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Harvesting cereals at Dja'de el-Mughara in the northern Levant: new results through microtexture analysis of Early PPNB sickle gloss (11th millennium cal BP)

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Abstract: The origin of cereal domestication is a key current issue of archaeological research in the Fertile Crescent. Archaeobotanical evidence highlights a complex scenario for when and where agricultural practices started. Gloss texture analysis of sickle blades with confocal microscopy represents a new contribution to the knowledge of this process. A previous study (Ibáñez et al., 2016) pointed to the Middle Euphrates in the Levant as one region where cereal cultivation occurred since the 13th millennium cal BP and progression towards cereal domestication was since then continuous, culminating in the mid-10th millennium cal BP, in the Middle PPNB. However, the transition from the Early to the Middle PPNB – between 10,200–9,800 cal BP –, a key period previous to the appearance of the first domestic cereals, is not fully understood. This paper presents the quantitative analysis of gloss microtexture on 48 sickle blades from the Early PPNB levels of Dja'de el-Mughara (c. 10,650–10,350 cal BP), where pre-domestic cultivation of wild cereals is attested by archaeobotanical studies. Gloss texture analysis of sickle blades indicates that though reaping semi-ripe cereals associated to cutting wild cultivated cereals is dominant, other group of tools reaped cereals in an advanced degree of maturity. Tools used for cutting green cereals are also present, suggesting that wild cereals in natural stands were also exploited. This study exhibits the complexity of the cereal harvesting strategies at this transitional period, suggesting the exploitation of cereal populations that were in different phases of the domestication process. The results were then compared with the previous research about 50 sickle elements from several sites from the Late Natufian (13th millennium cal BP) to the Late PPNB (late 10th millennium cal BP) in the Middle Euphrates.

Keywords:

1. Introduction

Across southwest Asia between 12th to 7th millennia cal BP, subsistence of human groups evolved progressively from acquisition (hunting, gathering and collecting) to production (animal husbandry and agriculture; Willcox *et al.* 2008), modifying their social interaction and relationship with the environment (Cauvin 1994; Belfer-Cohen, Goring-Morris 2011). The origins of plant domestication, defined as an evolutionary process resulting from cultivation of morphologically wild plants, is a primary current issue of archaeological research in the Fertile Crescent (Nesbitt 2002; Fuller 2007; Zeder 2011; Fuller *et al.* 2012; Zeder 2015).

New archaeobotanical evidence has substantially improved our knowledge of a key turning point in human history by highlighting a complex scenario for when and where agricultural practices started (Purugganan, Fuller 2009; Zeder 2011). It has been demonstrated that the cultivation of wild and domesticated cereals developed at different times in multiple regions across southwest Asia (Willcox 2013) and was conditioned by the regionally diverse plant-based subsistence strategies adopted by Pre-Pottery Neolithic groups (Arranz *et al.* 2016a). Furthermore, the moment when cereals with no brittle rachises, considered the main trait of domestication, became dominant was preceded by a long period of wild cereals cultivation that began at least during the Pre-Pottery Neolithic A (11,800–10,700 cal BP; Tanno, Willcox 2006; Willcox *et al.* 2008; Willcox 2012).

However, if the general process of cereal cultivation leading to domestication in the Levant is well established, there is still a lack of knowledge about the rhythm of this transition at a regional scale. This is due to the scarcity of archaeobotanical studies that analyze extended collections of charred seeds and chaff. The preservation of

charred seeds and chaff is irregular in archaeological sites and the systematic flotation of sediments has not always been a standard procedure. Because of this, the analysis of sickle blades can be a complementary source of information about the process of cereal domestication, as sickle elements are ubiquitous in Neolithic sites and the preservation of harvesting traces is, in most of them, optimal.

Harvesting tools likely played a primary role in crop domestication, operating an involuntary selection of seeds with solid rachis, “the mutant individuals”, present in tiny proportion among wild populations of cereals (Hillman, Davies 1990). To better understand the appearance and development of this protracted model of domestication, some researchers were interested in the function of sickle blades (Anderson *et al.* 1991; Anderson 1992; Unger-Hamilton 1992). Harvesting with sickle creates a micropolish along the edge of the flint blades. Diachronic evolution in sickle micropolish texture from the Epipalaeolithic to the Neolithic, described by functional analysis at high magnification, shows that, over time, micropolish appears flatter and more abraded. By means of experimentation, this evolution has been related to changes in harvesting strategies, linked to the shifting of cereal characteristics during the process of cereal cultivation and domestication (Anderson 1992; Unger-Hamilton 1992; Ibáñez *et al.* 1998).

In wild stands, individual plants ripen at different times. For the same plant, spikelets mature from the tip of the seed head down and fall spontaneously at maturity due to their brittle rachis (Zohary *et al.* 2012). On the contrary, domestic cereals, with tough rachises, ripen in a more homogenous fashion in the fields and spikelets do not fall at maturity. Therefore, to avoid natural seed dispersal, wild cereals were most likely sickle-harvested in a green state, when stems were just yellowing and first grains have detached from the seed head. This produces domed and smooth usewear traces, whereas domestic cereals could be harvested at a ripe state, resulting in a flatter and more abraded micropolish (Anderson 1992). Experimentations show also that wild cultivated cereals could be sickle-harvested in a semi-ripe state, when the average of the crops were ripe enough so the grain was near maturity but most was still attached to the ear. At this stage, the stems were a mixture of yellow and green, depending on the maturity of each individual plant. In this way, the crop could be harvested without significant grain loss, so maximum yield recovery was assured (Anderson 1992).

Differences in humidity of cereals when harvested explain contrasts in the appearance of microtexture of polish from cutting cereal stems at different stages of maturity (Anderson 1992). The general diachronic evolution in sickle micropolish texture during the process of transition from wild – with brittle rachises – to domestic cereals – with tough rachis – could thereby be linked to the possible practice of an increasingly mature crop harvest method to maximize the yield.

However, differences in microtexture of polish related to the state of maturity of cereals are so subtle that distinguishing them with the standard method of the high-power optical microscopy is difficult. To solve this, a methodological innovation based in texture analysis of 3D images of microwear polish obtained with confocal microscopy was attempted (Evans, Donahue 2008; Evans, Macdonald 2011; Stemp, Chung 2011; Stemp *et al.* 2013; Stevens *et al.* 2010). This methodology made it possible to use sickle micropolish texture to infer the precise humidity condition of cereals when harvested over the course of cultivation and domestication (Ibáñez *et al.* 2014; Ibáñez *et al.* 2016). Confocal microscopy was successfully employed to discriminate traces produced on some experimental tools used for harvesting wild cereals growing in natural stands, wild cultivated cereals and domestic cereals, thus reproducing the three successive phases in the process of cereal domestication. Traces were also studied on tools used for cutting reeds (Ibáñez *et al.* 2016).

