composition of the same (powdered) specimens. The analyses were carried out at the CCI-T-UB laboratory of the University of Barcelona, following the procedures already described (Martinez Ferreras, *et al.* 2013), and at the Geoscience laboratory of the University of Montpellier II.

The petrographic composition was examined through thin-section optical microscopy (OM), using an Olympus BX43F polarising microscope; measurements, evaluations, and photographs were taken using an Olympus DP73-WDR digital camera and the Stream Basic image analysis software.

The chemical composition was investigated through wavelength dispersive X-ray fluorescence (WD-XRF), using a PANalytical-Axios PW 4400/40 spectrometer. This allowed for the identification of 29 major, minor and trace elements, including Fe₂O₃ (as total Fe), Al₂O₃, MnO, P₂O₅, TiO₂, MgO, CaO, Na₂O, K₂O, SiO₂, Ba, Rb, Th, Nb, Pb, Zr, Y, Sr, Ce, Ga, V, Zn, Cu, Ni, Cr, Mo, Sn, Co and W. Of these, Mo and Sn were discarded due to their low counting statistics, while Co and W due to a possible contamination from the tungsten carbide cell of the mill used in the preparation of the samples. Glass beads were prepared for the determination of major and minor elements, using 0.3 g of

specimen. The concentration of the trace elements was measured through powder pills prepared using 5 g of specimen. The quantification of the elements was obtained by using a calibration line performed with 60 International Geological Standards. The loss on ignition (LOI) was calculated from calcinations of 0.3 g of dried specimen, heated at 950°C for 3 hours.

The mineralogical composition was determined by powder X-ray diffraction (XRD), using a PANalytical X'Pert PRO MPD powder diffractometer. Crystalline phases were investigated using the software HighScore Plus by PANalytical.

3. RESULTS

Petrographic characterization

Thin section analysis was carried out on the twelve selected samples in order to confirm and refine the macroscopic determination. The petrographic fabrics were defined according to the characteristics of the matrix (groundmass) and the microstructure (micromass). We paid particular attention to the identification and description of the aplastic inclusions (frequency, size, shape, distribution, and type). Each mineralogical description follows a bipartite presentation itemizing the minerals in the fine fraction, then the minerals in the coarse fraction⁴.

The petrographic composition confirms that all the specimens analysed consist of calcite-tempered *dolia*, although some differences in the characteristics of the groundmass and the presence or absence of specific non-plastic inclusions have been recognised (Fig. 4a). Most of the specimens exhibit a Fe-rich, heterogeneous and low vitrified matrix.

3. DOL1, DOL2: La Nautique, Narbonne (Aude); DOL3, DOL5 : La Barque, Allan (Drôme); DOL4, DOL7: Le Molard, Donzère (Drôme); DOL6 : La Bâtie-Rolland (Drôme); DOL8 : L'Auribelle basse, Pézenas (Hérault); DOL9 : Saint-Sauveur, Lattes (Hérault); DOL10 : Le Pendut, Magalas (Hérault); DOL11 : Saint-Bézard, Aspiran (Hérault); DOL12 : Vareilles, Paulhan (Hérault).

4. The inclusions in the fine fraction correspond to the smallest grains (< 0.125 mm) and are abundant in the clay matrix. Conversely, the coarse fraction corresponds to the largest inclusions (> 0.125 mm), which may appear as natural components included in the clayey raw material procured for the manufacture, or deliberately added and mixed with the clayey raw material by the potters.

The fine fraction is abundant and is mainly composed of small crystals of quartz together with common phyllosilicates and opaque minerals. Some aggregates of a different clayey material, also containing small crystals of quartz, appear combined with the main clay, suggesting that different clayey raw materials were probably mixed. The coarse fraction is mainly composed of angular and rhombohedral shaped mono-crystalline calcite (≤ 10 mm) followed by sub-rounded to rounded ferruginous grains (≤ 8 mm), which could be considered fine-grained sedimentary rocks with Fe-rich matrix. Sub-angular to sub-rounded monocrystalline quartz (< 1 mm) is frequent; sub-rounded fragments of metamorphic rocks (principally quartzite and quartz-mica schist, < 1 mm) are common, and lamellae of muscovite (< 0.5 mm) are rare. DOL8 presents a very similar clay matrix and the non-plastic inclusions correspond to the same lithic elements already described (Fig. 4b). Nevertheless, the crystals of quartz and metamorphic rocks are more abundant. In addition, nodules of monocrystalline (micrite) calcite are common. The *dolium* DOL3 exhibits the same non-plastic inclusions although it differs in the characteristics of the matrix (Fig. 4c). The latter is rather heterogeneous and contains large and elongated streaks of very pure clay mixed with a more abundant clayey material, darker in colour. The optical activity of the matrix is very high suggesting a low firing temperature. The fine fraction is less frequent and finer than in the previous fabrics. It comprises very small lamellae of phyllosilicates, very fine grains of quartz and opaque minerals. Angular and rhombohedral mono-crystalline calcite (≤ 4 mm) is prevalent in the coarse fraction, together with some nodules of microcrystalline (micrite) calcite. Ferruginous nodules and sub-angular to sub-rounded monocrystalline quartz (< 1 mm) are frequent, while quartzite and quartz-mica schist are common.

Apart from the differences detected, all the *dolia* analysed were manufactured using the same type of non-plastic inclusions. Their composition and characteristics suggest that raw materials of different geological origin were mixed to obtain specific coarse clayey pastes. Indeed, the shape and composition of the fine fraction denotes the use of a Fe-rich alluvial sediment taken from a river or river banks. The sub-angular to sub-rounded crystals of quartz and metamorphic rocks and the ferruginous nodules, usually ≤ 8 mm grain-sized, could be naturally included in the alluvial sediments. However, the shape and the variety of size that characterize the crystals of calcite suggest that they were added by crushing a calcareous rock from a karstic source which forms mainly in limestone regions.

