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From macrotraces to micro-tomography: a multi-scale approach for detecting and characterising the "Spiralled Patchwork Technology" in Northern Mediterranean Neolithic pottery assemblages

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Abstract: The macro- and mesoscopic analysis of the *Impresso-Cardial* pottery assemblage from the Pendimoun rock shelter located in Castellar (Alpes-Maritimes, France) revealed a range of previously unrecognised macrotraces and mesostructures on all pottery vessels, independently of their shape or size. These traces suggested a forming sequence involving the juxtaposition and merging of "spiralled patches". This *chaîne opératoire* is unique as it differs from all the operational sequences previously identified in the Early Neolithic contexts of Europe. The macrotraces and mesostructures indicative of the juxtaposition of spiralled patches are more or less visible depending on the state of preservation of the pottery. In addition, due to the lack of an archaeological or ethnographic reference framework, the observations need to be completed in order to confirm the underlying technical actions. These limitations have led us to implement a multi-scale approach based on the analysis of archaeological and experimental samples, combining analysis of microfabrics, 3D surface scanning (topographical analysis) and micro-computed tomography (µ-CT) at different resolutions. Non-destructive µ-CT enables the identification of forming techniques and methods through the 3D visualisation of the internal architecture of the vessels, including interfaces between assembled elements, porous system, and mineral inclusions. Here we present the criteria for identifying this unique forming sequence, as well as the multi-scale approach we developed to build an integrated frame of reference for SPT used to support our archaeological interpretations.

Keywords: ceramic technology, forming sequence, *chaîne opératoire*, macrotraces, microfabrics, µ-CT, technical tradition, European Neolithic

Résumé : Parce qu'elles dépendent du processus d'apprentissage durant lequel le producteur acquiert des automatismes difficilement modifiables, les chaînes opératoires céramiques révèlent des habitudes motrices et permettent d'identifier et de différentier des producteurs et, plus largement, des communautés de pratique. La restitution des séquences de gestes techniques sous-jacents au façonnage des poteries archéologiques se fonde prioritairement sur l'examen approfondi des macrotraces laissées par le producteur lors du montage. Cette étape cruciale de l'analyse s'appuie sur plusieurs études expérimentales ayant démontré que les différents types de pression appliqués sur la matière argileuse pendant le façonnage tendent à orienter les pores et les inclusions inhérents à la pâte selon des schémas spécifiques ; à produire des macroporosités de formes variées dans la structure interne de la poterie, par exemple à l'interface entre éléments assemblés ; et à laisser des signatures topographiques distinctes sur les surfaces des poteries.

L'analyse macro- et mésoscopique de l'assemblage céramique Impresso-Cardial provenant de l'abri sous roche de Pendimoun situé à Castellar (Alpes-Maritimes, France) a révélé un ensemble de macrotraces et de mésostructures jusqu'alors inédites. Identifiées sur l'ensemble des céramiques quels que soient leur forme ou leur format, ces traces suggèrent une séquence opératoire particulièrement complexe dans le cadre de laquelle les poteries sont façonnées par juxtaposition de « patches spiralés » d'environ 4,5 cm de diamètre. Ces patches, tous façonnés par enroulement d'un colombin en spirale, sont adjoints contre un support concave ou convexe pour former la partie inférieure des vases, puis positionnés en rangées pour monter leur partie supérieure. Les macrotraces et mésostructures diagnostiques de la « technique des patches spiralés » (« *Spiralled Patchwork Technology* », abrégé SPT) sont néanmoins plus ou moins visibles selon l'état de conservation des poteries analysées. En raison de l'absence de référentiels archéologique, expérimental ou ethnographique, les observations doivent en outre complétées afin de s'assurer des actions techniques à leur origine. Ces limites nous ont conduit à développer une approche multi-échelle fondée à la fois sur les échantillons archéologiques et sur des contrôles expérimentaux façonnés dans des conditions maîtrisées afin de développer un cadre de référence enrichissant la lecture des macrotraces et des mésostructures pour SPT. Cette démarche combine l'examen des microfabriques sur lames minces en plan tangentiel, l'analyse topographique des poteries *via* la restitution des surfaces en 3D et l'analyse de la structure interne des céramiques *via* la micro-tomographie (µ-CT).

Pour les céramiques, l'approche des microfabriques consiste à examiner les déformations plastiques et/ou la réorganisation spatiale des différentes unités structurelles composant les matériaux argileux (système poreux, inclusions de nature différente, matrice) à la suite des actions techniques qui y ont été appliquées. Cette approche offre une clé d'entrée cruciale pour appréhender la structure interne des céramiques de Castellar – Pendimoun. Validant l'emploi de modules spiralés comme éléments de base pour le façonnage des poteries des niveaux Impresso-Cardial, cette approche a permis de pister les signatures spatiales internes propres à la technique des patches spiralés.

Pour compléter ce référentiel, l'imagerie par micro-tomographie (µCT) a constitué un jalon essentiel du protocole développé : non invasive, cette méthode révèle avec une exceptionnelle lisibilité le système poreux et les inclusions non plastiques présentes dans l'argile en trois dimensions, ouvrant de multiples perspectives pour l'approche qualitative et quantitative des procédés de fabrication des céramiques anciennes. Dans le cadre de cette étude, les jeux de données µCT issues de tessons archéologiques et de briquettes expérimentales ont dans un premier temps été analysés qualitativement, afin d'identifier les traceurs spécifiques de la technique des patches spiralés dans la structure interne des échantillons. Dans un second temps, un protocole de traitement quantitatif des données µCT a été développé. Dans ce cadre, la transformée de Hough, un algorithme permettant la reconnaissance de formes, a été appliquée afin de pister automatiquement les principaux alignements dans les jeux de données. Ce travail de modélisation nous a permis de nous affranchir de la diversité des macrotraces et mésostructures observées sur les tessons archéologiques et expérimentaux et de proposer un cadre d'analyse des données indépendant de l'analyse visuelle des tessons. L'acquisition micro-tomographique de poteries à profil restitué, conduite dans un troisième temps, a ensuite fourni de précieuses informations sur la séquence opératoire complète de SPT. Cette démarche a en effet révélé les modalités exactes de juxtaposition des patches spiralés en rangées horizontales, une information qui n'était que partiellement accessible sur la base du seul examen macroscopique des surfaces et des sections des poteries. Des analyses corrélatives combinant µCT et analyses topographiques réalisées sur des récipients à profil restitué ont enfin permis d'établir un lien direct entre les caractéristiques de surface (convexités) et celles de la structure interne (alignements d'inclusions minérales organisées en spirales).

En définitive, le développement d'un protocole analytique combinant analyses en 2D et 3D a révélé un ensemble de caractéristiques diagnostiques de la technique des patches spiralés, qui consolident et enrichissent significativement nos interprétations initiales fondées sur la lecture macroscopique en surface et en section des céramiques. Les analyses des microfabriques *via* la micro-tomographie révèlent des marqueurs spécifiques de la technique des patches spiralés (par exemple, alignements d'inclusions minérales ou de pores) qui corroborent ceux identifiés par l'examen macroscopique des surfaces et des sections (par exemple, cassures, discontinuités, organisation générale de la pâte en section ou dans le plan tangentiel). À cet égard, le protocole développé pour l'analyse de l'assemblage céramique issue des niveau Impresso-Cardial de Castellar – Pendimoun fournit le premier référentiel pour la technique des patches spiralés et constitue une étape essentielle pour la démonstration de la mise en œuvre de cette tradition technique qui diffère de toutes les séquences opératoires précédemment identifiées dans les contextes du Néolithique ancien européen.

Mots-clés : technologie céramique, séquences de façonnage, chaîne opératoire, macrotraces, microfabriques, µ-CT, tradition technique, Néolithique européen

INTRODUCTION

The reconstruction of ceramic technical traditions is pivotal for understanding past societies' social structure and historical trajectories. Centred around the concept of *chaîne opératoire*, which defines a series of actions transforming raw material into a finished product (Cresswell, 1976), this approach enables to identify "ways of doing" passed on from generation to generation within given social groups. Invariably involving tutors and apprentices that are socially related, such transmitted "ways of doing" define traditions whose geographical extension outlines the perimeter of communities of practice (Roux, 2016). The reconstruction of the complete *chaînes opératoires* of pottery production encompasses the identification of the raw materials used and their modes of preparation, the forming and finishing sequences, the surface treatments and ornaments, the firing conditions and post-firing treatments, as well as the uses of the vessels. The detailed characterisation of these different stages of production and use among the earliest pottery productions of the Northern Mediterranean formed the main focus of the ANR CIMO project. As part of this project, the *Impresso-Cardial* ceramic assemblage recovered from the Pendimoun rock shelter at Castellar (Alpes Maritimes, France) acted as a key corpus, on which a wide array of high-resolution analytical protocols was developed and tested in order to reconstruct with an unprecedented resolution the entire ceramic technical sub-system (see Binder, Gomart *et al.*, this volume; Cassard *et al.*, this volume; Drieu *et al.*, 2020 and this volume; Gabriele *et al.*, this volume; Lardeaux *et al.*, this volume; Mouralis *et al.*, this volume).

The present article focuses on the high-resolution reconstruction of ceramic forming practices in the *Impressa* and Cardial layers of the site. The initial examination of the assemblage through the lens of fashioning techniques revealed an array of previously unrecognised macrotraces. Observed on the entire *Impressa* and Cardial assemblage independently from the vessels' morphology or size, these macrotraces were particularly challenging to decipher due to the lack of a frame of reference. Nevertheless, their thorough analysis enabled us to detect the implementation at the site of a unique fashioning sequence we termed "Spiralled Patchwork Technology" (SPT), and for which no archaeological nor experimental frame of reference was available (Gomart *et al.*, 2017). In order to test our technological hypothesis and build a complementary body of evidence, we developed a protocol combining different analytical methods and scales of observation, which include exhaustive macrotraces characterisation, pottery experiments, as well as 2D and 3D imaging (microfabrics, 3D surface scanning and micro-tomography). In addition, as part of the subsequent ToMat project, we developed a protocol for the quantitative processing of the complex micro-tomographic data we obtained using applied mathematics. Here we present the integrated analytical approach we developed for the detection and characterisation of SPT that enabled us to unravel the detailed pottery forming sequence implemented in the *Impresso-Cardial* layers at Castellar – Pendimoun, and more broadly in the *Impresso-Cardial* contexts located west of the Apennine range (Gomart, Binder, Gabriele *et al.*, this volume).