In this paper, we apply this methodology to the study of sickle blades from the last EPPNB levels of Dja'de el-Mughara in the Middle Euphrates area (Coqueugniot 1998; Coqueugniot 2014). The pre-domestic cultivation of wild cereals seems to be effective during Dja'de III, and even before (Douché, Willcox 2018), dated between *ca* 10,490-10,250 cal BP according to the summed probability distribution of 14^C dates (Coqueugniot 2014). Contemporaneous occupations are poorly documented in the Middle Euphrates area (submerged village of Mureybet, phase IV_A; Ibáñez 2008) or in the northern Levant in general (Nevalı Çori in Anatolia (Hauptmann 2011) and Tell Ain el Kerkh in northwestern Syria; Tsuneki *et al.* 2006); Dja'de is, therefore, crucial for understanding the regional evolution of agricultural practices (Douché, Pichon 2018; Douché, Willcox 2018). By analyzing for the first time a substantial sample of sickles blades (48 specimens), this study considerably improves our knowledge of the establishment of farming society in the northern Levant just before 10,000 cal BP.

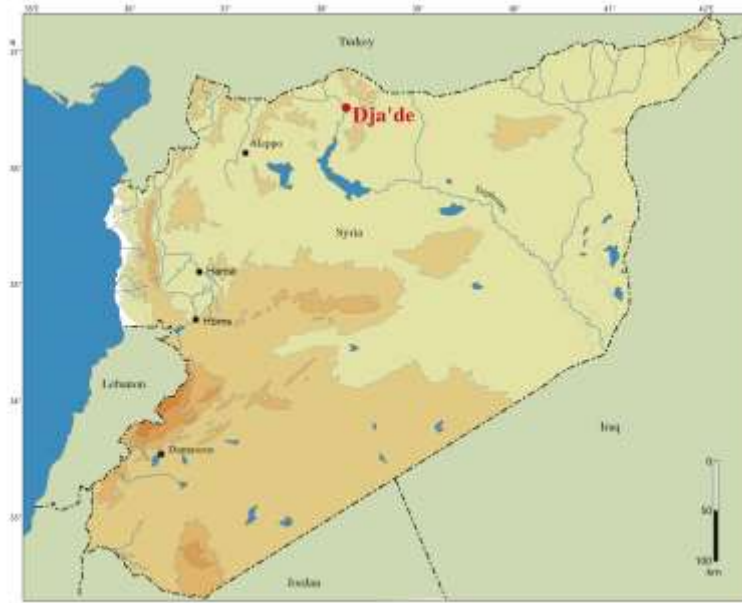


Fig. 1. Situation of Dja'de el Mughara in Syria (©MOM).

2. Dja'de el-Mughara

Tell Dja'de el-Mughara is located in northern Syria on the left bank of the Euphrates river (Figure 1). The site was excavated from 1991 to 2010 by a French team directed by É. Coqueugniot. During the early Neolithic, the site was occupied from the final Pre-Pottery Neolithic A (PPNA) to the Early Pre-Pottery Neolithic B (EPPNB) (Coqueugniot 1998; Coqueugniot 2014). The village is situated in the area with mean annual rainfall between 250 and 300 millimeters. The local environment, alluvial plain and steppic hinterland, constituted a rich ecological niche with complementary resources (wild plants, wood, fauna and lithic raw material) favourable to the settlement of a (semi-) permanent occupation (Coqueugniot 1998; Helmer *et al.* 1998; Willcox *et al.* 2008). The stratigraphic sequence was divided in three main phases according to the architecture and the lithic industry (Coqueugniot 1998; Coqueugniot 2000; Coqueugniot 2014): “Dja'de I” (ca 11,260-10.780 cal BP, corresponding to the Late PPNA), “Dja'de II” (ca 10.750-10.450 cal BP, corresponding to the beginning of the Early PPNB) and “Dja'de III” (ca 10.490-10.240 cal BP, corresponding to the second half of the Early PPNB as known at Mureybet, phase IV_A).

The flint sickles that are the subject of our paper were recovered in Dja'de III¹. During this phase, the domestic architecture is characterized by mud walls with stone frame forming rectangular and single-celled houses. Grill-plans and hearths and combustion features are present in open-areas. Many burials were discovered: most of the skeletons were deposited inside a rectangular building entitled ‘*Maison des morts*’ (“House of dead”; Coqueugniot 1998; Chamel 2014; Baker *et al.* 2017; Chamel, Coqueugniot 2019). The low sexual dimorphism observed on bovines from DJIII, compared to the PPNA populations, suggest their domestication, resulting from a human selection and herd management (Helmer *et al.* 2005; Helmer *et al.* 2018).

The archaeobotanical results have shown that crops were represented by cereals and pulses, the former being dominated by barley (*Hordeum spontaneum*) and the later by lentil (*Lens* sp.). While during the first phase of the occupation (DJI), the proportion and the frequency of cereals were higher than pulses; the tendency was reversed during the Early PPNB (DJII and DJIII; Figure 2).

¹ Contemporary levels of Dja'de III were discovered at Mureybet (phase IV_A in a secondary position in a small area; Cauvin 1977) and at Cheikh Hassan (Abbès 2003), but these were submerged by the Euphrates river following the construction of the Taqba dam.

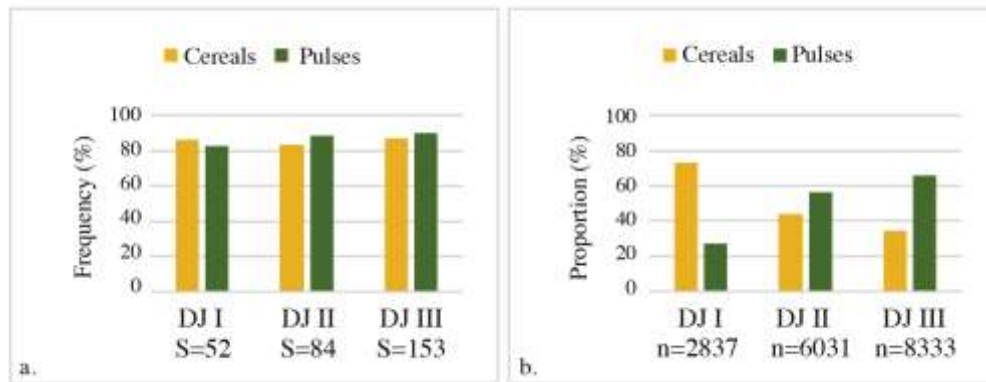


Fig. 2. a. Frequency (number of samples in which a taxon occurs) of cereals (including barley, rye, wheats and *Cerealia* spp.) and pulses (bitter vetch, faba bean, lentil, pea and indeterminate pulses) in each phase. S=Number of samples. b. Proportion of crops (cereals and pulses) in each occupation phase at Dja'de. The graph shows that the quantity of pulses increases whereas that of cereals decreases through time. n=Number of remains.

Present in ca 80% of all samples, barley (*Hordeum spontaneum*) is the most frequent taxa (Douché, Pichon 2018; Douché, Willcox 2018). Rye (*Secale* sp.), attested by grains and chaff remains, is the second most important cereal in terms of proportion and frequency that increase between the beginning and the end of the Neolithic occupation (Figure 3). Similarly, einkorn (*Triticum boeoticum*) and emmer (*Triticum dicoccoides*) wheat present a lower proportion and ubiquity that tend to increase through time.