Geochemical characterization

The geographic range of the group 1 specimens raised questions as to the homogeneity of these vessels. In addition to the data provided by the petrographic analysis, the examination of the geochemical characterization is required to evaluate the compositional variation among the *dolia* classified in group 1. In the scope of studies on the provenance of archaeological ceramics, the geochemical characterization is especially useful when the reference chemical groups of the production centres are known. Since the *dolia* examined herein were recovered in consumption centres and no analytical database of the same materials is available, the aim of this analysis is to evaluate the dis(similarity) of the chemical composition of the jars attributed to group 1 in order to test the coherency of the macroscopic and petrographic fabrics previously defined.

The normalised chemical composition of the twelve samples analysed by wavelength dispersive X-ray fluores-

Figure 4: (See colour plate XI) Microphotographs of thin sections taken under plane polars (PPL) and crossed polars (XPL) at the same magnification (20x); a) representative individuals of the main fabric identified; b) the *dolium* DOL8; c) the *dolium* DOL3.

Figure 4 : (Voir planche couleur XI) Microphotographies des lames minces en lumière polarisante non analysée (LPNA) et en lumière polarisante analysée (LPA) au même grossissement (20x); a. Individus représentatifs de la même fabrique; b. le *dolium* DOL 8; c) le *dolium* DOL3 (V. Martínez Ferreras).

cence (WD-XRF) is given in Figure 5a. It reveals that all the vessels consist of calcareous ceramics (CaO from 10 to 19 wt%), except DOL5 that is border calcareous (CaO 4.2 wt%). Moreover, all the samples contain high SiO₂ (48 - 60 wt%) and low MgO (0.2 - 0.4 wt%) contents; nevertheless, some differences in these and other elements among the samples can be clearly observed.

In order to obtain a first insight into the variability of the data set, the Compositional Variation Matrix (CVM) was calculated taking into account the 25 chemical elements (Buxeda, 1999; Buxeda and Kilikoglou, 2003). The CVM provides the total variation, which corresponds to a very high value ($tv = 3.55$), representative of a polygenic assemblage. The CVM also provides information on the variation that each element introduces into the data set; in this case, the highest values are related to K₂O, Rb, and P₂O₅. The examination of Figure 5b reveals that the variability in K₂O is mainly due to the higher values presented by samples DOL4 (4 wt%) and DOL8 (1 wt%) with respect to the rest of the *dolia* (0.2 - 0.6 wt%). The Rb content is also especially high in DOL4 (100 ppm) and also in DOL3 (36 ppm) and DOL8 (25 ppm), while in the rest of the samples the Rb values oscillate between 6 and 15 ppm. The high variability observed in P₂O₅ is mainly due to differences in the composition of this element among the *dolia* analysed. In most of the samples, the P₂O₅ values range from 0.03 wt% (in DOL3) to 0.2 wt% (in DOL8 and DOL10); however, the values are higher in the specimens DOL5 (0.5 wt%) and DOL3 (0.3 wt%). The variability in P₂O₅ could be related to post-depositional alterations occurred in the wares presenting higher values. These perturbations are common in pottery deposited in anthropised environments such as cultivated areas or in contact with burials (Maritan and Mazzoli, 2004; Maritan *et al.*, 2009).

Further multivariate statistical treatment was carried out in order to visualise the distribution of the pottery sherds according to the (dis)similarity of the compositional data. First, the subcomposition Fe₂O₃ (as total Fe), Al₂O₃, MnO, TiO₂, MgO, CaO, Na₂O, K₂O, Rb, Th, Nb, Zr, Y, Ce, Ga, V, Zn, Cu, Ni and Cr was log-ratio transformed using SiO₂ as divisor (Buxeda, 1999). Then, a Cluster Analysis (CA) was performed by means of the centroid agglomerative method and the squared Euclidean distance. The dendrogram (Fig. 5c) shows that most of the *dolia* are clustered in a single group, while three individuals (DOL3, DOL4 and DOL8) appear more distanced due to some differences in their chemical composition. The main group includes all the specimens characterised to present high CaO (12 - 19 wt%) and Cr (114 - 171 ppm) contents, and lower Na₂O (0.05 - 0.15 wt%), Rb (6 - 15 ppm) and Cu (1 -

7 ppm) values than the rest of the samples. Among these individuals, the composition of DOL5 slightly differs. It consists of a border calcareous fabric (CaO 4.2 wt%) with higher concentrations in Fe₂O₃ (6 wt%), Al₂O₃ (18.5 wt%), TiO₂ (1.18 wt%), SiO₂ (59.7 wt%), Nb (22 ppm), Zr (327 ppm), Ga (22 ppm) and V (109 ppm). DOL3 and DOL4 exhibit low Fe₂O₃ and Cr content, high CaO, Al₂O₃, Ga and V values, as well as the highest MnO, Rb, Pb and Zn concentrations. However, main chemical difference between these two *dolia* concerns the K₂O content, which is higher in DOL4 (4 wt%). DOL8 is also calcareous and exhibits low Fe₂O₃, Al₂O₃, TiO₂, Th, Nb, Ga, V and Ni concentrations. It mainly differs due to the Na₂O content (0.34 wt%), which is the highest value of the dataset.

According to the chemical data, nine of the twelve *dolia* analysed could be attributed to a single pottery production, which includes *dolia* found in different sites located in the Drôme, Hérault and Aude departments. The *dolia* DOL3, DOL4 and DOL8 exhibit major chemical differences and should be considered as different productions, although they were manufactured using similar raw materials to those of the main group, which were processed in an analogous way.

Even if the variability observed among the *dolia* analysed is very high, we have to highlight that they consist in very coarse fabrics, which generally exhibit higher intrinsic variability than the fine pastes. Therefore, the compositional differences highlighted by geochemical analyses could be interpreted as both, the use of distinct clay deposits for a single production centre during the period of activity, or the proof of the existence of several workshops located in a neighbouring zone or in nearby areas with similar geological characteristics.