A NEW SET OF MACROTRACES AT PENDIMOUN, A NEW OPERATIONAL SEQUENCE FOR THE EUROPEAN NEOLITHIC

The *Impresso-Cardial* pottery assemblage from Castellar - Pendimoun: petrographic and stylistic variability

Located on the French Riviera in Castellar (Alpes Maritimes) at 690 m above sea level, the Pendimoun rock-shelter was extensively excavated between 1985 and 2006 (Binder *et al.*, 1993 and 2020). Along with the Arene Candide cave (Maggi, 1997; Binder and Maggi, 2001; Panelli, 2019), this site is one of the few occupations in the Western Mediterranean for which the internal periodisation of the *Impresso-Cardial* Complex can be detailed on the basis of stratigraphic observations. The initial Neolithic occupations of Castellar – Pendimoun, attributed to the beginning of the *Impressa* and then to the Cardial, are subdivided into a large number of stratigraphic units, and cover a large part of the 6th millennium, up to the emergence of the Square-Mouthed-Pottery Culture and Pre-Chassey features (Binder *et al.*, 1993). The stratified structures and deposits belonging to the *Impressa* stage have provided a large set of AMS dates performed on short-lived materials, including carbonised cereal seeds. The Bayesian modelling made it possible to date the initial phase PND-1A between 5730 and 5660 BCE, and the following PND-1B between 5650 and 5440 BCE (Binder *et al.*, 2017; Binder, Gomart *et al.*, this volume). The successive Cardial occupations (PND-2A and 2B) are respectively dated between 5440 and 5200 BCE in the northern sector, and between 5330 and 5020 BCE in the southern sector of the site (Binder *et al.*, 2017; Binder, Gomart *et al.*, this volume). The associated ceramic assemblage, that includes a minimum number of 211 vessels, is characterised by a wide range of shapes and sizes, including collared and spheroidal vases, as well as open truncated conical and cylindrical pots, often with a flattened base. The pottery is characterised by a variety of decorations made with diverse tools (Binder and Sénépart, 2010; Cassard, 2020; Cassard *et al.*, this volume). The petrographic analysis of the clay materials exploited for pottery manufacturing revealed the use of three types of clay materials: first, glauconitic clay materials accessible in the vicinity of the site; second, clay materials stemming from the alterations of granitic rocks the potential sources of which are more distant; and third, artificially mixed pastes including both granitic and glauconitic clay materials (Binder and Sénépart, 2010; Gabriele, 2014; Gabriele *et al.*, this volume; Lardeaux *et al.*, this volume).

Pottery surface and section analysis

The reconstruction of the sequences of technical gestures underlying pottery forming relies first and foremost on the thorough identification of macroscopic features and meso-structures left by the producer during pot building. This crucial step of analysis is based on experimental and ethnographical studies (Rye, 1981; Pierret *et al.*, 1996; Roux, 2016 and 2019) which have shown that the different types of pressure applied on plastic clay material during pottery forming tend, first, to orient the pores and inclusions that are inherent to the paste according to specific patterns; second, to produce macro-porosities of various shapes in the pottery internal structure, for instance at the interface between assembled clay elements; and third, to leave distinct topographical signatures on pottery surfaces. Therefore, the macro- and mesoscopic analysis of the Castellar – Pendimoun assemblage focused on the complete *Impresso-Cardial* pottery assemblage and centred on the vessels' surface topography, as well as on the shape, orientation and spatial distribution of the voids and non-plastic inclusions in radial and equatorial sections, and in the tangential plan. Macrotrace and mesostructure reading was conducted with the naked eye, as well as using a magnifying glass and a binocular microscope. It was complemented by 3D surface scanning of the whole corpus that allowed a high-resolution analysis of the vessels' surface topography (Cassard *et al.*, this volume).

This comprehensive reading revealed a series of macrotraces on the examined pottery vessels, visible on their base, body and rim:

– The vast majority of the vases show breakage and fracture networks that are predominantly arciform or circular (fig. 1, red dashed lines), to the extent that many sherds are characterised by a circular shape. These circular sherds measure between 42 and 49 mm in diameter and are between 9 and 13 mm thick.

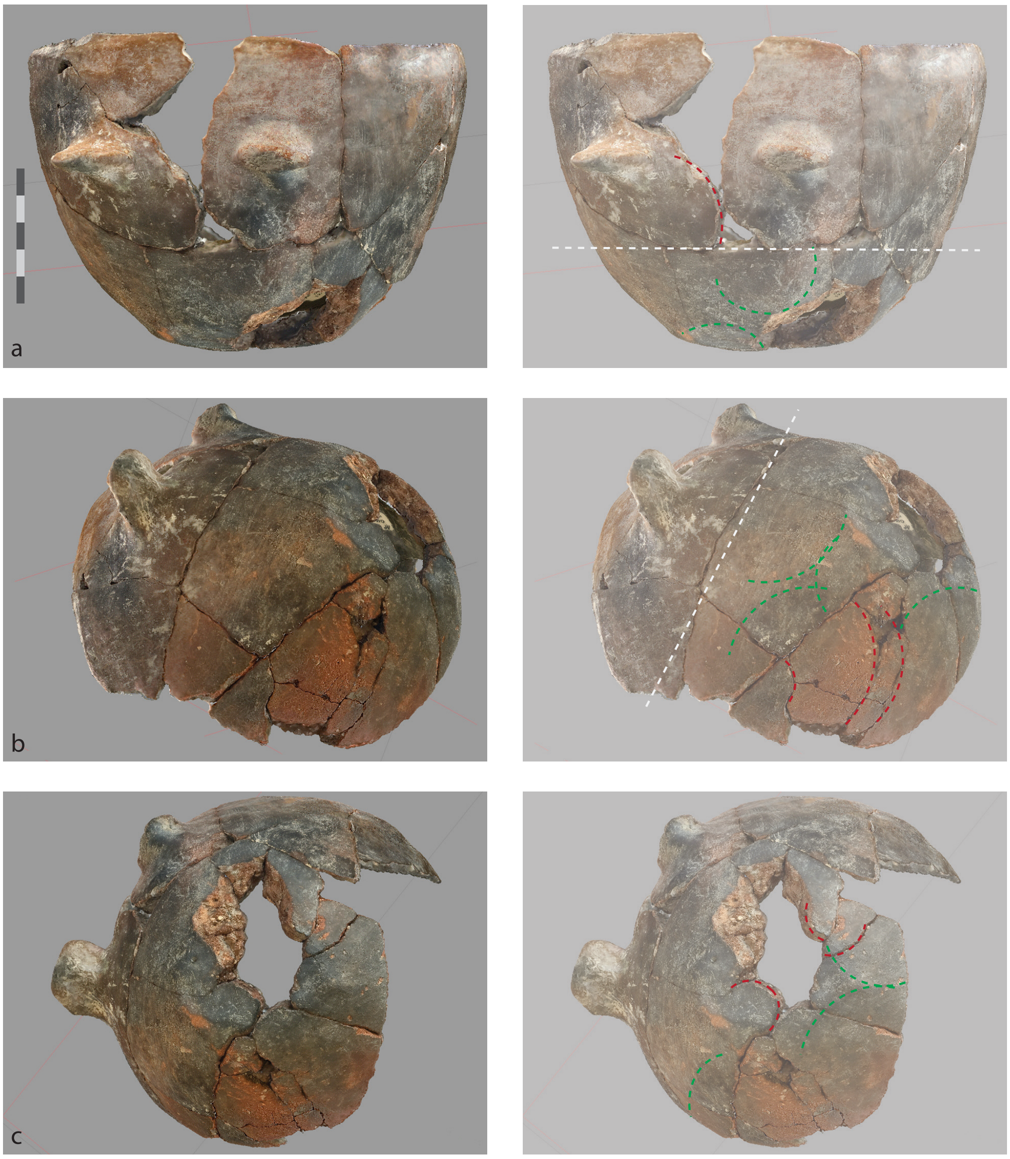

Fig. 1 – The main macrotraces identified on the Impresso-Cardial pottery from Castellar – Pendimoun. Red dotted lines: networks of arciform or circular fractures; green dotted lines: circular convexities visible on the inner or outer surface; white dotted lines: horizontal fracture midpoint horizontal fracture.

***Fig. 1 –** Les principales macrotraces identifiées sur les poteries Impresso-Cardial de Castellar – Pendimoun. Lignes pointillées rouges : réseaux de cassures arciformes ou circulaires. Lignes pointillées vertes : convexités circulaires visibles sur la surface interne ou externe des poteries. Lignes en pointillés blancs : fracture horizontale à mi-panse.*

– Most vessels are characterised by significant variation in thickness and a bumpy surface; a feature that was described in a previous study (Binder and Sénépart, 2010). The profile of the vases is characterised by the presence of multiple circular convexities visible on the inner or outer surface (fig. 1, green dashed lines). Delineated by the arciform and circular fracture networks described above (fig. 1b), these convexities are most often associated with depressions suggesting the application of discontinuous finger pressure on the pottery walls. The position of these convexities and digital pressures on the vessels' profile tends to vary according to vessel partonomy, which is particularly visible on surface scanning acquisitions of complete vessels (fig. 2). Significant topographical differences can indeed be observed between the lower and upper parts of the vases, the transition between these two parts being most often marked on reconstructed vessels by a midpoint horizontal fracture (fig. 1a and fig. 1b, white dashed lines and fig. 2). The lower part of the vessels, most often shows differential topography between the inner and the outer surface (fig. 2): in the case one of these two surfaces is characterised by a bumpy and uneven topography, the other shows a more even topography. In contrast, the upper part of the vessels is invariably characterised by a bumpy and uneven surface topography on both the inner and outer surfaces.

– In association with those peculiar topographical features, sub-circular and mesostructural ellipsoidal pat-

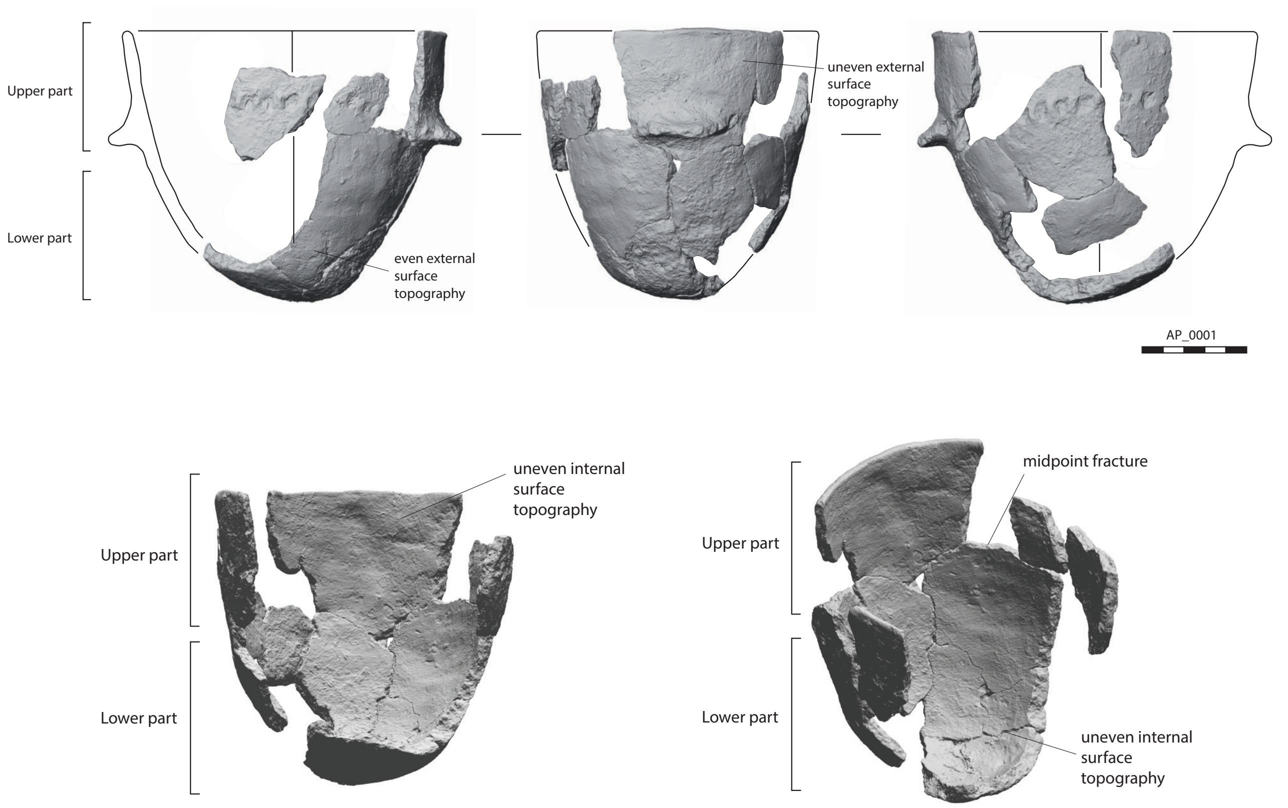

Fig. 2 – 3-D surface acquisition of a complete Impresso-Cardial vessel from Castellar – Pendimoun showing significant topographical differences between its lower and upper parts.