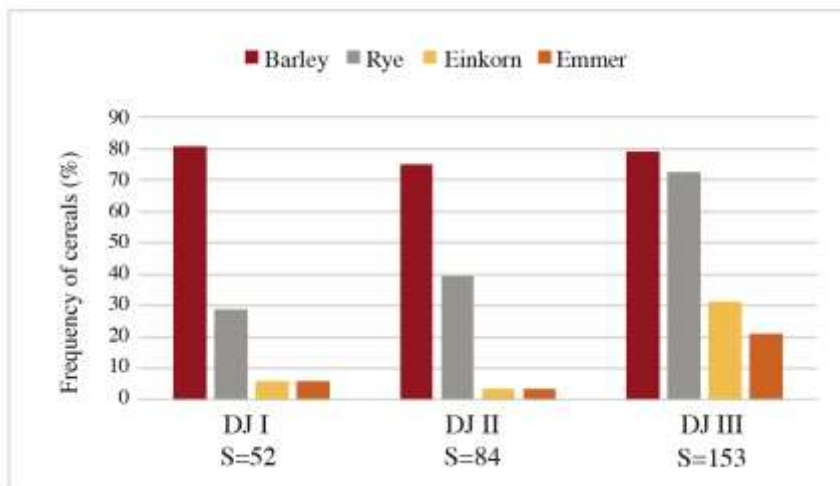


Fig. 3. Frequency (number of samples in which a taxon occurs) of the four cereals recovered at Dja'de. S=Number of samples

The morphological analysis of rachis and spikelet bases indicates the exploitation of wild cereals (brittle rachis) during the three phases of the occupation (Douché, Pichon 2018, Douché, Willcox 2018). Despite the recovery of domestic types chaff, their proportion remains low (ca 5%) compared to wild type, with a smooth abscission scar (ca 95%). In spite of the absence of morphological domestication of cereals, their cultivation is evidenced by their high frequency, the morphological aspect of caryopsis, showing well-developed grains, and the presence of a wide range of wild taxa, reflecting potential arable weeds (Douché, Pichon 2018; Douché, Willcox 2018).

3. Previous studies of harvesting tools from Dja'de III levels

The lithic industry is essentially based on a bipolar laminar knapping made with soft stone hammer and a fine grain flint (Coqueugniot 1994; Arimura 2020). Among the tools, Byblos arrowheads, blades with “ergot” and glossy blades are characteristic elements. Functional analysis of glossy flint blades from Dja'de III shows that cereals were harvested with sickles (Pichon 2017a; Pichon 2017b; Douché, Pichon 2018; Pichon 2019). The blades were intensively used, showing extended micropolish, and cutting edges were resharpened. In comparison with experimental tools, sickles were likely used during several hours and the specificity of the tools for plant

reaping could explain the low rate of reuse of glossed tools in other activities (Pichon 2017a; Pichon 2017b; Pichon 2019). Reaping was practiced close to the ground to recover the stems, maybe for using them in the domestic space such as components of the architecture (i.e. mud walls, fences, roof coverings, mats; Douché, Pichon 2018) or feeding bovids (see below).

According to the gloss and adhesive distribution, curved hafts, with one long blade or multiple short elements inserted in parallel to the handle, could be used for the harvest (Pichon 2017a; Pichon 2017b; Pichon 2019). The existence of curved handles is supposed at the Early PPNB levels at Mureybet (Ibáñez *et al.* 2008) and is attested during the Middle PPNB at Halula (Borrell, Molist 2007) and at Nahal Hemar (Bar-Yosef, Alon 1988). According to the experiments, the evidence of curved sickles represents an important evolution in the harvesting techniques as it improves the harvester's gesture compared to the Epipalaeolithic straight sickles (Astruc *et al.* 2012; Ibáñez *et al.* 1998).

Archaeobotanical remains, intense use of sickles and apparitions of curved handles are evidence of a growing exploitation of cereals and intensification of agricultural practices at Dja'de during the Early PPNB. Harvests may have taken place in the spring and early summer, when the grain matures with viable grain (Pichon 2019), but had to be made before complete ripening of the spikelets in order to avoid excessive grain loss due to their brittle rachis (Anderson *et al.* 1991). Nevertheless, the microscopic analysis of glossed tools showed an important variability in terms of topography (more or less flat), in the degree of abrasion and in the quantity of striations (Pichon 2017b). According to the experiments, several factors can explain this variability: 1) time of use: more developed micropolish is flat; 2) the raw material: the finer the grain of flint, the flatter the micropolish; 3) the moisture content of the plant: the dryer the stems, the flatter, more abraded and dull the micropolish, 4) the presence of abrasive particles between the tool and the plant: the lower the cut, the more streaked and abraded the edge (Korobkova 1981; Anderson 1992; Unger-Hamilton 1992; Ibáñez *et al.* 1998; Ibáñez *et al.* 2016). This variability could be linked to a different time of use between blades, to the position of the blades in the haft — experiments have showed that the mesial cutting blades are more solicited during the use — or to the type of flint. But here, this variability is present between the more developed micropolish and between fine-grained blades. On the other hand, the variation of the quantity of humidity content on the stems seems a more relevant hypothesis: domed and smooth micropolish resembles experimental usewear traces from green or semi-ripe harvest, whereas flat, dull and rough micropolish looks like experimental usewear from ripe harvesting (Unger-Hamilton 1991; Anderson 1992). Thereby, we used the texture analysis of 3D images of microwear polish obtained with confocal microscopy to infer the precise humidity condition of cereals when harvested during Dja'de III (Ibáñez *et al.* 2014; Ibáñez *et al.* 2016). Assuming the hypothesis that the moisture content of cereal stems when harvested can be related to their wild or domestic state (Ibáñez *et al.* 2016), the main objective of our study to understand the agricultural practices in Dja'de during the origins of cereal agriculture.

4. Method and materials

4.1. The method

The methodological procedure is described in detail in a previous publication (Ibáñez *et al.* 2016).

Nineteen experimental tools were used to harvest cereals, six for domestic cereals, five for wild cultivated cereals and six for wild cereals spontaneously growing in natural stands; two reed-cutting tools were also included in the analysis (Ibáñez *et al.* 2016, Table 1, 67). Cereals were reaped close to the ground (ca 20 cm from it). Experiments harvesting wild cereals (*Triticum boeoticum*, *Triticum dicoccoides* and *Hordeum spontaneum*) growing in natural stands were carried out in southern Syria (Jebel el Arab) and in Israël (Jordan Valley) with wooden and antler sickle handles armed of fine grained flint inserts or a single blade. In each case, wild cereals were reaped before maturity, when the grain was already formed, but the plants were not fully ripe (Figure 4).