Mineralogical characterization

The XRD analysis of the twelve *dolia* has enabled the identification of the mineralogical composition and to obtain an estimation of the equivalent firing temperatures (EFT) (Cultrone *et al.*, 2001; Maggetti *et al.*, 2011). The diffractograms point to the presence of quartz, calcite and illite-muscovite as the main primary mineralogical phases. K-feldspars and plagioclase appear in a minor degree. Hematite is the iron oxide found in the *dolia* fired in oxidising conditions, while magnetite was found on DOL3, the single specimen presenting a dark matrix derived of its firing in reducing conditions (Fig. 6). The only clear firing phase identified is gehlenite, which has been detected in all the samples except in the border-calcareous *dolium* DOL5.

		Fe2O3	Al2O3	MnO	P2O5	TiO2	MgO	CaO	Na2O	K2O	SiO2	Ba	Rb	Th	Nb	Pb	Zr	Y	Sr	Ce	Ga	V	Zn	Cu	Ni	Cr	LOI
Group 1 (n=11)	a.m.	4,9	17,5	0,01	0,20	1,05	0,3	16,2	0,1	0,4	59	273	15	17	21	26	305	26	83	42	21	108	26	5	27	173	14,3
	Standard deviation	0,9	2,4	0,01	0,13	0,13	0,1	4,9	0,1	0,3	3,1	165	11	2	2	11	32	3	11	17	3	17	5	3	6	32	2,6
Group 1A (n=6)	a.m.	5,2	17,9	0,01	0,14	1,07	0,3	16,8	0,1	0,3	58	186	11	18	21	24	303	27	81	43	22	114	25	4	30	191	15,0
	Standard deviation	0,3	0,9	0	0,1	0	0	1,9	0,1	0,1	1,8	77	4	1	1	2	30	2	6	20	1	12	3	2	4	15	1,4

	Fe2O3	Al2O3	MnO	P2O5	TiO2	MgO	CaO	Na2O	K2O	SiO2	Ba	Rb	Th	Nb	Pb	Zr	Y	Sr	Ce	Ga	V	Zn	Cu	Ni	Cr	LOI
DOL001	5,7	17,3	0	0,1	1,10	0,3	14,2	0,2	0,3	60,6	247	6	18	22	27	327	27	87	27	21	110	30	8	31	189	13
DOL002	5,3	17,3	0	0,1	0,99	0,3	17,8	0,2	0,3	57,5	155	12	17	20	23	296	24	79	31	20	116	22	3	26	202	15
DOL003	4,0	20,8	0	0,3	1,11	0,3	12,0	0,1	0,7	60,5	297	42	18	22	58	272	26	82	57	26	121	39	11	19	104	14
DOL004	3,8	21,0	0	0,1	0,99	0,5	13,6	0,2	4,4	55,3	261	111	23	22	96	227	24	111	64	27	109	46	15	24	105	9,8
DOL005	6,7	20,4	0	0,5	1,31	0,2	4,6	0,1	0,2	65,9	279	9	20	25	25	361	31	80	42	24	121	28	5	36	200	9,3
DOL006	5,1	17,1	0	0,1	1,10	0,3	16,2	0,1	0,6	59,4	94	18	17	22	20	333	26	83	24	22	108	26	3	24	180	14
DOL007	5,0	18,8	0	0	1,05	0,3	16,6	0,1	0,3	57,8	112	9	17	21	26	301	31	74	74	23	136	22	5	30	215	15
DOL008	3,6	13,2	0	0,2	0,81	0,4	17,5	0,4	1,2	62,7	420	29	14	16	23	270	23	114	47	16	79	24	4	19	147	14
DOL009	5,3	19,2	0	0,2	1,08	0,3	16,1	0,1	0,3	57,5	220	7	17	21	23	250	28	77	62	22	112	27	3	36	183	16
DOL010	4,9	17,9	0	0,2	1,10	0,2	19,8	0,1	0,3	55,3	287	12	19	22	24	310	27	88	43	22	104	25	3	30	175	17
DOL011	4,6	16,7	0	0,1	1,02	0,3	20,6	0,1	0,2	56,2	685	7	16	21	16	320	25	79	29	20	93	21	2	25	165	17
DOL012	3,6	13,4	0	0,1	0,92	0,3	22,8	0,1	0,4	58,3	206	16	13	18	21	321	22	74	23	17	83	24	5	20	138	18

Figure 5: Normalised chemical results of the *dolia* obtained by WD-XRF. Concentrations of major and minor oxides are in %, other minor and trace elements are in ppm, and the lost on ignition (LOI) in %. a./ Group 1 and 1A averages. b./ Individual samples results. c./ Dendrogram resulting from the cluster analysis of the twelve analysed *dolia*.

Figure 5 : Résultats chimiques normalisés des *dolia* obtenus par WD-XRF. Les concentrations majeure et mineure des oxydes sont exprimées en %, les autres mineurs et éléments traces sont en ppm, et la perte au feu (PAF) est en %. a./ Moyenne des groupes 1 et 1A. b./ Résultats par échantillons. c./ Dendrogramme résultant de l'analyse de grappe des douze *dolia* analysés.

Gehlenite is a metastable phase produced in calcareous pastes fired at temperatures up to 800°C. The crystallisation of gehlenite derives of the thermal reactions that occur in the primary Ca-rich material until it becomes a fired clay ceramic (Cultrone *et al.*, 2001; Trindade *et al.*, 2009; Maggetti *et al.*, 2011; Fabbri *et al.*, 2014). Under prolonged firings, carbonates decompose through decarbonation at temperatures between 600°C and 800°C, depending on the type and grain-size. During this process, carbon dioxide gas (CO₂) is released, and free-lime (CaO) is formed. Up to 800°C the dehydroxylation of the clay minerals to form the pseudo-amorphous phase of meta-clay takes place. During

this process, the free-lime of the decarbonated calcite reacts with Si and generates nucleation and crystallization of several metastable phases such as gehlenite and diopside, which continuously react with increasing temperature. Gehlenite starts to crystallise at temperatures ranging from 800°C to 850°C, while diopside occurs at c. 800-850°C but in very low concentration and forms drastically at 900-950°C. According to these data, the equivalent firing temperature of the twelve *dolia* analysed has been estimated around 850°C. A lower firing temperature (below 850°C) is suggested to the *dolium* DOL5 since its diffractogram only exhibits primary phases.