***Fig. 2** – Acquisition de surface en 3-D d'un vase Impresso-Cardial complet de Castellar – Pendimoun caractérisé par d'importantes différences topographiques entre sa partie inférieure et sa partie supérieure.*

Fig. 3 – Sub-circular and ellipsoid patterns of 7-10 mm height (magenta dotted lines) identified in both radial and equatorial sections on Impresso-Cardial vessels from Castellar – Pendimoun. These configurations, which evoke sections of thin coils, are systematically intersected by long oblique to sub-vertical discontinuities (black dotted lines). After Gomart *et al.*, 2017.

***Fig. 3** – Configurations sub-circulaires et ellipsoïdes de 7-10 mm de hauteur (lignes en pointillés magenta) identifiées en plans radial et équatorial sur les poteries Impresso-Cardial de Castellar – Pendimoun. Ces configurations, qui évoquent des sections de colombins fins, sont systématiquement recoupées par de longues discontinuités obliques à sub-verticales (lignes en pointillés noirs). D'après Gomart* et al.*, 2017.*

terns of 7-10 mm height are observed in both radial and equatorial sections. These patterns, which are evocative of sections of thin coils, are systematically intersected by long oblique to sub-vertical discontinuities (fig. 3).

– Some sherds characterised by desquamated surfaces offer a view of their internal structure in the tangential plan. In this case, a generally circular organisation of porosity and non-plastic inclusions enclosed in the network of circular breaks can be observed, and sometimes coiled elements can be distinguished (fig. 4).

– While some vessels present a rim with a specific undulated shape (fig. 5), number of ceramics show a regular rim, associated with a horizontal undulation on the outer and inner surfaces (fig. 6a).

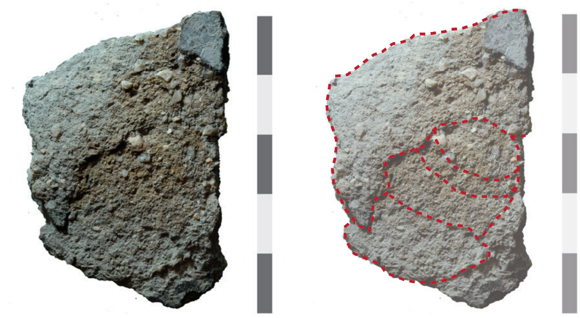

Fig. 4 – *Impresso-Cardial* sherd from Castellar – Pendimoun characterised by a desquamated surface offering a view of its internal structure in the tangential plan. A generally circular organisation of porosity and non-plastic inclusions is associated with a discontinuity underlining a wound longitudinal element (red dotted line).

***Fig. 4 –** Tesson Impresso-Cardial de Castellar – Pendimoun caractérisé par une surface desquamée offrant une vue de sa structure interne en plan tangentiel. Une organisation généralement circulaire de la porosité et des inclusions non plastiques est associée à une discontinuité décrivant un élément longitudinal enroulé (ligne rouge pointillée).*

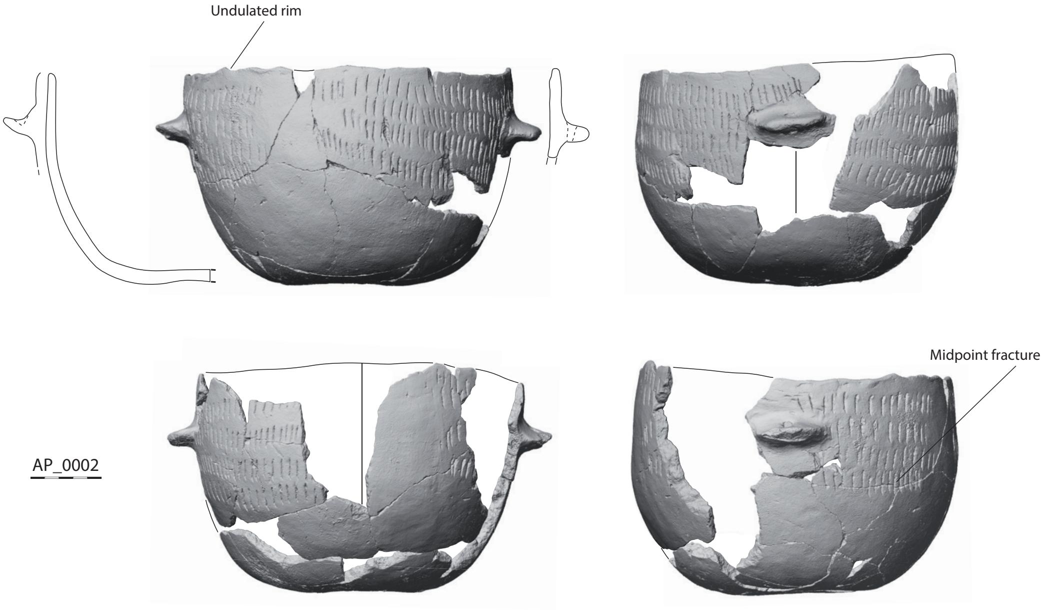

Fig. 5 – 3-D surface acquisition of an *Impresso-Cardial* vessel from Castellar – Pendimoun showing a horizontal midpoint fracture and an undulated rim.

***Fig. 5 –** Acquisition de surface en 3-D d'un vase Impresso-Cardial de Castellar – Pendimoun caractérisé par une fracture horizontale à mi-panse et un bord ondulé.*

"Spiralled *Patchwork*", an unparalleled forming technique implemented as part of a complex forming sequence

To be interpreted in terms of technical gestures, macrotraces must be compared to experimental or actualist reference works. In the case of the Pendimoun ceramic assemblage, the body of identified macrotraces could not be directly linked with an existing frame of reference. The interpretation of the series of observations made on pottery surfaces and sections was therefore based on theoretical classification of mechanical stress states associated with the different types of pressure applied to the clay material (Pierret, 2001; Roux, 2016 and 2019).

The networks of arciform or circular breaks and the bumpy surface topography (fig. 1) suggest that the ceramics were formed by juxtaposing circular modules, while the clay material was still very plastic. Each of these modules or "patches", the thickness and diameter of which can be easily measured, show striking regular diameters and thicknesses for the same vase, but also from one vase to another. The use of circular modules for building the vases' walls could echo the sequential slab technique described for instance in the Neolithic of the Levant (Vandiver, 1987) or of Central Europe (Kreiter *et al.*, 2017; Thér *et al.*, 2019). However, in Castellar – Pendimoun, the fact that these circular basic elements are also characterised by thin coils (fig. 3), the cross-sections of which are unusually invariably visible in both the radial and equatorial sections, implies a different and particularly complex *chaîne opératoire*, in which the forming of each basic element involves coiling. This hypothesis is reinforced by the occurrence in the vessels' tangential plan of a general circular organisation of porosity and non-plastic inclusions circumscribed to the arciform fracture networks, and of wound elongated elements (fig. 4). Altogether, these observations suggest that each of these circular modules or "patches" was initially formed by winding a thin coil in spiral, before being juxtaposed and fused to build the pottery walls.

The differences observed with regard to surface topography between the lower and the upper parts of

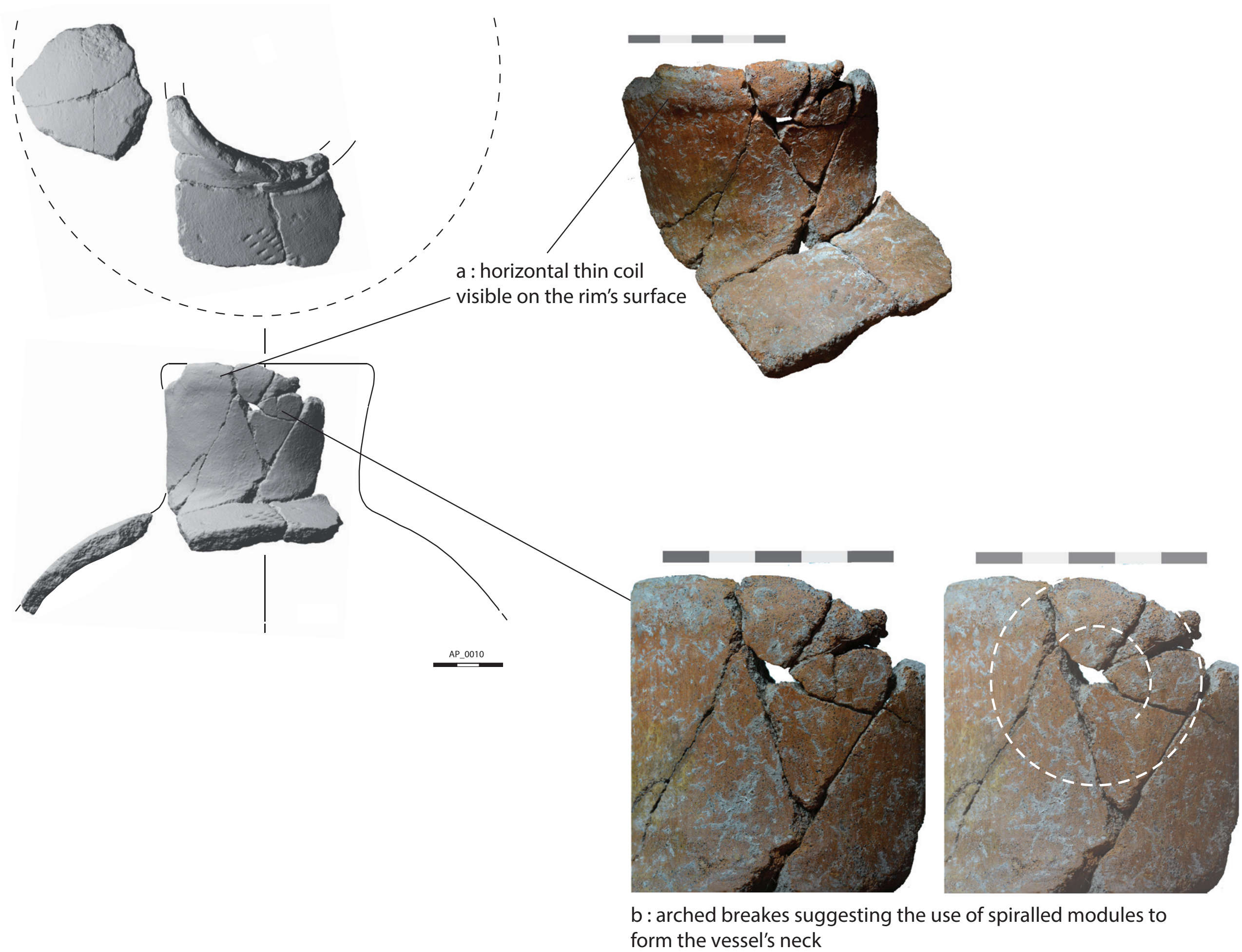

Fig. 6 – *Impresso-Cardial* collared pottery from Castellar – Pendimoun characterised by arciform fractures and circular convexities located on its neck (white dotted lines). The vessel's rim shows a horizontal undulation suggesting the application of a thin coil during forming.