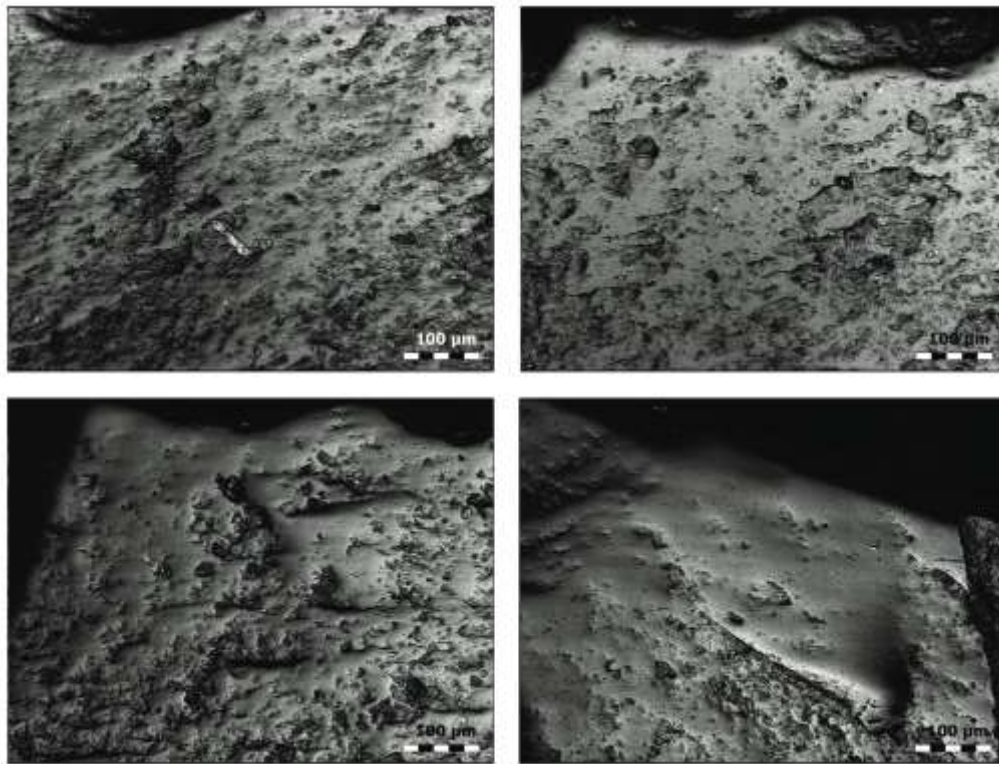


Fig. 4. Use-wear polish from harvesting wild cereals in natural stands.

Wild cultivated cereals (*Triticum boeoticum thaoudar*) were experimentally sown and harvested in southern Mediterranean France (CNRS laboratory of the “Institut de Préhistoire Orientale” in Jalès, Ardèche; Anderson *et al.* 1991). The harvest took place when the grain was near maturity and most was still attached to the stem (Figure 5). Thus, depending on the maturity of each individual plant, there were a mixture of yellow and green stems, there were a mixture of yellow and green stems. Tests of germination showed that, despite the mix of stages of grain maturity in the seed head, 90% of them germinated: this semi-ripe harvest gave an acceptable yield (Anderson 1992).

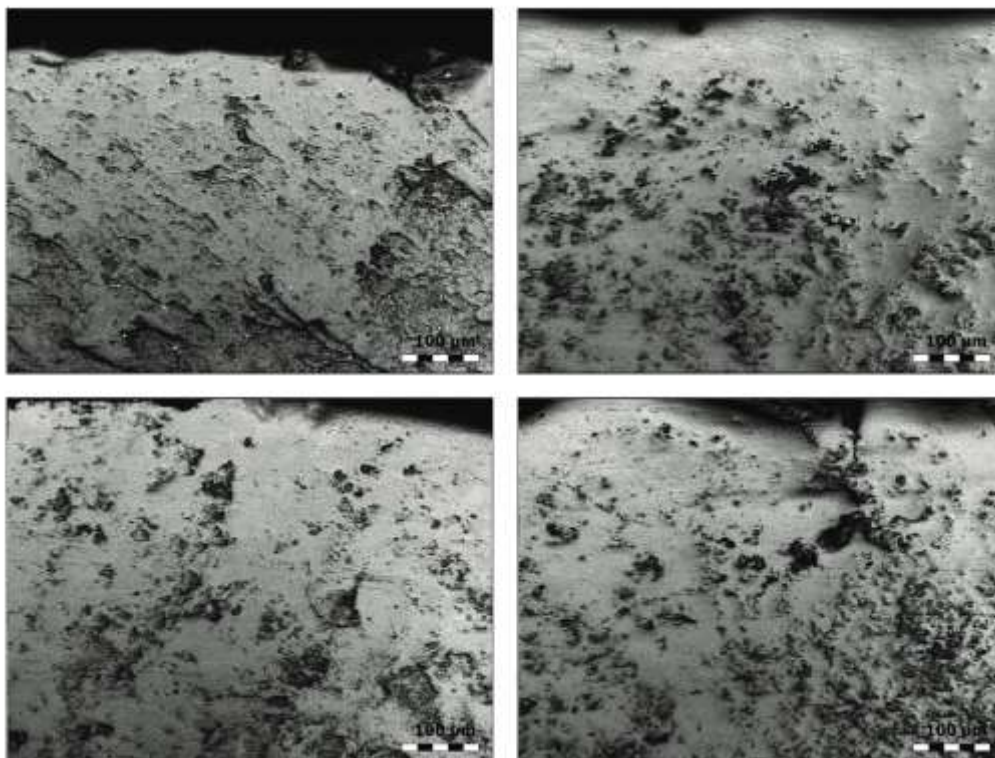


Fig. 5. Use-wear polish from harvesting wild cultivated cereals.

Experiments harvesting domestic cereals were carried out in multiple places. *Triticum spelta* was harvested in Spain (in Zureda, Asturias), with a wooden sickle with flint inserts, matching the Karanovo type sickles. *Triticum aestivum*, *Triticum dicoccum* and *Triticum monococcum* were harvested in France (Jalès and Seranon). Domestic wheats were harvested ripe (Figure 6), except one experiment of cutting semi-ripe einkorn in southeast France (Séranon).

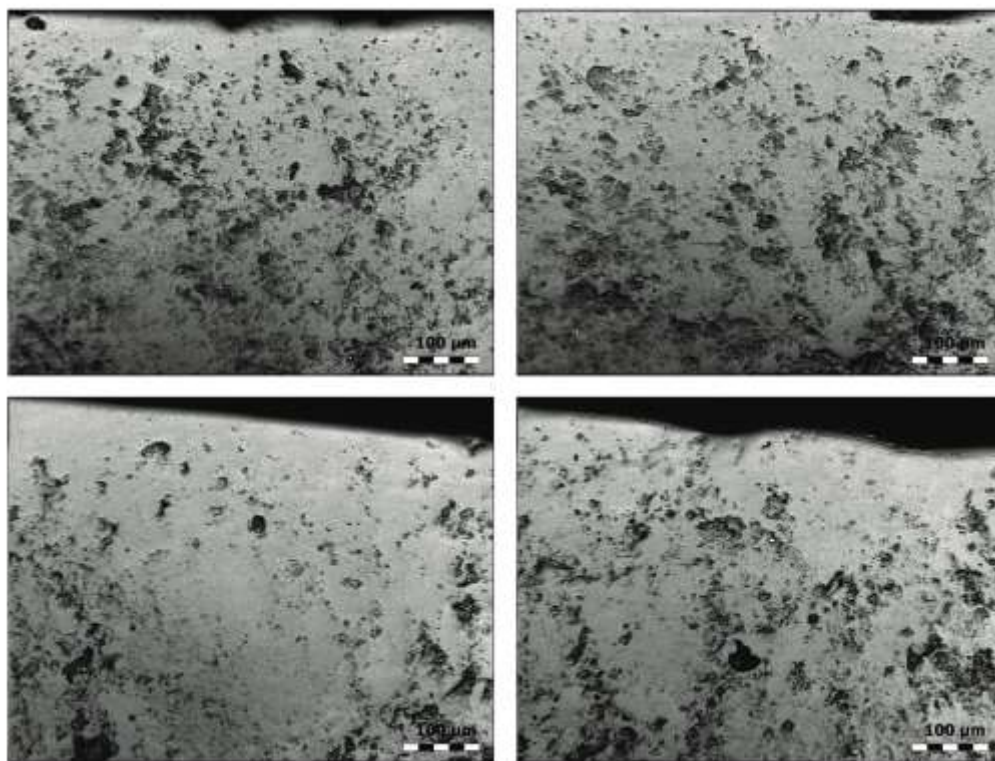


Fig. 6. Use-wear polish from harvesting domestic cereals.