Figure 6: Diffractograms of representative *dolia*; cal= calcite; gh= gehlenite; hm= hematite; ill= illite- muscovite; kfs= K-feldspar; pl= plagioclase; mag= magnetite; qtz= quartz.

Figure 6 : Diffractogramme représentatif des *dolia* étudiés; cal= calcite; gh= gehlenite; hm= hematite; ill= illite- muscovite; kfs= K-feldspar; pl= plagioclase; mag= magnetite; qtz= quartz.

5. DISCUSSION: CHARACTERISTICS OF AN UNUSUAL PRODUCTION

Signs of technological optimization

The study of the technological characteristics of *dolia* with calcite tempers points to the unprecedented technical optimization of *doliaire* craftsmanship, highlighting once again the extraordinary sophistication of this production. In particular, this progress is perceptible in the “recipe” used for paste preparation. The respective quantities of clay and temper were determined based on the comparative tables generally used for sedimentary petrographic descriptions (Terry and Chilingar, 1955). According to these tables, the proportion of calcite temper is around 20 %. In this way, we estimated that nearly 560 kg of unfired clay and 160 kg of temper were required for the manufacture of a *dolium* of 15 hl (Carrato, 2017, p.133).

The abundance of calcite deposits may explain the predominant use of this temper, but from a technical perspective, it nonetheless raises difficulties during firing, as primary calcite starts to decompose at 700-750°C and their total decomposition creates porosities. In addition, clay and calcite present divergent reactions during firing, putting pressure on the cohesion of the paste; clay reduces in volume when heated whereas calcite dilates (Cultrone, *et al.*, 2001; Trindade, *et al.*, 2009, 2010; Maggetti, *et al.*, 2011; Fabbri, *et al.*, 2014). XRD analyses were undertaken to rule out perturbations in the chemical and mineralogical composition of the samples due to weathering processes, but they also allow for the detection of primary crystalline phases, or modifications linked to firing. All the *dolia* analysed show predominant primary crystalline phases and only gehlenite as incipient firing phase, suggesting low firing temperatures in all the cases. However, thin section observation shows that the crystals near the surface, in direct contact with the laboratory atmosphere, were often destabilized, whereas the elements near the heart of the paste did not undergo any modification. These differences are due to the fact that the *dolia* have very thick walls and the effects of the temperature during the firing were smaller in the core of the walls than in the surfaces.

The low temperatures required to not destabilize the calcareous inclusions involved a great control of the firing process. At the same time, this low temperature undoubtedly represented significant fuel saving, indicating the will of the workshop owners to reduce production costs by implementing technological improvements. On the other hand, this decrease in temperature did not guarantee optimal clay firing, although it seems to improve the fracture tough-

ness, which was also enhanced by adding large amounts of non-plastic inclusions of different size and composition to a Fe-rich clayey material (Kilikoglou, *et al.*, 1995, 1998; Vekinis and Kilikoglou, 1998; Tite, *et al.*, 2001). The study of the composition of the group 1 paste suggests that the choice of calcite may be interpreted as a deliberate act aiming to reduce the quantity of fuel necessary for *dolia* firing and consequently, to reduce production costs.

An ideal geographic implantation; the hypothesis of the Middle Rhône Valley

The calcite temper group 1 presents a more extensive diffusion zone than all of the other pastes identified in Narbonese Gaul (Fig. 7). It is recorded from Lyon to Narbonne, in the Rhône Valley and along the Languedoc coastline, over nearly 400 km. Specimens from hinterland sites, such as the Middle Hérault Valley, have also been identified. Lastly, a specimen was found near Marseille, on the site of the Garanne *villa* at Berre-l'Étang (Bouches-du-Rhône), which seems to correspond to the easternmost evidence of this paste.

The size of these *dolia* production installation(s) must have been considerable, in view of the diffusion area of *dolia* and the number of vessels. Paradoxically, archaeological research has not revealed any such installations in Narbonese Gaul. In fact, the identification and excavation of *dolia* workshops are almost inexistent in the province. As mentioned above, only the Saint-Bézard workshop at Aspiran (Mauné, *et al.*, 2006) has yielded two large kilns, and traces of a third kiln, clearly designed to fire these large terracotta containers. Other workshops are often assumed to have existed, but no comparable production structures have ever been brought to light⁵.

5. For example, we refer here in particular to about fifteen alleged workshops in France with elements discovered during prospection or excavations. The identification of some of them is based on solid markers (stamps, traces of large kilns, paste with local temper, large basin for clay preparation), such as: le Petit-Clos II-III in Perpignan (Pyrénées-Orientales) (Kotarba, *et al.*, 2007, pp. 482-489); Salauze in Laure-Minervois (Aude) (Malignas, *et al.*, 2008); Mas de Bourgade in Servian (Hérault) (Mauné, 2003b) and Capitou in Servian (Hérault) (Mauné, 2014, p. 157). Other identifications are based on less reliable evidence, in particular on overfired *dolia* elements, which were frequently reused. This is the case for the sites of: Poujols in Laissac (Aveyron) (Gruat, *et al.*, 2011, p. 187); rue de la Piale in Albi (Tarn) (Cambon, *et al.*, 1995, p. 59); Fount-de-Rome in Fleury-Saint-Pierre (Aude) (Dellong, 2003, pp. 537-539); Téoulet in Villepsy (Aude) (Passelac, 2007, p. 115); Clairac I in Béziers (Hérault) (Ugolini and Olive, 2012); Grangettes in Puissalicon (Hérault) (info. G. Fédère); La Garcine in Mirabeau (Vaucluse) (Tallah, 2004, p. 279); Tournon in La Bouilladisse (Bouches-du-Rhône) (Rothé and Trezigny, 2005, p. 789); la Pinède in Castellet (Var) (Brun, 1999,