***Fig. 6** – Poterie Impresso-Cardial de Castellar – Pendimoun caractérisée par une série de fractures arciformes et de convexités circulaires situées sur son col (lignes en pointillés blancs). Le bord de la poterie présente une ondulation horizontale suggérant l'application d'un colombin fin pour son façonnage.*

the complete vessels (fig. 2) imply distinct roughing-out processes. On the lower part of the vessels, convexities and digital imprints occur either on the inner or the outer surface, suggesting the application and merging of the spiralled modules against a concave support (when the uneven topography occurs on the inner surface while the outer surface is flatter) or against a convex support (when the uneven topography occurs on the external surface while the inner surface is flatter). In contrast, on the vessels' upper part, the uneven topography on both the inner and the outer surface indicates a sequential juxtaposition of spiralled modules that are here fused through discontinuous finger pressure, without any support. The occurrence of a midpoint horizontal fracture on most complete vessels (visible on vessels shown in fig. 1a, and 1b, fig. 2 and fig. 5) in line with the hypothesis of different processes of spiralled patches adjunction between the lower and upper parts, suggests a possible drying stage occurring between the forming of the two parts. This recurring line of fragility could be due to a difference in hygrometry between the lower part – which was formed at first and therefore slightly dried out, and the upper part – which was built at a later stage and therefore slightly more humid. This assumption is reinforced by differences observed between the lower and the upper parts in the decorative *chaîne opératoire*: most impressions are indeed located on the upper part of the vessels, *i.e.* the part that was probably the most humid at the end of forming and thus the one which had the most suitable consistency for the impressions to be visible, while these are mostly absent from the lower part that was probably dryer and consequently less appropriate for the application of decorations (Cassard, 2020; Cassard *et al.*, this volume). Moreover, the fact that this line of fracture is generally horizontal (and not undulated such as the lip of certain vessels whose rim was formed using only spiralled patches) suggests that the edge of the lower part may have been cut on in order to level it and make it plane prior to the adjunction of new spiralled patches for building the vessel's upper body.

The undulated shape characterising the lip of some ceramics (fig. 5) suggests the forming of the rim by juxtaposing spiralled patches in a horizontal row. Other vessels show a more even and flatter lip associated with horizontal undulation on the rim's outer and inner surfaces: for these, the use of a thin coils to form their rim can be assumed (fig. 6a). Strikingly, spiralled patches seem to also have been used to form the neck of collared pottery, as suggested by the presence of typical arciform fractures and circular convexities on this specific part of some vessels (fig. 6b).

Lastly, it is important to note that the identified macrotraces do not necessary appear on all vessels: while some fragments yield for instance only arciform breaks, others exhibit a circular shape or arciform lines of tension associated with circular convexities. Consequently, only the exhaustive examination of the pottery assemblage enabled us to cross-check the whole body of evidence and assume the implementation at Castellar – Pendimoun of this specific forming sequence using spiralled patches added according to different processes on the lower and upper parts of the vessels.

AN INTEGRATED APPROACH FOR CHARACTERISING NEW MARKERS OF SPT

Identified for the first time in the *Impresso-Cardial* layers of Castellar – Pendimoun on the basis of an atypical set of macrotraces, the "Spiralled Patched Technology" (SPT) had never been documented in any other archaeological nor contemporaneous context. It was therefore imperative to confirm the presence of SPT *via* a different scale of observation not relying solely on surface and section macrotrace evidence. To do this, we developed a multiscale protocol relying on the high-resolution reconstruction of pottery internal architecture, which entailed the analysis of both archaeological pottery and experimental samples formed in controlled conditions.

Experimental vessels

The setting up of an independent frame of reference for SPT first required the development of an experimental protocol adapted to our research question. The objective was to test the hypotheses formulated on the SPT forming sequence through macrotrace reading based on the theoretical classification of mechanical stress states linked to the different types of pressure applied on plastic clay material.

To do this, we built five experimental vessels and compared the macrotraces obtained on these controls to those identified on the Castellar – Pendimoun archaeological ceramics (fig 7). For this purpose, industrial clays of two distinct colours were used, as advocated by Valentine Roux (Roux, 2016), with the aim of observing the macrotraces formed on the surfaces and in section as a result of the different types of pressure applied while juxtaposing and merging the spiralled patches.

This experiment substantially refined our understanding of the entire SPT forming sequence. It notably raised questions regarding first, the management of drying phases so that the vessels do not to collapse under their own weight during forming; second, the modes of juxtaposition of the circular modules in order to obtain pottery walls without voids; and third, the type and intensity of pressure (with or without a support) needed to merge the spiralled patches and obtain a wall of roughly uniform thickness. While these questions remain partly open, they proved to be crucial in the cross-talk between experimental and archaeological material and facilitated significantly the interpretation of specific sets of macrotraces such as the differential topography between the lower and the upper parts of the vessels.

Exploring pottery internal structure in 2D: the microfabric approach

In a second step, a set of tangential thin sections was produced. A selection of three sherds, corresponding to spiralled patches given their circular shape and surface topography, were selected. The thin-sections were cut out of the core of these sherds and over their entire surface, in order to access their internal structure and carry out microfabric analysis.

For ceramics, the microfabric approach involves the examination of the plastic deformations and/or spatial reorganisation of the different structural units composing the clay materials (porous system, inclusions of different nature, matrix) as the result of specific technical actions applied to them. While this approach has so far been thoroughly applied in later contexts to distinguish between wheel thrown and wheel coiled ceramics (Courty and Roux, 1995; Roux and Courty, 1998; Thér and Toms, 2016), it has been used only to a limited extent for ceramics formed without kinetic rotational energy (Courty and Roux, 1995; Thér *et al.*, 2019; Derenne, *et al.*, 2020).

The thin-section analysis performed as part of the present research was conducted using optical and scanning electron microscopes and focused on the profile and organisation of the porous system and inclusions, discontinuities and voids. The thin-section presented in figure 8 shows different features in plane polarized light (PPL), in cross polarized light (XPL) and under SEM (BSE image). In PPL, a clear spiral-shaped discontinuity is visible at the centre of the sherd (fig. 8b, black dashed line). It seems to delineate the extremity of a coil at the starting point of a spiralled patch. In XPL, this central spiral-shaped discontinuity appears less visible, but alignments of small mineral inclusions are clearly apparent along its edges (fig. 8a). These alignments are a well-known diagnostic feature of perpendicular pressure applied on plastic earth while rolling it on a flat surface, *i.e.* coil forming (Roux, 2016). This observation is strengthened by the profile of the matrix, inclusion network, and by the larger minerals' major axis all showing a general circular organisation

1 : Formation of a spiralled patch by winding a thin coil

2 : Smootingh of the spiralled patch

3 : Juxtaposition of spiralled patches against a convex support to form the vessel's lower part

4 : Specific traces on the vessel's outer surface following gestures of juxtaposition and merging of spiralled patches against the convex support

5 : Inner surface of the vessel's lower part before smoothing

6 : After smoothing the lower part's inner surface and cuting it to level it, adjunction of the first spiralled patches to form the upper part

7 : Adjonction and merging of spiralled patches to form the vessel's upper part

8 : Adjonction of the last spiralled patch

9 : Adjonction and merging of a thin coil to form the rim of the complete vessel

Fig. 7 – Forming sequence of the experimental vessels built on the basis of the hypotheses formulated through macrotrace reading on the *Impresso-Cardial* assemblage from Castellar – Pendimoun. Industrial earths of two distinct colours were used in order to observe the traces formed in surface and in section as a result of the different types of pressure applied while juxtaposing and merging the spiralled patches.

***Fig. 7 –** Séquence de façonnage des vases expérimentaux montés sur la base des hypothèses formulées grâce à la lecture des macrotraces sur l'assemblage Impresso-Cardial de Castellar – Pendimoun. Des terres industrielles de deux couleurs distinctes ont été utilisées afin d'observer les traces formées en surface et en section suite aux différents types de pression appliqués lors de la juxtaposition et de la fusion des patches spiralés.*

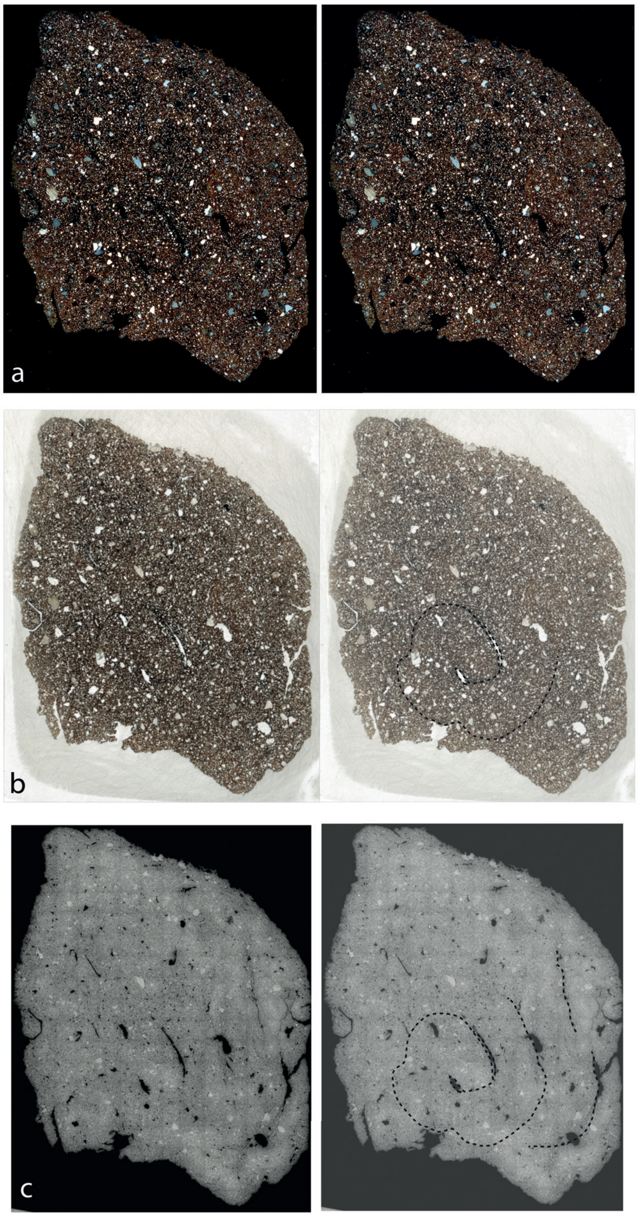

Fig. 8 – Thin-section from an *Impresso-Cardial* pottery of Castellar – Pendimoun in plane polarized light (PPL), in cross polarized light (XPL) and under SEM (BSE image).
Fig. 8 – *Lame mince issue d'une poterie Impresso-Cardial de Castellar – Pendimoun en lumière polarisée plane (PPL), en lumière polarisée croisée (XPL) et sous SEM (image BSE).*

consistent with the hypothesis of winding a coil to form the basic modules used in SPT. The general mapping of this same thin-section performed under SEM, which offers a unique view of the sherd's porous system, yields additional information. It shows very clear long voids and discontinuities (fig. 8c) in the exact same areas as the alignments of mineral inclusions visible under the optical microscope (fig. 8a) reinforcing the hypothesis of the use of a spiralled coil to form each patch.