Reed harvesting experiments were also carried out in southern France (Jalès), in shallow standing water and when the stems were firm but not brittle (Figure 7).

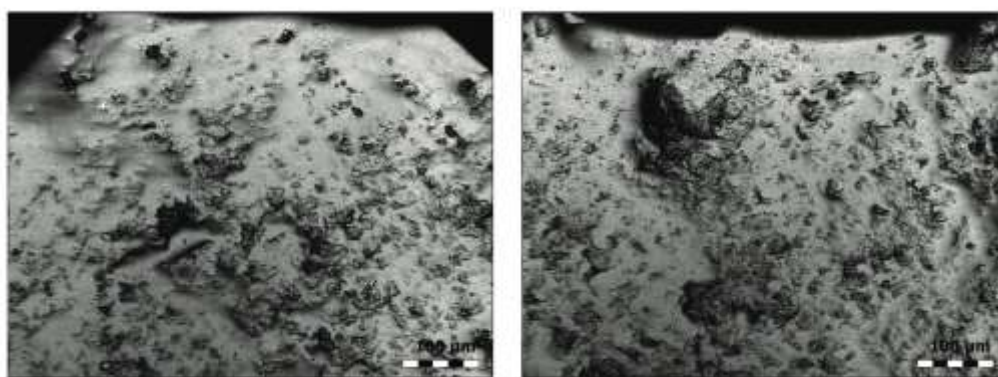


Fig. 7. Use-wear polish from harvesting reeds (100x).

Before the analysis, the experimental tools were cleaned with soapy water, gently rubbing the surface with the fingers. For each experimental tool, six to ten zones of 650x500 μm were measured where the micropolish was the most developed — polished areas covered more than 90% of the sampled surface — with the Sensofar Plu Neox scanning confocal microscope, using a 20X (0.45 NA) objective, with a spatial sampling of 0.83 mm, an optical resolution of 0.31 μm, a vertical resolution of 20 nm and a z-step interval of 1 μm. Subsamples of 200x200 μm were then selected from those 650x500 μm areas (ca three subsamples for each bigger samples), enabling the ability to choose areas with homogeneous and well developed micropolish without irregularities caused by the natural surface of the flint. A total number of 21 to 23 subsamples were taken for each

experimental tool. The scanning confocal microscope generates a three-dimensional characterization of the surface. The 3D images were processed using the Sensomap 7 software from Digital Surf. The lack of horizontality of the sampled surface was corrected by a leveling operator, using the Least Squares (LS) Plane Method and the polish texture was isolated from irregularities of the flint topography by moving a small filtering matrix over the surface. The arithmetic mean operator consists in averaging each point with its 13x13 neighboring points and the polish texture is calculated by subtracting the filtered surface from the source surface.

Eleven quantitative parameters of texture analysis were measured for each subzone. There are *amplitude parameters*, a class of surface finish parameters characterizing the distribution of heights (Sa, the mean height of the surface; Sq, the square root mean height; Sz, the distance between the highest peak and the deepest valley; Sp, the maximum peak height and Sv, maximum valley depth area); *spatial parameters*, which quantify the lateral information present on the X and Y-axes of the surface based upon spectral analysis (Sal, expressing the content in wavelength of the surface; Str, which measures whether the surface is isotropic); *hybrid parameters* considering both the amplitude and the spacing (Sdq, the root-mean-square value of the surface slope; Sfd, indicating the complexity of the surface using the fractal dimension theory) and *parameters measuring the micro-valley network* obtained after the vectorization of the surface, searching for all the furrows contained by a surface and measuring its mean depth (MDF) and mean density (MDenF).

Data collected from each sub-area was entered into SPSS statistical software, which developed discriminant functions to distinguish the four groups (green wild cereals, cultivated wild cereals harvested in a semi-ripe state, ripe domestic cereals and reeds). Quadratic discriminant function analysis built a predictive model for group membership, which is composed of discriminant functions based on quadratic combinations of predictor variables when these variables show different variance-covariance matrices (heteroscedasticity showed by the Box's M test). Three quadratic discriminant functions were obtained to distinguish the subsamples of use-wear polish resulting from cutting the three cereal types (wild in natural stands/green cereals, wild cultivated/semi-ripe cereals and ripe/domestic cereals) and reeds. Statistical data processing consisted of evaluating how the discriminant explanatory variables discriminate the different groups and testing the potential of the classification by discriminant functions.

Various statistical indicators showed that the discriminant functions allowed consistent discrimination between the four groups (Ibáñez *et al.* 2016). Significant mean differences (Wilks' Lambda) were observed for all the predictors mentioned in the previous section and for discriminant functions. While the log determinants were quite similar, Box's M indicated that the assumption of equality of covariance matrices was violated, so a quadratic discriminant analysis was chosen.

Eigenvalue values showed that Function 1 explains 64,8% of the variance, Function 2 of the 21,1% and Function 3, 14,1%. The structure matrix indicated main within-group correlation between variables Sa, Sq, MdF, Sdq, Sz, MDenF; Sp, Sv, Str with the first function, Sal with the second and Sfd with the third. The classification table showed 73% correct classification for the three groups of different cereal harvesting polish and reeds, and 77.1% of cases correctly classified dealing only with the three groups of different cereal harvesting polish. The projection in the new representation system showed that the clusters were correctly discriminated from one another by the functions 1 and 2. Finally, the evaluation of discriminant function performance by estimating error rates — by classifying each experimental tool against the rest of the experimental tools not being tested — provided a high rate of correct classification of the experimental tools.

The research team (Ibáñez *et al.* 2016) explained the discriminant capacity between usewear polish of the three cereal types and reeds by the different degree of humidity present on the reaped stems. Thus, this method enables the reliable classification of tools used for harvesting cereals in three states of humidity and identifies the state of ripeness of the cereal when harvested, but not its genetic characteristics. We are aware that gloss texture could be affected by other factors that have not been experimentally tested yet, as the height of plant cutting (near of far from the ground), the type of harvested cereal (barley, emmer, einkorn...), the time of use. New experiments dealing with these variables are being carried out in order to gain more detailed knowledge of plant cutting gloss. Nevertheless, the influence of ripeness stage on use-wear formation has been already observed experimentally (Anderson 1992) and the role of water in the development of silica polish has been also pointed out (Fullagar 1991). Therefore, plant humidity is one of the key-factors in determining cereal polish characteristics. As explained before (see the introduction), the experimentation showed that when one is aiming to achieve the highest yield productivity, wild cereals growing in natural stands are cut in a green state, cultivated wild cereals in a semi-ripe state and domestic cereals in a ripe state. In this case, the recognition of the three states of maturity of cereals (green, semi-ripe and ripe) in an archaeological collection of sickles is a good indication, in conjunction with the archaeobotanical information, of the characteristics of cereals being harvested (Ibáñez *et al.* 2016).