Although the workshop cannot be accurately located, the available markers nonetheless allow us to suggest a working hypothesis about the production area location. By combining data related to the location of the archaeological evidence and the petrographic composition of the samples analysed, we can assume that the production zone is near the Rhône, where calcareous formations and karstic caves are abundant. In addition, the composition of the alluvial sand, with few elements from the metamorphic and granitic bedrock of the Massif Central, could point to the hypothesis that the workshop or workshops should be probably located on the left bank of the Rhône. However, metamorphic and granitic elements of this type are so rare that a production zone on the Rhône could be ruled out. These markers may imply that the production zone is on a tributary of the Rhône, with a left bank confluence.

The two most likely production zones going up the Rhône from Arles to Lyon are the Rhône-Drôme confluence and Rhône-Roubion. These two sectors are about fifteen kilometres apart, and contain alluvial sands with this composition, as well as large quantities of karstic calcite, in particular in the caves of the Diois Valley, near the Drôme River. Moreover, the geological map reveals that Pliocene clay deposits are very abundant in this sector, mainly on the right bank of the Drôme between Livron-sur-Drôme and Crest and on both banks of the Roubion between Saint-Marcel-lès-Sauzet and La Laupe (Fig. 8).

The toponymy in the northern sector of the Drôme-Rhône confluence indicates a brick and tile tradition in this area. Three hamlets called “La tuilière – tilemaking”, “La tuilerie – the tiler” or “La potière-potter” and seven modern tileries were identified in this zone, which is about fifteen kilometres long. In addition, the location of these sites on the edge of the Drôme and the abundance of raw materials make this sector an ideal choice for manufacturing. A study of the archives and early geological maps confirms that the history of pottery activities in this zone goes back a long way. In a book dating to 1835, M. Delacroix wrote that the production of bricks and tiles was so important that it supplied the whole department with construction materials (Delacroix, 1835, p. 374). In the same passage he cites the townlands with the most active production⁶. We observe that the latter are situated along the left bank of the Rhône or at the confluence of the Rhône and the Drôme. The geological map of Crest dated to 1977 also states that

pp. 314-416) and Saint-Ariès in Ventavon (Hautes-Alpes) (Guillaume, 2004).

6. Mirmande, Hauterives, Saillans, Crest, le Bourg-lès-Valence, Loriol, Montboucher, Chabeuil, Érome, Ponsas, Eymeux, la Garde-Arhémar and Savasse.

Figure 7: (See colour plate XII) Diffusion map of group 1 *dolia* with calcite temper and hypothetical location of the production workshop (H. Bohbot and C. Carrato).

Figure 7 : (Voir planche couleur XII) Carte de diffusion de *dolia* du groupe 1 à dégraissant de calcite et emplacements supposés de la zone de production (H. Bohbot et C. Carrato).

the numerous tileries used the Pliocene clay between Livron-sur-Drôme and Crest⁷.

In the southern sector of the Rhône-Roubion confluence, the former Saint-Marcel-lès-Sauzet priory was named *in loco Fellinis* in 985 by Count Lambert, which is the modern trend of *Figlinae* latin name for potter workshop. The change of name came about during the next generation when Sauzet castle became a county seat (Bois, 1995). In a document dated to 1789, significant “tile earth” deposits are declared to be unused due to a lack of wood. The Roubion was floatable like the Drôme.

In our opinion, all of these elements reinforce the possibility that raw material deposits were exploited in ancient times in the middle Rhône Valley, between Montélimar and Loriol-sur-Drôme. The position of these deposits near a river would also have facilitated production exportation by river. Unfortunately, the archaeological map (Planchon, *et al.*, 2010) reveals little information

about ancient settlement in this sector. The rare operations carried out there have mainly recorded an important sedimentary cover of the alluvial plain, which seems however to be less important in the southern production zone. However, if one or several workshops using this paste with calcite temper were in operation during ancient times, then traces of this pre-industry may not have totally disappeared in this zone.

In order to validate these assumptions, magnetic prospections are planned in the coming years. However, this research should be preceded by a mapping work (old and recent maps) to limit the size area of intervention. This will include the removal of urbanised areas or areas that have undergone major redevelopment since Antiquity but also the target of the most suitable areas taking into account topographical data. Likewise, if the area to be explored remains too large, prospecting may be limited to a 10-20 km strip along the course of the rivers, considering the importance of proximity to the river tracks for this activity.

A providential chronology; a concomitant development of provincial viticulture

The comparison of the chronology of the advent of this group of paste with the development of wine making and olive growing in the Narbonnese province points to a similar

7. Outside this area, the geological map of Montélimar from 1979 also mentions the exploitation of clay, but also marls from the Upper Aptian, the Upper Cretaceous and the Pliocene, on the banks of the Rhône by brickworks or pottery centres. On the Dieulefit map dating from 1969, white or grey clay levels made up of 90% kaolinite were used for making fine pottery. On the other hand, for the rest of the Drôme department, the geological maps of Nyons, Valréas, Die, Luc-en-Diois and Valence do not mention any exploited clay deposits.

Figure 8: (See colour plate XII) Geological map of the two production areas suggested by the cross of archaeological, archaeometrical, geological and toponymic data (BRGM, 2019).

Figure 8 : (Voir planche couleur XII) Carte géologique des deux zones de production suggérées par le croisement des données archéologiques, archéométriques, géologiques et toponymiques (BRGM, 2019).

expansion. The evidence seems to imply that the centre or centres of *dolia* production with calcite temper developed in response to the significant increase in wine and oil production during the Tiberian period, between 20 and 40 A.D.