The analysis of microfabrics in the tangential plane integrating different modes of observation offers a key entry point for assessing the internal structure of the Castellar - Pendimoun ceramic vessels. Providing crucial additional evidence for the use of spiralled modules as the basic elements used for pottery forming, this approach allows to track down the internal "spatial signatures" specific to SPT and link them to surface and section features.

MICRO-TOMOGRAPHY, A METHODOLOGICAL BREAKTHROUGH TO CHARACTERISE THE SPIRALLED PATCHWORK TECHNOLOGY INDEPENDENTLY OF MACROTRACE EVIDENCE

A third step in the validation of the macro- and mesoscopic observations lied in the acquisition of micro-tomographic datasets. Micro-computed tomography (µ-CT) offers a methodological breakthrough in the study of ancient pottery manufacture: non-destructive, it enables remarkable readability of the porous system and non-plastic inclusions contained in the clay in three dimensions, opening up multiple, unprecedented perspectives for the reconstruction of ancient pottery manufacturing processes.

The application of µ-CT on ancient pottery involves, however, inherent challenges due to the nature of the clay material itself, which is very heterogeneous chemically and mineralogically, has different degrees of alteration and, when subjected to high temperatures, different firing states. While several recent studies have shown the strong potential of tomography acquired at different scales of resolution (from medical CT to µ-CT) to visualise the internal structure of ancient pottery and to identify the nature of their inclusions (Kahl and Ramminger, 2012, Sanger *et al.*, 2012; Sanger, 2016 and 2017; Kulkova and Kulkov, 2015 and 2016; Gomart *et al.*, 2017; Neumannová *et al.*, 2017; Kozatsas *et al.*, 2018; Park *et al.*, 2019; Nicolas, 2020), the use of this method for the characterization of manufacturing processes remains particularly challenging. Indeed, in order to assess the pottery manufacturing *chaîne opératoire*, it is necessary to access the internal architecture of large portions of vessels or whole vessels, which implies the acquisition of large volume samples and the processing of data on large regions of interest (ROI). Moreover, the inherent complexity of the ceramic material tends to yield extremely noisy datasets, which can be particularly difficult to interpret when visualising the reconstructed volumes.

Multi-scale µ-CT acquisition protocol

To overcome these challenges, our µ-CT analytical protocol followed several steps. First experimental briquettes formed out of sourced geomaterial were scanned in order to pin-point within the tomographic datasets the SPT internal "spatial signatures" already identified as part of the microfabric analysis (section "µ-CT data acquired from experimental briquettes and archaeological sherds"). Second, these spatial signatures were compared to datasets acquired from archaeological sherds, first visually (section "µ-CT data acquired from experimental briquettes and archaeological sherds"), then using specific algorithms (section "Internal structure data quantification: first results and future challenges"). Third, vessels with a preserved profile were acquired and subjected to correlated analyses providing new insights into the SPT forming sequence (section "µ-CT data acquired from vessels with reconstructed profile").

µ-CT data acquired from experimental briquettes and archaeological sherds

The first step of the acquisition protocol aimed at characterising the basic elements defining SPT. To do this, we expanded our existing body of experimental vessels by forming eleven experimental briquettes corresponding to the SPT basic units, *i.e.* spiralled patches. Another batch of five experimental controls was then built using the coiling technique. This technique, that implies the superimposition and merging of clay rolls, predominates in European early Neolithic contexts (Bosquet *et al.*, 2005; Gomart, 2010 and 2014; Gomart, 2020, Van Dooselaere *et al.*, 2013 and 2016; Angeli and Fabbri, 2017; Colombo, 2017; Kreiter *et al.*, 2017; Neumannová *et al.*, 2017; Thér *et al.* 2019). The clay materials sourced and sampled as part of the petrographic analysis carried out on the Castellar – Pendimoun ceramic assemblage (Gabriele *et al.*, this volume; Lardeaux *et al.*, this volume) were used to form these experimental controls. The first series of experimental briquettes was made by winding and then smoothing a 9 mm thick coil, so as to obtain a circular slab about 5 cm in diameter and 8 mm thick, corresponding to a basic SPT module (spiralled patch). The second series of experimental briquettes was formed by superimposing approximately 9 mm thick coils (a diameter frequently observed on pottery vessels in the European Neolithic), which were then merged and smoothed to obtain a square piece of approximately 7 cm on each side and 8 mm thick.

The objective here was to understand the fine structure of the SPT pottery internal architecture by examining the behaviour of the different types of geomaterials under different types of pressure applied during forming and, thereby, track the typical spatial signatures of SPT in the tomographic datasets of both experimental controls and archaeological sherds. To do this, a series of eight archaeological sherds showing characteristic macrotraces (surface topography, fractures, discontinuities, spatial organisation of the pores and inclusions) corresponding to SPT basic elements (spiralled patches) was subjected to µ-CT. A second series of seven non-diagnostic archaeological sherds, *i.e.* not showing any specific macrotrace, was then acquired.

Experimental briquettes and archaeological sherds, whose maximum size is limited to twelve centimetres were scanned using a SkyScan-1178 X-ray micro-computed tomography system (Bruker) with a beam energy of 60kV, a 0.5 mm thick aluminium filter, 0.9° rotation step and a resolution of 104 µm. Data were visualized and processed using the free image-processing package Fiji (https://fiji.sc), and then segmented using the Amira software (FEI). Semi-automated and automated thresholding was used to segment the porous system and mineral inclusions. The same experimental briquettes and archaeological sherds were scanned on the Metrology beamline of the Synchrotron Soleil with a 7 µm voxel edge, using the very-high definition (30Mpx) x-ray camera developed at IPANEMA in half horizontal collection mode. With the high brilliance of the source available at the Synchrotron, the white-beam mode with filtering was used, hence obtaining a pink-beam, and large horizontal slit aperture.

On both experimental and archaeological samples, the morphology, density and organisation of the porosity and mineral inclusions revealed alignments of pores and inclusions trapped in the different assembled elements, as well as discontinuities corresponding to the junctions between these same elements. The µ-CT data obtained on the two sets of experimental controls show that their internal structure is characterised by radically different patterns (fig. 9). The series of experimental briquettes formed by winding a coil in spiral shows alignments of pores organised in a generally circular pattern (at left on fig. 9), consistent with the microfabric evidence presented in section "Exploring pottery internal structure in 2D: the microfabric approach". In contrast, the set of briquettes built by superimposing thin coils shows a porous system composed of elongated voids with a clear horizontal orientation (at right on fig. 9).

The µ-CT data obtained from the *Impresso-Cardial* sherds of Castellar – Pendimoun yielded valuable evidence to support the hypothesis of the use of juxtaposed spiralled patches. The fragment shown in figure 10, made from a granitic clay material, was selected for µ-CT scanning because of its diagnostic macrotraces, *i.e.* desquamated outer surface revealing a circular organisation of the clay particles and an arched discontinuity suggesting

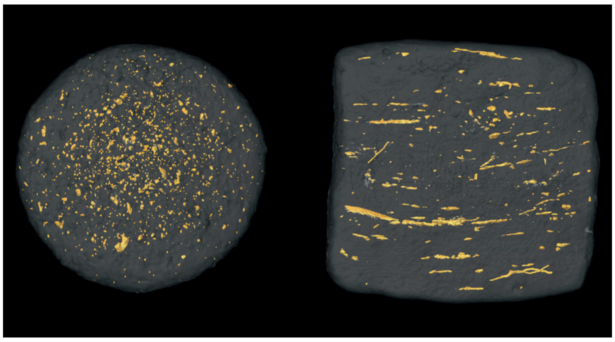

Fig. 9 – Segmented surface (grey) and pores (yellow) of a spiralled experimental control (left) and an experimental control formed using thin superimposed coils (right) acquired by µ-CT. Their internal structures are characterised by radically different patterns. After Gomart *et al.*, 2017.

Fig. 9 – *Segmentation de la surface (gris) et des pores (jaune) d'une briquette expérimentale spiralée (gauche) et d'une briquette expérimentale façonnée par superposition de colombins fins (droite) acquises par µ-CT. Leur structure interne est caractérisée par des géométries radicalement différentes. D'après Gomart* et al.*, 2017.*