4.2. Archaeological sample from Dja'de III

The same procedure was used to classify 48 glossy blades from Dja'de III, the most recent Pre-Pottery Neolithic phase on the site, dated between ca 10,490-10,240 cal BP and corresponding to the second half of the Early PPNB. These blades were mostly discovered during the first excavations campaign made on the site in the early 1990s, and exported by the director of the mission, É. Coqueugniot, for usewear analysis, with the agreement of the Syrian General Directorate of Antiquities and Museums.

Most of the blades are coming from the upper occupations levels of the sectors B (15 blades) and C (13 blades), located in the center of the tell and excavated during the first campaigns (Figure 8). In those sectors, the occupations levels are characterized by a succession of clay floors and destructions layers, light constructions (post holes), ash pits and several grill-plans (narrow and parallel low walls). These areas, having delivered few architectural vestiges and featuring light constructions, correspond to activity places. In sector [C], it seems that the upper most levels correspond to some garbage pits (pits III) containing an ashy sediment, many burnt and fragmented bones, and flint pieces: some blades of this study are coming from this secondary stratigraphic context. Some other glossy blades were discovered in the sectors D (3 blades), A (4 blades), SB (9 blades) and ST (4 blades), which delivered rectangular houses, associated with outdoors spaces, post holes and grill-plans. At the time of the occupation, the village of the Early PPNB had to include rectangular houses separated by open areas in which were installed external structures (the so-called grill-plans probably having supported light platforms) and activity places² (Coqueugniot 1998).

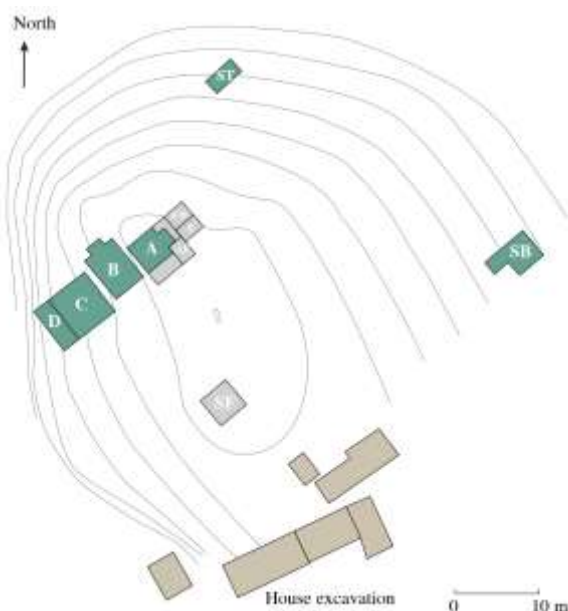


Fig. 8. Map of the site with excavation areas: studied sample is coming from green areas (according to fields report edited by É. Coqueugniot).

The analyzed archaeological tools were chosen among those that are present in France and were studied for the PhD research of one of us (F. Pichon). The tools showing macroscopic gloss that were previously identified as used for plant cutting using the conventional use-wear method were selected. They were very scarcely affected by post-depositional surface modification (i.e. abrasion or striations). Before proceeding with the analysis, they all were cleaned with soapy water. We did not use more aggressive cleaning procedures (acids and basics) in order to avoid the elimination of potential residues of the harvested plants or the mastic used to stick the blade into the haft. All the archaeological glossed tools had been made in fine-grained flint, as was the case for the experimental tools. Before proceeding with the analysis, they all were cleaned with soapy water. The same procedure as described previously for the experimental collection was applied to the archaeological tools: 1) use of a metallographic microscope (Leica DM 2500 M at 100 and 200 magnifications), choosing the appropriate areas for proceedings to the measurement with the Sensofar Plu Neox scanning confocal microscope (i.e. most-developed usewear micropolish along the edge, on both ventral and dorsal sides); 2) selection of six to ten zones of 650x500 μm per tools; 3) selection of three to four subsamples of 200x200 μm from each bigger areas.

² The glossy blades that we have studied are coming from the multiple successive soils of occupation associated with these light structures as well as layers of destruction, without it being possible for now to determine precisely the nature of the original layer, the study and publication of the stratigraphic documentation being in progress by the research team.

5. Results

5.1. Classification of the archaeological sickles from Dja'de III according to the discriminant function

From a total of 1145 3D images corresponding to 48 tools, 31,06% were classified in the group of ripe cereals, 56,47% in the group of semi-ripe cereals, 9,04% in the group of green cereals reaped in natural stands and 3,43% in the group of reeds³ (Table 1; Figures 9-12). Harvesting of semi-ripe cereals, the experimental group used for cutting wild cultivated cereals, is the dominant group in Dja'de III.

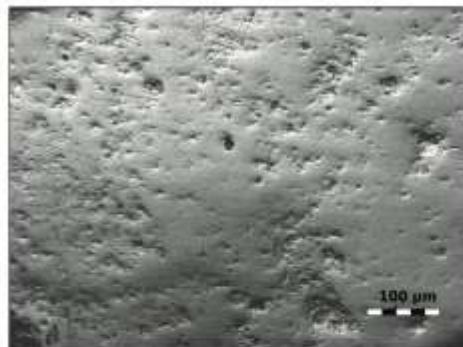
Tool's number	Cont ext	Subsa mples	Predictive memberships				Percentage for each predictive memberships				Result
			Ripe	Semi-ripe	Green	Reeds	Ripe	Semi-ripe	Green	Reeds	
DJB244	DJ III	24	3	20	1	0	12,50	83,33	4,17	0,00	Semi-ripe cereals
DJB289	DJ III	24	9	13	1	1	37,50	54,17	4,17	4,17	Unclassified
DJB293	DJ III	24	7	17	0	0	29,17	70,83	0,00	0,00	Semi-ripe cereals
DJB300	DJ III	24	1	11	12	0	4,17	45,83	50,00	0,00	Unclassified
DJB1094	DJ III	24	9	15	0	0	37,50	62,50	0,00	0,00	Semi-ripe cereals
DJB1281	DJ III	24	17	6	1	0	70,83	25,00	4,17	0,00	Ripe cereals
DJB2137	DJ III	24	5	16	2	1	20,83	66,67	8,33	4,17	Semi-ripe cereals
DJB2139	DJ III	24	5	19	0	0	20,83	79,17	0,00	0,00	Semi-ripe cereals
DJB2251	DJ III	23	10	5	1	7	43,48	21,74	4,35	30,43	Unclassified
DJB3048	DJ III	24	2	5	17	0	8,33	20,83	70,83	0,00	Green cereals
DJB3076	DJ III	24	7	16	1	0	29,17	66,67	4,17	0,00	Semi-ripe cereals
DJB3100	DJ III	23	0	21	2	0	0,00	91,30	8,70	0,00	Semi-ripe cereals
DJB3213	DJ III	24	6	18	0	0	25,00	75,00	0,00	0,00	Semi-ripe cereals
DJB3148	DJ III	24	13	10	0	1	54,17	41,67	0,00	4,17	Unclassified
DJB1207	DJ III	24	7	12	2	3	29,17	50,00	8,33	12,50	Unclassified
DJC315	DJ III	24	1	21	2	0	4,17	87,50	8,33	0,00	Semi-ripe cereals
DJC354	DJ III	24	3	17	3	1	12,50	70,83	12,50	4,17	Semi-ripe cereals
DJC376	DJ III	24	2	19	3	0	8,33	79,17	12,50	0,00	Semi-ripe cereals
DJC438	DJ III	24	8	7	6	3	33,33	29,17	25,00	12,50	Unclassified
DJC2248	DJ III	24	10	10	3	1	41,67	41,67	12,50	4,17	Unclassified
DJC2244	DJ III	24	8	16	0	0	33,33	66,67	0,00	0,00	Semi-ripe cereals
DJC2208	DJ III	20	6	13	0	1	30,00	65,00	0,00	5,00	Semi-ripe

³ Remains of reed stems knots have been discovered in archaeobotanical assemblages.