The scale of manufacture characteristic of this production area is perfectly clear when we examine the general chronology of *doliare* manufacture during the Roman period in Narbonese Gaul. According to our knowledge, it appears that the earliest identified workshops, dating from the end of the first century B.C. and the first decades of the first century A.D., seem to correspond to domanial production structures with micro-regional and regional diffusion (Carrato, 2017, pp. 159-164). The emergence of a workshop during the period ranging from 20 to 40 A.D.⁸, with much

more intensive production activity than previously recorded, thus upsets this relatively stable pattern. This stage seems to represent a change in the production process, although it was not possible to determine whether small workshops regressed as a result of this new competition.

In any event, the study of the sites from this period shows that the use of *dolia* with calcite temper became widespread in most of the Narbonese province, apart from the southeast quarter. From the Claudian period onwards, these workshops became the sole suppliers of the *dolia* used in the whole Rhône Valley, and also became predominant in the western zone of the province, as far as Narbonne.

As an example of this supremacy, the 350 *dolia* from storehouse 1 from the Vareilles *villa* in Paulhan (Hérault), one of the largest known storehouses in Narbonese Gaul (Mauné, 2003a), come from this workshop, which is theoretically located nearly 250 km from there.

The acceleration of *dolia* production as a result of the creation of large production centres with wide diffusion zones

8. In the Drôme, storehouses of *dolia* with this paste, located near the alleged production zone, are dated to the second quarter or the middle of the first century A.D. at the earliest (in Chabrilan, Saint-Martin 1 (Bonnet and Horry, 2010) and Donzère, Le Molard (Odiot, 1996). In the Hérault, this paste is evidenced in *dolia* in wine storehouses installed during the same period. At the site of Saint-Bézard in Aspiran (Carrato, 2017) for example, they are not used in the first phase of the storehouse dated to 17/25 A.D. – where locally made *dolia* are used – but are massively used during the reconstruction of the southern angle of the storehouse at around 50/60 A.D. In the neighbouring *villa* of Vareilles at Paulhan

(Mauné, 2003a), the large storehouse 1 equipped with *dolia* with this paste was built during the fifth decade A.D. Further away, at the site of Port la Nautique in the Aude, *dolia* from this production appear in levels dated to 20-40 A.D. (Carrato, 2017, p. 161).

corresponds chronologically to the expansion of viticulture, and to a lesser extent of olive growing (Brun, 2005; Brun and Laubenheimer, 2001). This point is perfectly illustrated by the increase in storage capacities from the first half of the first century B.C. onwards, closely followed by the multiplication of the number of operations (Carrato, to be published), by the decrease in importations of Spanish wine amphorae at the end of the Augustan period (Duperron, 2014, p. 140, pp. 145-146) and by the emergence at the same time of local and regional workshops producing wine amphorae (Laubenheimer, 1985; Laubenheimer and Schmitt, 2009; Mauné, 2009; 2013). From the second half of the second century A.D., the number of newly created centres decreased sharply, as did storage capacities and the number of amphora workshops, clearly demonstrating the early stages of the third century economic downturn.

6. CONCLUSIONS: THE PROOF OF PRE-INDUSTRIAL *DOLIA* MANUFACTURE

This overview enabled us to show that the archaeometric analysis of a considerable batch of *dolia* fragments from use contexts can lead to the extraction of unprecedented markers of the production and transport conditions of the largest known ceramic vessel during antiquity.

Through the study of significant corpus of *dolia* with calcite temper, we can decipher the means used by the economic actors of the Narbonese province to meet the exponential demand for these containers, alongside the unprecedented development of local viticulture from the first quarter of the first century A.D. onwards. The development of the alleged large workshop supports the intensity of production, made possible by certain technical optimizations leading to the reduction of firing time, and the scale of the diffusion range of the *dolia*, probably favoured by an implantation along the Rhône in order to take advantage of this major circulation route.

On account of the degree of optimization of production means and the constant quest for profitability, this unprecedented discovery revives the debate on the characterization of the Roman economy, which periodically presents pre-industrial characteristics. This overview also underscores once again the interest of studying objects on a regional scale, in order to bring to light poorly known economic mechanisms, which remain inaccessible for global studies.

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References

- Bois, M., 1995. Le prieuré de Saint-Marcel-lès-Sauzet (Drôme), In: *Congrès Archéologique de France 150^e session Moyenne vallée du Rhône 1991*. p. 231-238.
- Bonnet, C. and Horry, A., 2010. Céramiques de la basse vallée de la Drôme du I^{er} s. av. J.-C. au VI^e s. apr. J.-C.; les sites de Saint-Martin et l'Hortal à Chabrillan (Drôme). *Revue Archéologique de la Narbonnaise*, 43, p. 255-290.
- Brun, J.-P., with coll. of Borréani, M., 1999. *Le Var*. Paris, CNRS.
- Brun, J.-P., 2005. *Archéologie du vin et de l'huile en Gaule romaine*. Paris, Errance.
- Brun, J.-P., and Laubenheimer, F., eds., 2001. *La viticulture en Gaule*. Paris, CNRS.
- Buxeda i Garrigós, J., 1999. Alteration and contamination of archaeological ceramics: the perturbation problem. *Journal of Archaeological Sciences*, 26, p. 295-313.
- Buxeda i Garrigós, J. and Kilikoglou, V., 2003. Total Variation as a Measure of Variability in Chemical Data Sets, a L. van Zelts (ed.), *Patterns and Process: a Festschrift in honour of Dr. Edward V. Sayre*, Smithsonian Centre for Materials Research and Education, Suitland, Maryland, pp. 185-198.
- Cambon, C., Carozza, L., Malet, L., Provost, M., Devillers, B., Gangloff, N., Ruffat, A. and H. and Salinier, J.-F., 1995. *Le Tarn*. Paris, CNRS.
- Carrato, C., 2017. *Le dolium en Gaule narbonnaise (I^{er} a.C.-III^e p.C.). Contribution à l'histoire socio-économique de la Méditerranée nord-occidentale*. Bordeaux, Ausonius Edition.
- Carrato, C., to be published. Dynamique de la production vinicole en Gaule Narbonnaise à l'époque romaine à partir de l'étude des capacités de stockage (I^{er} s. av.-V^e s. apr. J.-C.). ». In *Report on the XIXth International Congress of Classical Archaeology, Cologne/Bonn, 22-26 may 2018*.