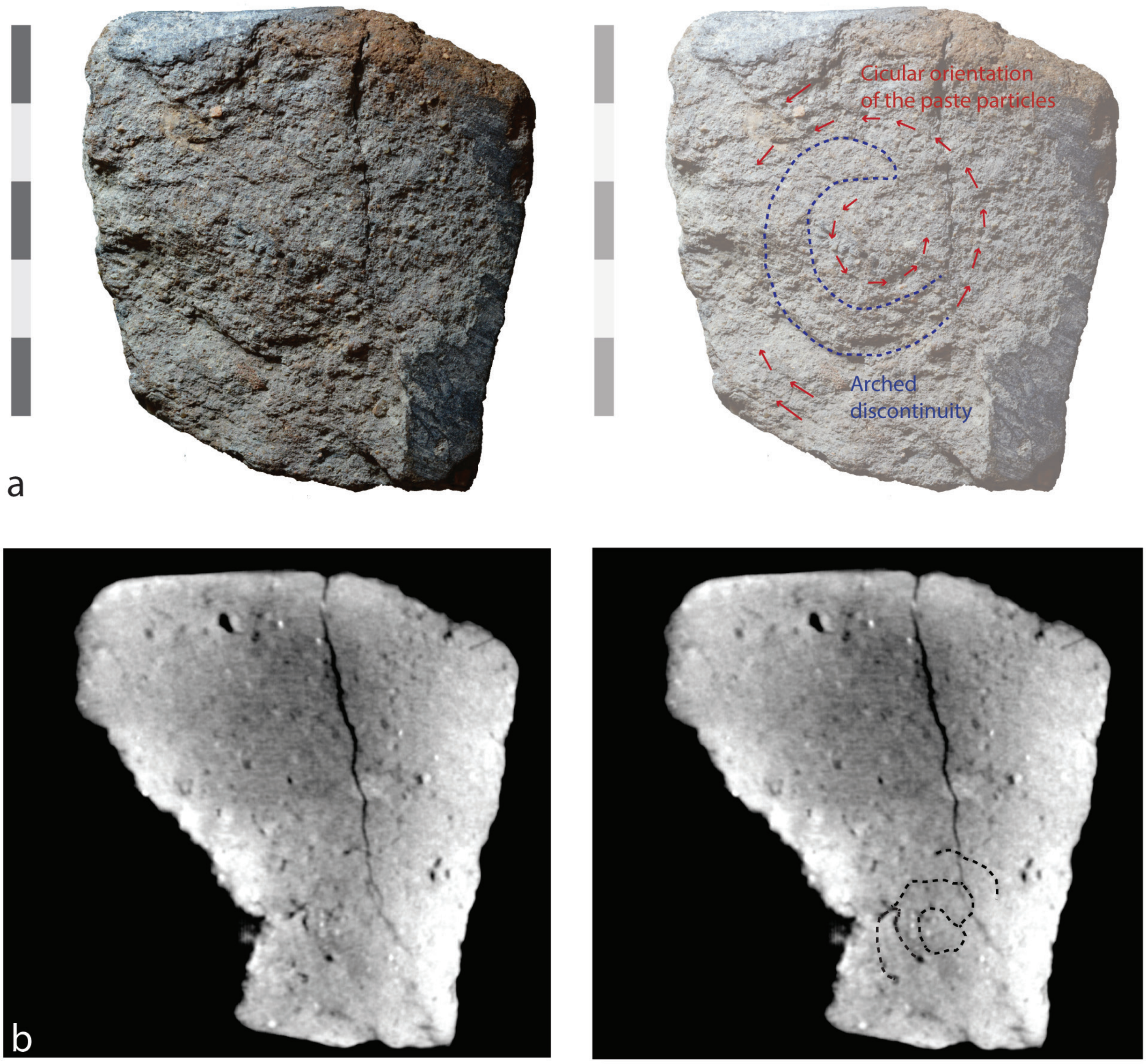

Fig. 10 – Pottery fragment from Castellar – Pendimoun selected for µ-CT scanning because of its diagnostic macrotraces (*i.e.* desquamated external surface revealing a circular organisation of the clay particles and an arched discontinuity suggesting the presence of a wound coil). The central virtual slice (tangential plan) stemming from this sherd µ-CT acquisition displays an equivalent pattern (*i.e.* arched discontinuities) that is not positioned in the same area as that visible in macroscopic analysis.

***Fig. 10** – Fragment de poterie de Castellar – Pendimoun sélectionné pour l'analyse µ-CT en raison de ses macrotraces diagnostiques (i.e. surface externe desquamée révélant une organisation circulaire des inclusions et discontinuité arciforme suggérant la présence d'un colombin enroulé). La coupe virtuelle centrale (plan tangentiel) issue de l'acquisition µ-CT de ce même tesson présente une configuration équivalente (discontinuité arciforme) qui n'est cependant pas localisée dans la même zone que celle visible en analyse macroscopique.*

the presence of a wound coil (fig. 10a, blue dashed line). The central virtual slice (tangential plan) stemming from this sherd µ-CT data displays an equivalent pattern, *i.e.* arched discontinuities underlining the possible centre of a spiralled coil (fig. 10b, black dashed line). This specific pattern is, however, not positioned in the same area as that visible in macroscopic analysis. Here, two different spiralled patches, that were probably juxtaposed onto each other, exhibit the same type of configurations but these are identified using two distinct analytical methods. The µ-CT evidence in the core of the sherd mirrors the macroscopic evidence near the surface, thus enriching and validating the interpretations based on surface and section features.

Figure 11 shows a 3D reconstruction of the mineral inclusions (in red) contained in a sherd characterised by a granitic clay material, that was not showing specific diagnostic macrotraces except slightly arched fractures. The spatial organisation of these inclusions shows a generally circular pattern, consistent with the macroscopic and microfabric data. Within this network of inclusions, arched empty boundaries (green dashed lines) are also apparent and underline the points of contact of the coils that are wound to form the spiralled patches used during building. These arched empty interfaces are consistent with the macrotraces observed on other sherd's surfaces, *i.e.* tangential arched lines and breaks (such as those observed on fig. 4 and

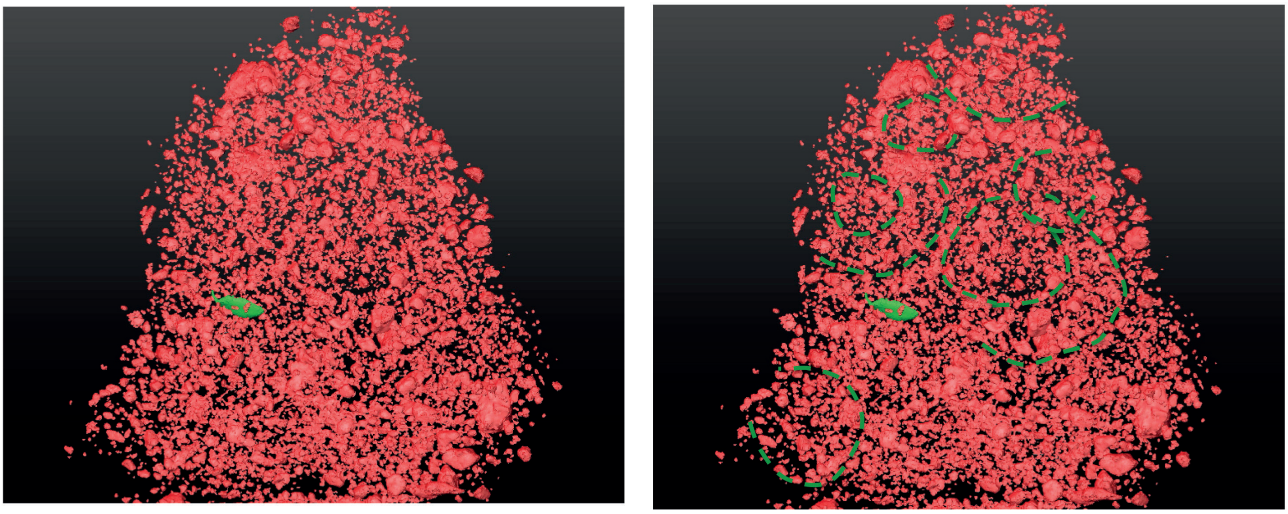

Fig. 11 – 3-D reconstruction of the mineral inclusions contained in a pottery sherd from Castellar – Pendimoun acquired by µ-CT. The spatial organisation of these inclusions shows a generally circular pattern, as well as arched empty boundaries (dotted green lines) which underline the points of contact of the spiralled coils used during forming.

***Fig. 11 –** Reconstruction 3-D des inclusions minérales contenues dans un tesson de Castellar – Pendimoun acquis par µ-CT. L'organisation spatiale de ces inclusions est généralement circulaire. Le tesson présente en outre des « effets de paroi » arciformes (lignes vertes pointillées) qui soulignent les points de contact des colombins enroulés en spirale lors du façonnage.*

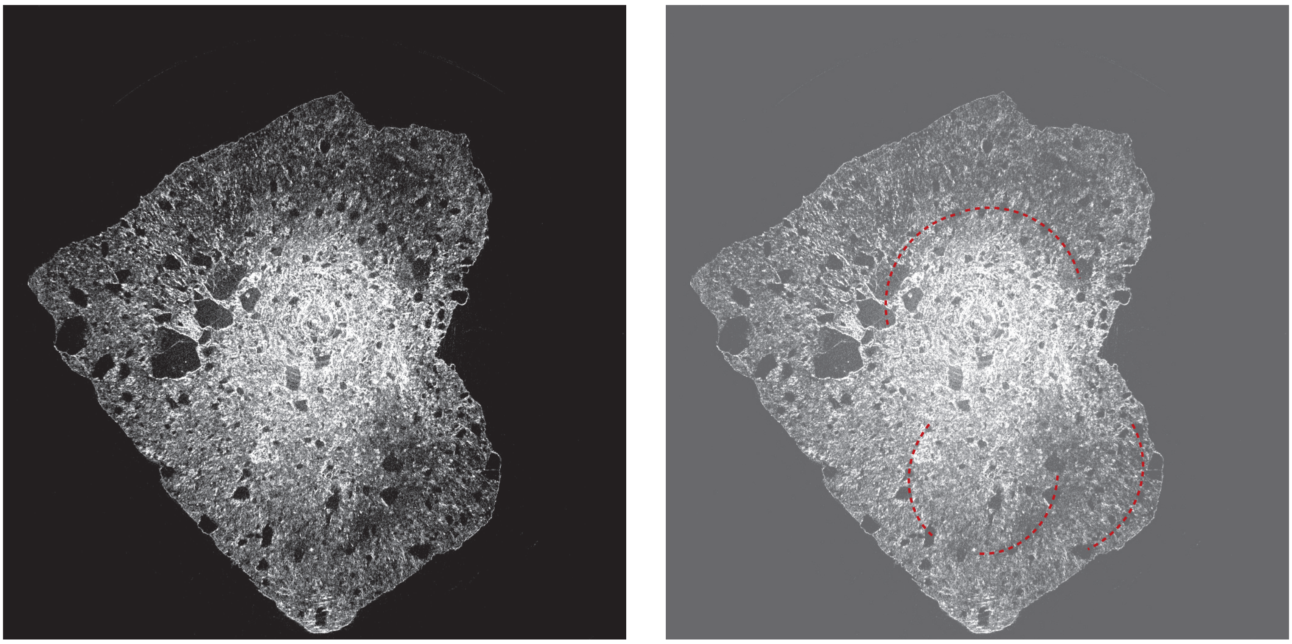

Fig. 12 – Virtual slice (tangential plan) from the core of a pottery sherd from Castellar – Pendimoun acquired by high-resolution µ-CT. Despite the slight artefacts visible on the image (white circles) due to data acquisition and reconstruction, this sherd shows a series of arched alignments of crystalline elements and glauconites (dotted red lines) possibly underlining two distinct overlapping SPT modules.

***Fig. 12 –** Coupe virtuelle (plan tangentiel) du centre d'un tesson de Castellar – Pendimoun acquis par µ-CT à haute résolution. Malgré les artefacts visibles sur l'image (cercles blancs) dus à l'acquisition et à la reconstruction des données, ce tesson montre une série d'alignements arciformes d'éléments cristallins et de glauconites (lignes rouges pointillées) décrivant probablement deux modules SPT distincts et juxtaposés.*

fig. 10). Another type of configuration could be identified in the high-resolution µ-CT datasets acquired at the Synchrotron Soleil. Figure 12 shows a virtual slice (tangential plan) stemming from the core of a sherd, made from a mixture of granitic and glauconitic clay materials, that was not showing diagnostic macrotraces. Despite the slight artefacts visible on the image (white circles) due to the data µ-CT acquisition and reconstruction, this sherd is strikingly characterised by a series of arched alignments of crystalline elements and glauconites (red dotted lines) possibly underlining two distinct overlapping SPT modules. These mineral inclusions trapped within the coils used to form these two juxtaposed spiralled patches, mirror the alignments identified as part of the microfabric analysis (fig. 8a).

Ultimately, µ-CT analyses carried out on experimental briquettes and archaeological sherds with and without diagnostic macrotraces revealed an array of specific markers for SPT differing from those identified through surface and section macroscopic reading. These new markers, which confirm the spiralled structure of the circular modules used to form the *Impresso-Cardial* vessels at Castellar – Pendimoun, form a crucial independent body of evidence for this previously undocumented forming sequence.