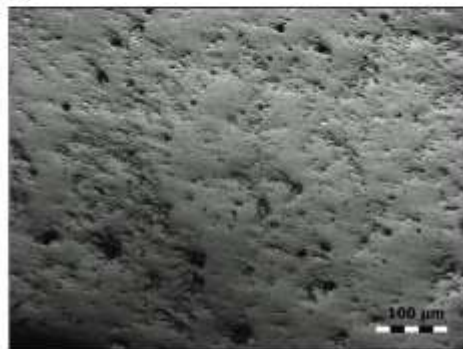
											cereals
DJC2167	DJ III	24	5	15	2	2	20,83	62,50	8,33	8,33	Semi-ripe cereals
DJC5019	DJ III	24	6	17	1	0	25,00	70,83	4,17	0,00	Semi-ripe cereals
DJC92	DJ III	24	16	5	0	3	66,67	20,83	0,00	12,50	Ripe cereals
DJC8	DJ III	24	13	11	0	0	54,17	45,83	0,00	0,00	Unclassified
DJC1024	DJ III	24	14	10	0	0	58,33	41,67	0,00	0,00	Ripe cereals
DJC2057	DJ III	24	14	9	1	0	58,33	37,50	4,17	0,00	Ripe cereals
DJA3135	DJ III	24	13	8	3	0	54,17	33,33	12,50	0,00	Unclassified
DJA3145	DJ III	24	0	20	4	0	0,00	83,33	16,67	0,00	Semi-ripe cereals
DJA3235	DJ III	24	10	10	2	2	41,67	41,67	8,33	8,33	Unclassified
DJA3308	DJ III	24	0	24	0	0	0,00	100,00	0,00	0,00	Semi-ripe cereals
DJD17	DJ III	23	3	19	1	0	13,04	82,61	4,35	0,00	Semi-ripe cereals
DJD81	DJ III	24	12	6	5	1	50,00	25,00	20,83	4,17	Unclassified
DJD3316	DJ III	24	14	7	1	2	58,33	29,17	4,17	8,33	Ripe cereals
DJSB24	DJ III	24	0	24	0	0	0,00	100,00	0,00	0,00	Semi-ripe cereals
DJSB26	DJ III	24	7	15	1	1	29,17	62,50	4,17	4,17	Semi-ripe cereals
DJSB1043	DJ III	24	0	6	18	0	0,00	25,00	75,00	0,00	Green cereals
DJSB1049	DJ III	24	6	18	0	0	25,00	75,00	0,00	0,00	Semi-ripe cereals
DJSB1079	DJ III	24	2	16	6	0	8,33	66,67	25,00	0,00	Green cereals
DJSB2024	DJ III	24	16	6	0	2	66,67	25,00	0,00	8,33	Ripe cereals
DJSB2045	DJ III	24	10	14	0	0	41,67	58,33	0,00	0,00	Semi-ripe cereals
DJSB2256	DJ III	24	7	16	0	1	29,17	66,67	0,00	4,17	Semi-ripe cereals
DJSB2393	DJ III	24	4	16	0	4	16,67	66,67	0,00	16,67	Semi-ripe cereals
DJST1027	DJ III	24	4	19	1	0	16,67	79,17	4,17	0,00	Semi-ripe cereals
DJST1031	DJ III	24	2	20	1	1	8,33	83,33	4,17	4,17	Semi-ripe cereals
DJST1040	DJ III	24	20	4	0	0	83,33	16,67	0,00	0,00	Ripe cereals
DJST1069	DJ III	24	19	4	0	1	79,17	16,67	0,00	4,17	Ripe cereals
Total subsamples of		1145	356	646	104	39	Average of percentage for each predictive memberships				
							31,06 %	56,47 %	9,04 %	3,43 %	

Table 1. Classification of the archaeological tools from Dja'de III according to the four experimental groups. When more than 55% of the samples from each archaeological tool were classified in one group, the tool was considered as belonging to that group. When predicted membership classification in any of the four groups did not reach 55% of the samples, the tool was considered as unclassified.

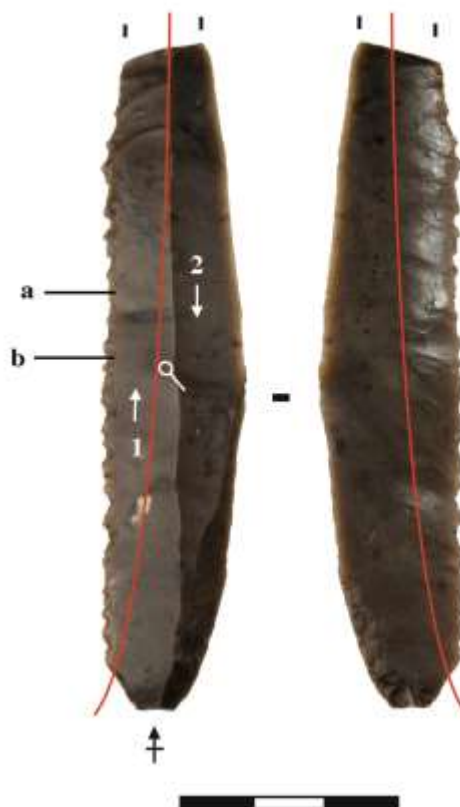
DJSB1079



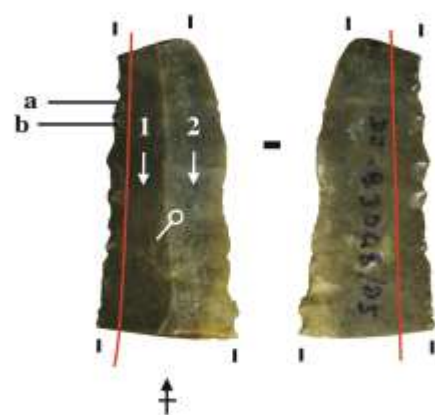
a.



b.