- Checa, M. U., 1901. Des bouteilles de seize milles litres. *Lectures pour tous, Revue Universelle illustrée*, 3^e année n°2 novembre 1901, p. 149-154.
- Cultrone, G., Rodriguez-Navarro, C., Sebastian, E., Cazalla, O., and De la Torre, M.J., 2001. Carbonate and silicate phase reactions during ceramic firing. *European Journal of Mineralogy*, 13, p. 621-634.
- Delacroix, N., 1835. *Statistique du département de la Drome*. Valence: de Borel.
- Dellong, E., with coll. of Moulis, D. and Farré, J., 2003. *Narbonne et le Narbonnais*, Paris, CNRS.
- Descemet, M. C., 1880. *Inscriptions doliaries latines; marques de briques relatives à une partie de la Gens Domitia*. Paris, E. Thorin.
- Duperron, G., 2014. *Arles et Lyon, ports fluviaux de l'Empire romain. Le commerce sur l'axe rhodanien du I^{er} s. av. J.-C. au VI^e s. apr. J.-C.*, Vol. 1 synthèse. Ph. D. Université Montpellier Paul Valéry.
- Fabbri, B., Gualtieri, S., and Shoval, S. 2014. Review. The presence of calcite in archeological ceramics. *Journal of the European Ceramic Society*, 34, p. 1899-1911.
- Gasperoni, T., 2003. *Le fornaci dei Domitii; ricerche topografiche a Mugnano in Teverina*. Viterbo, Università degli studi della Tuscia.
- Gasperoni, T., 2005. Nuove acquisizioni dai praedia dei Domitii nella valle del Fosso del Rio. In: C. Bruun and F. Chausson, eds. 2005. *Interpretare i bolli laterizi di Roma e della Valle del Tevere; produzione, storia economica e topografia: Atti del convegno. Roma 2000*. Roma: Acta Instituti Romani Finlandiae. p. 103-120.
- Giannopoulou, M., 2010. *Pithoi; technology and history of storage vessels through the ages*. Oxford: Archaeopress.
- Gruat, P., Malige, G. and Vidal, M., with coll. of ASPAA, 2011. *L'Aveyron*. Paris, CNRS.
- Guillaume, M., 2004. La villa de Saint-Ariès. In: A. Jourdin-Annequin (dir.), 2004. *Atlas culturel des Alpes occidentales; De la préhistoire à la fin du Moyen Âge*. Paris, Picard, p. 159-161.
- Kilikoglou, V., Vekinis, G., and Maniatis, Y., 1995. Toughening of ceramics earthenwares by quartz inclusions: an ancient art revised, *Acta Metallurgica et Materialia*, 43, p. 2959-2965.
- Kilikoglou, V., Vekinis, G., Maniatis, Y., and Day, P., 1998. Mechanical performance of quartz-tempered ceramics: Part I, Strength and toughness. *Archaeometry*, 40, p. 261-277.
- Kotarba, J., Castellvi, G. and Mazière, F., 2007. *Les Pyrénées-Orientales*. Paris, CNRS.
- Laubenheimer, F., 1985. *La production des amphores en Gaule narbonnaise*. Paris, Les Belles Lettres.
- Laubenheimer, F. and Schmitt, A., 2009. *Amphores vinaires de Narbonnaise; production et grand commerce. Création d'une base de données géochimiques des ateliers*. Lyon, Maison de l'Orient et de la Méditerranée Jean Pouilloux.
- Lazzeretti, A., and Pallecchi, S., 2005. Le figlinae polivalenti; la produzione di *dolia* e di mortaria bollati. In: C. Bruun and F. Chausson, eds. 2005. *Interpretare i bolli laterizi di Roma e della Valle del Tevere; produzione, storia economica e topografia: Atti del convegno. Roma 2000*. Roma: Acta Instituti Romani Finlandiae. p. 213-227.
- Maggetti, M., Neururer, C., Ramseyer, D., 2011, Temperature evolution inside a pot during experimental surface (bonfire) firing. *Applied Clay Science*, 53, p. 500-508.
- Malignas, A., Sachot, G., Sanchez, C. and Convertini, F., 2008. Découverte d'un atelier de céramiques culinaires à Laure-Minervois (Aude). In: L. Rivet, ed. 2008. *Actes du congrès de la SFECAG. Escala-Empuries 2008*. Marseille, SFECAG. p. 803-811.
- Maritan, L., and Mazzoli, C., 2004, Phosphates in archaeological finds: implications for environmental conditions of burial. *Archaeometry*, 46, p. 673-683.
- Maritan, L., Angelini, I., Artioli, G., Mazzoli, C., and Saracino, M., 2009, Secondary phosphates in the ceramic materials from Frattesina (Rovigo, North-Eastern Italy). *Journal of Cultural Heritage*, 10, p. 144-151.
- Martínez Ferreras, V., Capelli, C., Cabella, R., and Nieto Prieto, X., 2013. From Hispania Tarraconensis (NE Spain) to Gallia Narbonensis (S France). New data on Pascual 1 amphora trade in the Augustan period. *Applied Clay Science*, 82, p. 70-78.
- Martínez Ferreras, V., 2017. Analyses géochimiques des pâtes de *dolia* d'époque romaine provenant de Gaule Narbonnaise. In: C. Carrato. 2017. *Le dolium en Gaule narbonnaise (I^{er} a.C.-III^e p.C.). Contribution à l'histoire socio-économique de la Méditerranée nord-occidentale*. Bordeaux: Ausonius Edition. p. 22-241.
- Mauné, S., 2003a. La villa gallo-romaine de Vareilles à Paulhan (Hérault; fouille de l'Autoroute A75) un centre domanial du Haut-Empire spécialisé dans la viticulture ?. In: S. Lepetz and V. Matherne, eds. 2003. *Cultivateurs, éleveurs et artisans dans les campagnes de Gaule romaine, matières premières et produits transformés: Actes du V colloque AGER*, Compiègne 2002. Amiens, Revue Archéologique de Picardie. p. 309-337.
- Mauné, S., 2003b. Paysage et usages du sol dans la région de Béziers (Gaule narbonnaise) entre le I^{er} s. av. J.-C. et le III^e s. apr. J.-C. In: L. Labruna and R. Pierobon, dir. 2003. *Paesaggio e utilizzazione della terra: diritto, economia, società: Atti del convegno internazionale, Roma 1999*. Roma: Quaderni camerti di studi romanistici. p. 250-294.
- Mauné, S., 2009. *Recherches récentes sur les ateliers de potiers de Gaule narbonnaise; contribution à l'histoire socio-économique d'une province romaine (I^{er} s. av. J.-C.-III^e s. apr. J.-C.)*. Habilitation à diriger des recherches, Montpellier-Lattes.