Internal structure data quantification: first results and future challenges

In order to fully exploit the potential of µ-CT for the study of SPT, a quantitative analysis of the acquired data is required. To do this, a mathematical signal processing protocol adapted to properties of ancient ceramics was developed (Coli *et al.*, 2021). This protocol is based on the Hough transform, an algorithm for pattern recognition, such as lines, representing each detected contour point in a two-dimensional parameter space and thus allowing the identification of the main alignments of points in the µ-CT 3D datasets. In order to overcome the complexity introduced by the diversity of clay materials characterising the Castellar - Pendimoun pottery assemblage (defined by mineral inclusions of different nature and shapes) and to move away from the µ-CT images' visual observations mostly based on the spatial distribution of mineral inclusions, this quantitative analysis focused on the samples' pore system.

This analytical protocol enabled to effectively discriminate the pore systems associated with the coiling technique on the one hand and SPT on the other hand, by comparing the scalar product distributions between the directions of the recovered lines and detect intersection points (fig. 13). The lines defining the coiling technique in experimental briquettes and an archaeological sherd from

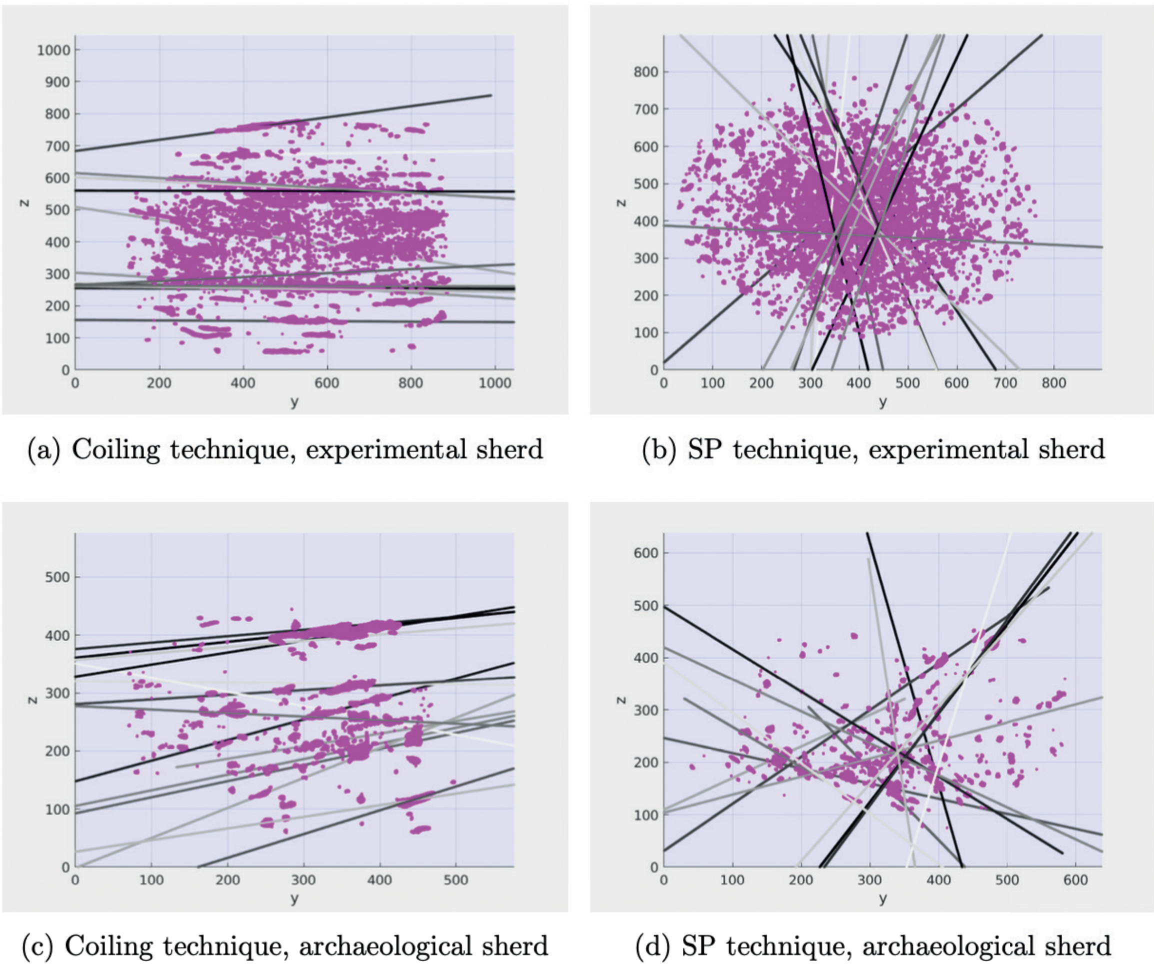

Fig. 13 – Automatic discrimination of the pore systems (represented in magenta) associated with the coiling technique and SPT on experimental briquettes and archaeological sherds acquired by µ-CT, using the Hough transform. The lines defining the coiling technique exhibit mostly the same horizontal direction, while the lines characterising SPT tend to intersect. After Coli *et al.*, 2021.

***Fig. 13 –** Discrimination automatique des systèmes poreux (représentés en magenta) associés à la technique du colombin et à SPT sur briquettes expérimentales et tessons archéologiques acquis par µ-CT, grâce à de la transformée de Hough. Les lignes définissant la technique du colombin présentent principalement la même direction horizontale, tandis que les lignes caractérisant la SPT ont tendance à se croiser. D'après Coli* et al.*, 2021.*

a later Neolithic context (Saint-Raphaël – La Cabre, Late Chassey culture: (Binder *et al.*, 2012) exhibit mostly the same horizontal direction (fig. 13a and fig. 13c), while the lines characterising SPT in both experimental and archaeological samples tend to intersect (fig. 13b and fig. 13d). Analysing these different samples *via* the detection of the same geometric shape, a line, allowed to overcome the diversity of the configurations observed on the archaeological sherds (lines, general organisation of the paste particles, as well as alignments and empty boundaries) and to corroborate in an unbiased manner the macrotrace analysis of the archaeological fragments on the one hand, and the visual examination of their µ-CT images on the other hand.

Based on the results of the Hough transform, preliminary tests involving Machine Learning methods were carried out to analyse and classify µ-CT images. Feature based approach (using the Hough transform) with Support Vector Machine (SVM), as well as data driven model with Convolutional Neutral Network (CNN) proved to be particularly efficient to analyse and classify the different images, and automatically differentiate the coiling technique from SPT (Dia *et al.*, 2021).

µ-CT data acquired from vessels with reconstructed profile

After qualitatively and quantitatively characterising the structure of the SPT basic elements, a series of ceramics with a reconstructed profile were subjected to µ-CT. The main question here pertained the modalities of assembling the spiralled patches during pottery building. To acquire complete (and almost complete) ceramics, a device with a large multi-axis manipulator allowing the acquisition of larger objects was required. A first test was conducted on one pottery from Castellar - Pendimoun using a medical CT scanner with a resolution of 600 µm at the imaging facility of the Pasteur University Hospital in Nice, France[1]. A series of ten ceramics were then acquired using the V|tome|x L 240 device (GE Sensing & Inspection Technologies Phoenix X-ray) of the AST-RX platform at the Museum of Natural History (MNHN) in Paris, with a beam energy of 165 kV and flux of 270 µA, a 360° rotation with a 0.12° rotation step and a higher resolution of 91 µm.

The tomographic acquisition from the Pasteur Hospital in Nice on one pottery made from a granitic clay material showed faint features in the tangential plan, *i.e.* arched lines underlining the contours of circular overlapping elements possibly corresponding to the edges of SPT modules (fig. 14a and fig. 14b). The resolution of the obtained images was nevertheless too low to visualise the exact structure of these elements. The µ-CT analyses performed on the AST-RX platform of the MNHN with higher resolution on the same vessel (fig. 14c and fig. 14d) and nine others provided highly informative images and offered new insights into the complete *chaîne opératoire* related to SPT forming. The 3D reconstruction of the mineral inclusions and the pore system of vase shown in figure 14 provides a complex image,

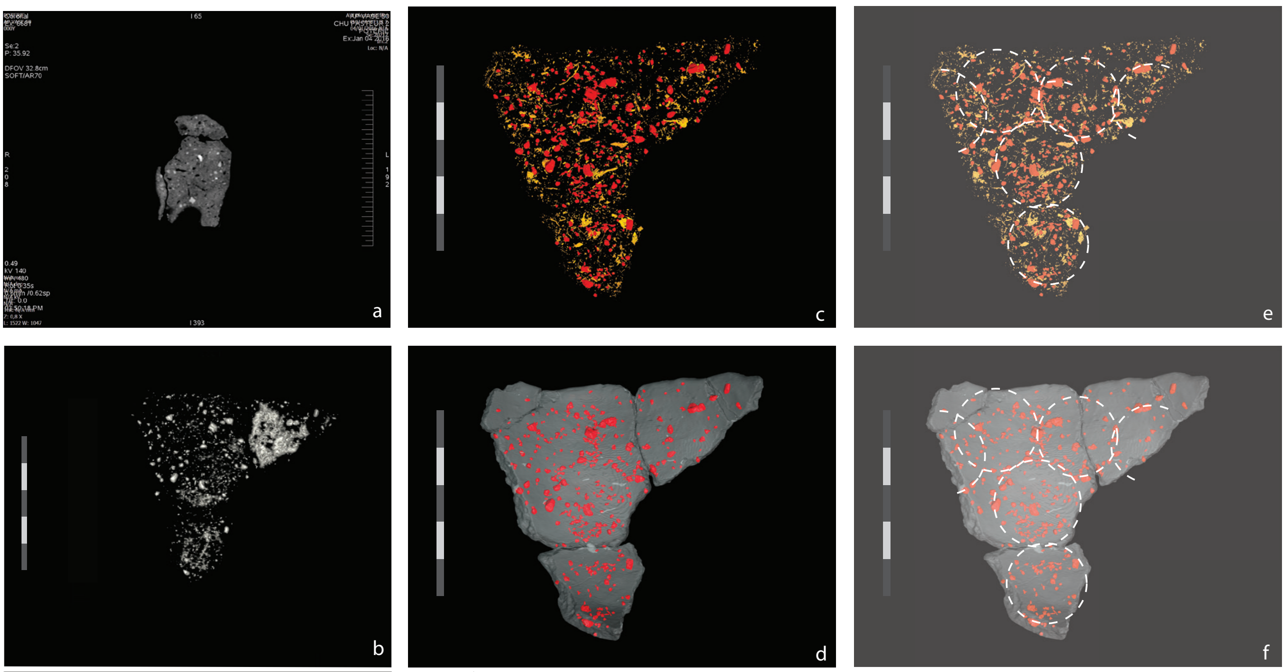

Fig. 14 – Acquisition µ-CT of an Impresso-Cardial vessel from Castellar – Pendimoun at different levels of resolution; a, b: medical µ-CT (Hôpital Pasteur Nice, resolution 600 µm); c, d, e, f: AST-RX (MNHN) industrial µ-CT (resolution 81 µm). Grey: vessel's surface; yellow: pores; red: inclusions. After Gomart *et al.*, 2017.