- Mauné, S., 2014. Entre Thongue et Libron (Hérault), une forêt aux portes de la colonie romaine de Béziers (I^{er}-III^e s. apr. J.-C.). In: F. Favory, dir. 2014. *Silva et Saltus en Gaule romaine: dynamique et gestion des forêts et des zones rurales marginales: Actes du VI^e colloque AGER, Rennes 2004*. Besançon, Presses Universitaires de Franche-Comté. p. 147-174.
- Mauné, S., Bourgaud, R., Lescure, J., Carrato, C. and Santran, C., 2006. Nouvelles données sur les productions céramiques de l'atelier de Dourbie à Aspiran (Hérault) (première moitié du I^{er} siècle apr. J.-C.). In: L. Rivet, ed. 2006. *Actes du congrès de la SFECAG, Pézenas 2006*. Marseille, SFECAG. p.157-188.
- Odiot, T., 1996. Donzère-Le Molard. In: *Harur, Formes de l'habitat rural en Gaule narbonnaise* 3, Spécial villa romaine. Juans-les-Pins, APDCA. p. 38-62.
- Pagès, G., 2008. *La métallurgie du fer en France méditerranéenne de l'Antiquité au début du Moyen Âge: jalons d'une approche interdisciplinaire*. Ph. D. Université Montpellier III Paul Valéry.
- Pallecchi, S., 2012. Appunti sull'organizzazione del lavoro negli stabilimenti romani per la produzione di ceramica pesante. In: A. Ciacci, P. Rendini and A. Ziffero, eds. 2012. *Archeologia della vite e del vino in Toscana e nel Lazio: dalle tecniche dell'indagine archeologica alle prospettive della biologia molecolare*. Borgo San Lorenzo, All'insegna del gilio. p. 469-484.
- Passelac, M., 2007. Ateliers céramiques domaniaux du bassin audois au Haut-Empire. In: J. P. Nolla Brufau, dir. 2007. *Pottery workshops and agricultural productions*. Girona, Universitat de Girona, p. 115-137.
- Planchon, J., Bois, M. and Conjard-Réthoré, P., 2010. *La Drôme*. Paris, CNRS.
- Romero Vidal, A. and Cabasa Calpe, S., 1999. *La Tinajería tradicional en la cerámica española*. Barcelona: Ediciones Ceac.
- Rothé, M.-P. and Tréziny, H., 2005. *Marseille et ses alentours*. Paris, CNRS.
- Steinby, E.M., 1993. Ricerche sull'industria *doliare* nelle aree di Roma e di Pompei; un possibile modello interpretativo? In: C. Zaccaria, ed. 1993. *I Laterizi di età romana nell'area nordadriatica: Atti del convegno, Udine 1987*. Roma, l'Erma di Bretschneider, p. 9-14.
- Tallah, L., 2004. *Le Luberon et Pays d'Apt*. Paris, CNRS.
- Terry, R. D. and Chilingar, G. V., 1955. Summary of Concerning some additional aids in studying sedimentary formations. *Journal of Sedimentary Petrology*, 25, pp. 229-234.
- Tite, M.S., Kilikoglou, V. and Vekinis, G., 2001. Review Article. Strength, toughness and thermal shock resistance of ancient ceramics, and their influence on technological choice. *Archaeometry*, 43, 3, p. 301-324.
- Tremoleda, J., Castanyere, P., Simon, J., Andrea Ferrer, A. 2018. *La Bòbila d'Ermedàs (Cornellà del Terri). Una indústria de producció d'època romana al Pla de l'Estany*, Girona, Universitat de Girona, Institut de Recerca Històrica.
- Trindade, M.J., Dias, M.I., Coroado, J., and Rocha, F. 2009. Mineralogical transformations of calcareous rich clays with firing: A comparative study between calcite and dolomite rich clays from Algarve, Portugal. *Applied Clay Science*, 42, p. 345-355.
- Ugolini, D. and Olive, C., with coll. of Gomez, E., 2012. *Béziers*. Paris, CNRS.
- Vaz Pinto, I., 1997. *Dolia* de São Cucufate et jarres modernes de l'Alentejo; essai d'ethnoarchéologie. In: R. Etienne and F. Mayet, eds. 1997. *Itinéraires Lusitaniens; trente années de collaboration luso-françaises: Actes de la réunion, Bordeaux 1995*. Paris, de Boccard. p. 111-156.
- Vekinis, G. and Kilikoglou, V., 1998. Mechanical performance of quartz-tempered ceramics: Part II, hertzian strength, wear resistance and applications to ancient ceramics. *Archaeometry*, 40, 2, p. 281-292.