***Fig. 14 –** Acquisition µ-CT d'un vase Impresso-Cardial de* Castellar – Pendimoun *à différents niveaux de résolution ; a, b : µ-CT médical (Hôpital Pasteur Nice, résolution 600 µm) ; c, d, e, f : µ-CT industriel, AST-RX (MNHN, résolution 81 µm). En gris : surface du vase ; en jaune : pores ; en rouge : inclusions. D'après Gomart* et al.*, 2017.*

within which circular modules can be identified due to the presence of empty boundaries outlining them, as well as alignments of mineral and pores (fig. 14c and fig. 14e). For this ceramic, the inclusions, and particularly the largest inclusions which are less prone to move during surface regularisation, were automatically selected during segmentation using the islands filter with a threshold of 50 voxels (fig. 14d). These appeared to be the best indicators of the localisation of the SPT modules on the vessel's profile, as underlined by circular and arched alignments of minerals about 4.3 cm in diameter corresponding to the edges of spiralled patches (fig. 14f). The spatial distribution of these patches on the vessel's body suggests they were juxtaposed in horizontal rows and staggered to avoid the formation of gaps during building.

Lastly, to establish a precise link between the surface features and the internal structure of complete vessels, a ceramic formed with glauconitic clay material was subjected to a correlative analysis associating micro-topographic analysis and µ-CT scanning (fig. 15). Surface topography was rendered by scanning in 3D the pottery surface using the Artec Spider device and conducting a planarity analysis on the Artec Studio software (https://www.artec3d.com). The largest inclusions contained in this same vessel were then automatically selected during µ-CT data segmentation using the islands filter. The data obtained from both analytical methods were then aligned and projected on the same image (fig. 15b) revealing on the one hand circular alignments of glauconites (figured in blue) underlining the edges and, in some cases, the internal structure of spiralled patches and distributed in horizontal rows (fig. 15d); and on the other hand a striking correspondence between the external surface topography and the localisation of some of the identified patches. Each convexity identified through the planarity analysis (figured in red) appeared indeed to match an underlying circular alignment of glauconites (fig. 15c).

The µ-CT datasets stemming from vessels with a preserved profile provided valuable information on the complete SPT operational sequence revealing the exact modalities of patches' juxtaposition in horizontal rows, an information that was not attainable on the basis of the macroscopic examination of pottery surfaces and sections. In addition, µ-CT carried out on vessels with a preserved profile significantly enriched the SPT body of evidence by allowing to establish a direct link between surface features (convexities) and the corresponding wall internal structure (alignments of mineral inclusions organised in spiralled patterns).

DISCUSSION AND CONCLUSION

The macro- and mesoscopic examination of surface and section features, the microfabric analysis and the multiscale µ-CT analyses carried out on the *Impressa* ceramic assemblage from the Pendimoun rockshelter revealed a forming sequence that had, until recently, no equivalent in any other archaeological context (Gomart *et al.*, 2017) and that has been, since then, uncovered in several early Neolithic contexts in the Mediterranean (Panelli, 2019; Caro, 2020; Cámara Manzaneda *et al.,* 2021; Gomart, Binder, Gabriele *et al.*, this volume). As part of this operational sequence we termed "Spiralled Patchwork Technology", the producers formed circular modules around 4.5 cm in diameter and 9 cm thick by winding a coil in a spiral, which they then juxtaposed and merged in a sequential pattern to build the walls of their pottery. A striking aspect of this *chaîne opératoire* lies in the uniformity of the gestures implemented, regardless of the raw material used, the shape, the format or the decorative style of the vessels. All the vases analysed, without exception, whether made from local materials (glauconitic clay materials) or from more distant ones (granitic clay materials), are characterised by a unique array of macro- and microstructures indicating a same sequence of technical actions, as well as specific dimensions: in spite of the diversity of pottery shapes and formats in the *Impressa* layers of Castellar - Pendimoun on the one hand, and of the disparities in the adhesive properties of the clay materials used on the other hand, the spiralled modules are all virtually defined by equivalent diameters (around 4.5 cm), as if they had been calibrated by the producers. This uniformity finds a surprising echo in other contexts in which SPT has recently been identified (*ibid*): roughly the same patch diameters were identified at all the other sites, despite their geographical distance (from Calabria to the Iberian Peninsula), or their attribution to a different temporal stage of the Neolithic (from Archaic *Impressa* to Epicardial).

The development of an integrated 2D and 3D analytical protocol as part of the CIMO and ToMat projects to detect and characterise SPT revealed an array of diagnostic features for SPT, supporting and significantly enriching the macro- and mesoscopic reading in surface and in cross-section. Lastly, microfabric and µ-CT investigations provide additional markers of SPT (empty boundaries, alignments of mineral inclusions or pores), consistent with those identified through the macro- and mesoscopic examination of pottery surfaces and sections (*e.g.* breaks, discontinuities, general organisation of the paste in section or in the tangential plan). In this respect, the analysis of microfabrics and the multiscale µ-CT analytical protocol applied to the Castellar – Pendimoun assemblage provide an integrated framework for SPT acting as a pivotal milestone for the demonstration of this technique's implementation in Early Neolithic contexts.

This multi-scale approach, which can be applied more widely to ancient pottery productions, represents a significant methodological breakthrough for the restitution of ancient ceramic traditions, provided that the different analytical methods are used appropriately. In this study, it has been shown that microfabric characterisation and µ-CT should be applied in parallel to both petrographic analyses – allowing for the characterisation of the raw materials used, as these react differently to the plastic deformations caused by the technical actions – and

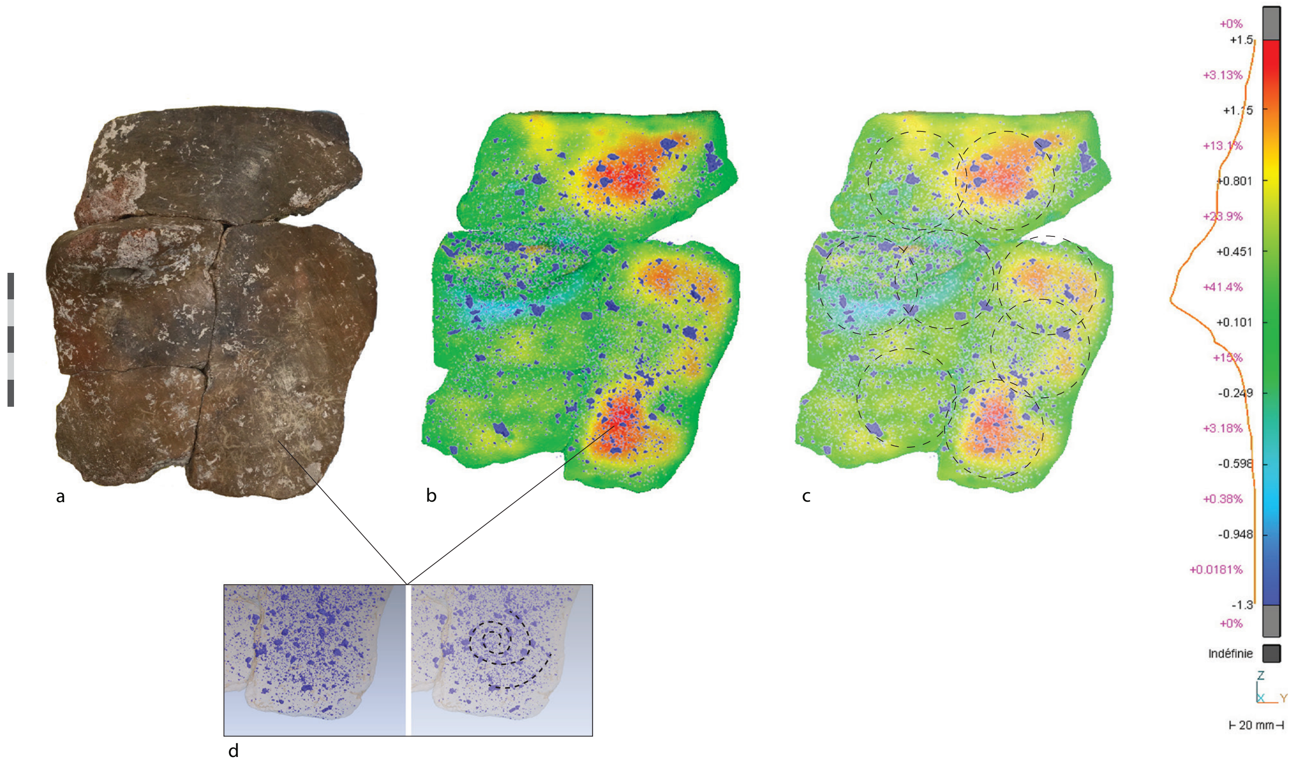

Fig. 15 – *Impresso-Cardial* vessel from Castellar – Pendimoun subjected to correlative analysis, associating micro-topographic surface analysis and µ-CT. The data obtained from both analytical methods are aligned and projected onto the same image revealing a striking correspondence between the outer surface topography and the localisation of some of the identified patches in the vessel's internal structure on the basis of inclusion reconstruction. Blue: inclusions reconstructed from µ-CT acquisition. The represented surface colour varies according to topographical variations (see colour scale on the right). The red areas correspond to a higher topographical level, *i.e.* convexities.

***Fig. 15 –** Vase Impresso-Cardial de Castellar – Pendimoun soumis à une analyse corrélative, associant analyse de surface micro-topographique et µ-CT. Les données obtenues via les deux méthodes d'analyse sont alignées et projetées sur la même image, révélant une correspondance entre la topographie de la surface externe et la localisation de certains des patchs identifiés dans la structure interne du vase sur la base de la reconstruction des inclusions. Bleu : inclusions reconstruites à partir de l'acquisition µ-CT. La couleur de la surface représentée varie en fonction des variations topographiques (voir échelle de couleurs à droite). Les zones rouges correspondent à un niveau topographique plus élevé, c'est-à-dire à des convexités.*

exhaustive macro- and mesoscopic analyses of the assemblages, in order to characterise their technical variability. Moreover, the µ-CT analyses should ideally be conducted on a large number of samples of different nature (sherds and complete vessels) so as to obtain different converging information for characterising technical actions beyond the macro- and mesoscopic evidence on the whole forming sequence. These results have to be articulated with an experimental protocol using sourced geomaterials to establish a direct link between the mode of action and the spatial organisation of the clay material components (Roux, 2016 and 2019). Lastly, in order to exploit these frames of reference in an unbiased manner, it is crucial to go beyond the sole qualitative visualisation towards quantitative analysis. In this regard, analyses using artificial intelligence (AI), which form the core of the ongoing Arch-AI-Story[(2)] research project, represent one of the future challenges for modelling and interpreting the remarkably noisy datasets stemming from pottery µ-CT analyses. Fundamentally, given the significant reference framework built in this study on the basis of a multi-scalar and integrated analytical protocol, SPT can now be reliably identified on other ceramic assemblages based on macrotraces and mesostructures.

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Notes

(1) This µ-CT acquisition was carried out in collaboration with Prof. B. Padovani, radiologist at the Pasteur University Hospital, Nice, France.
(2) Arch-AI-Story (I. Théry-Parisot dir., UCA, CEPAM).

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