DJB3048



— Limit of the micropolish
(sickle gloss)



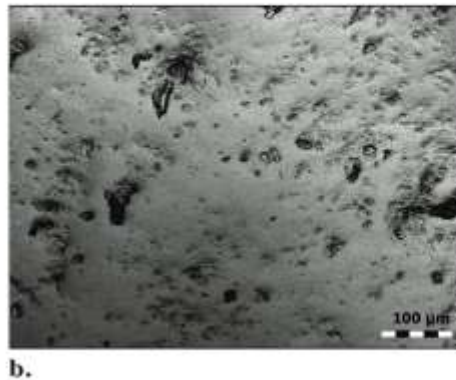
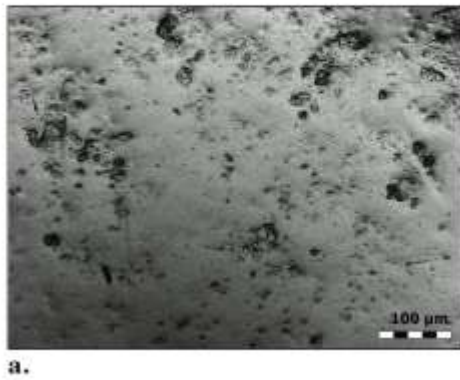
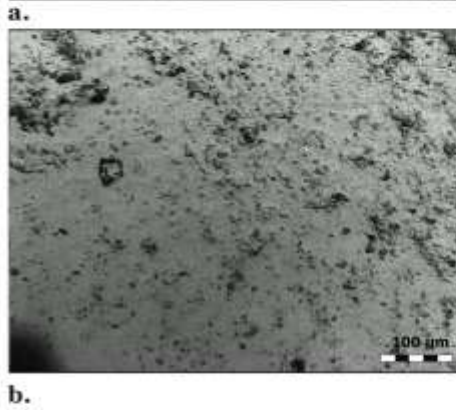
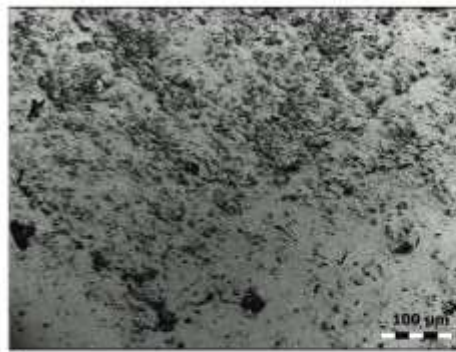
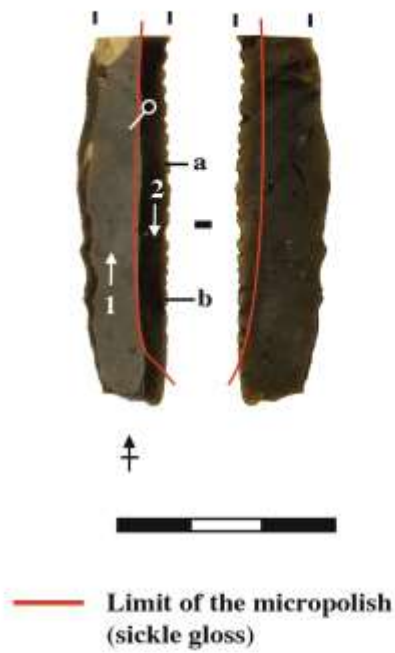
a.



b.

Fig. 9. Archaeological tool classified as used for harvesting green cereals. DJSB1079.

DJB244



DJB2045

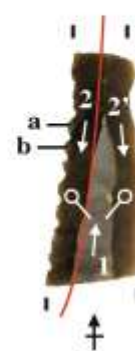


Fig. 10. Archaeological tools classified as used for harvesting semi-ripe cereals.

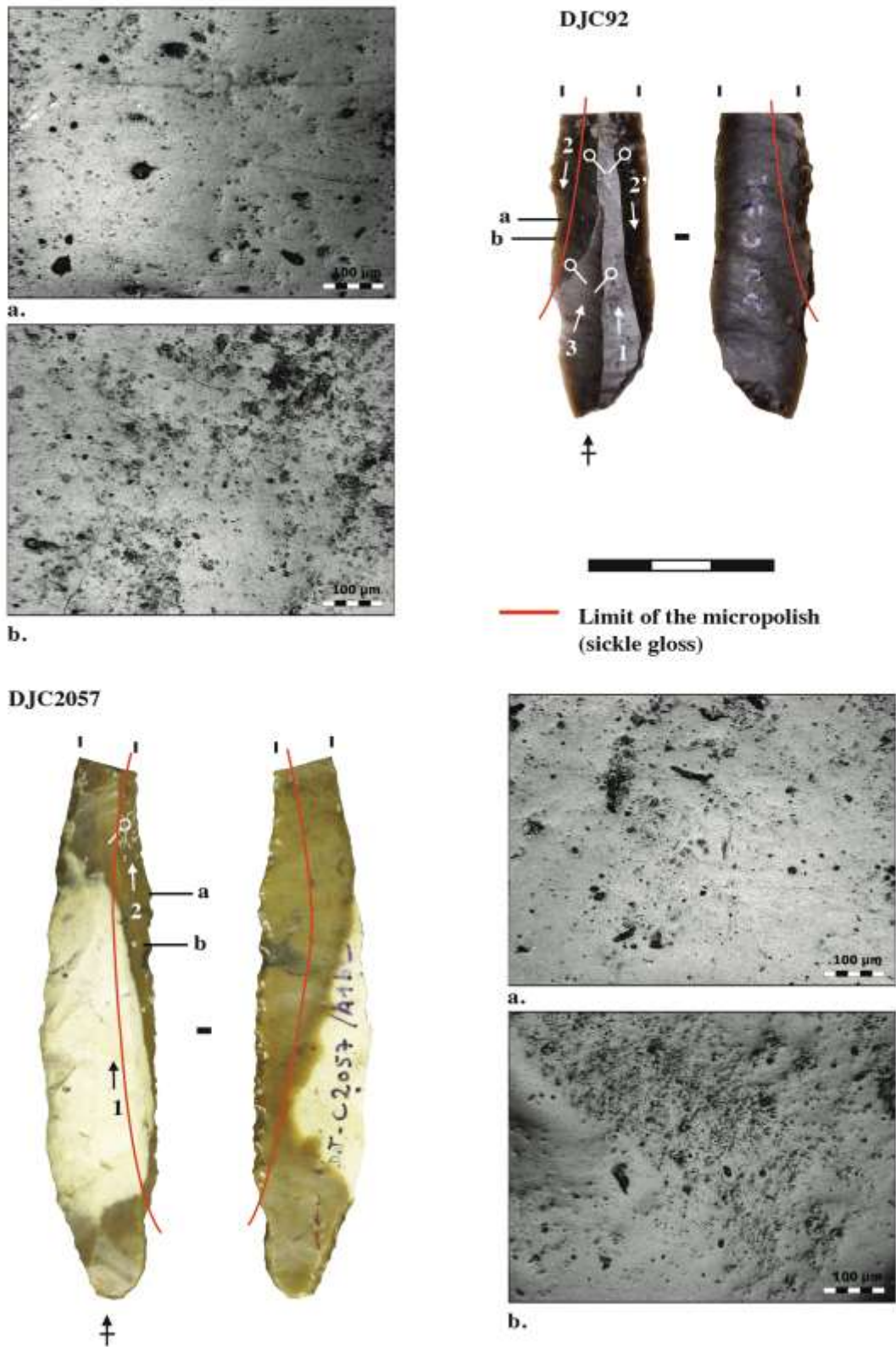


Fig. 11. Archaeological tool classified as used for harvesting ripe cereals. DJC92.

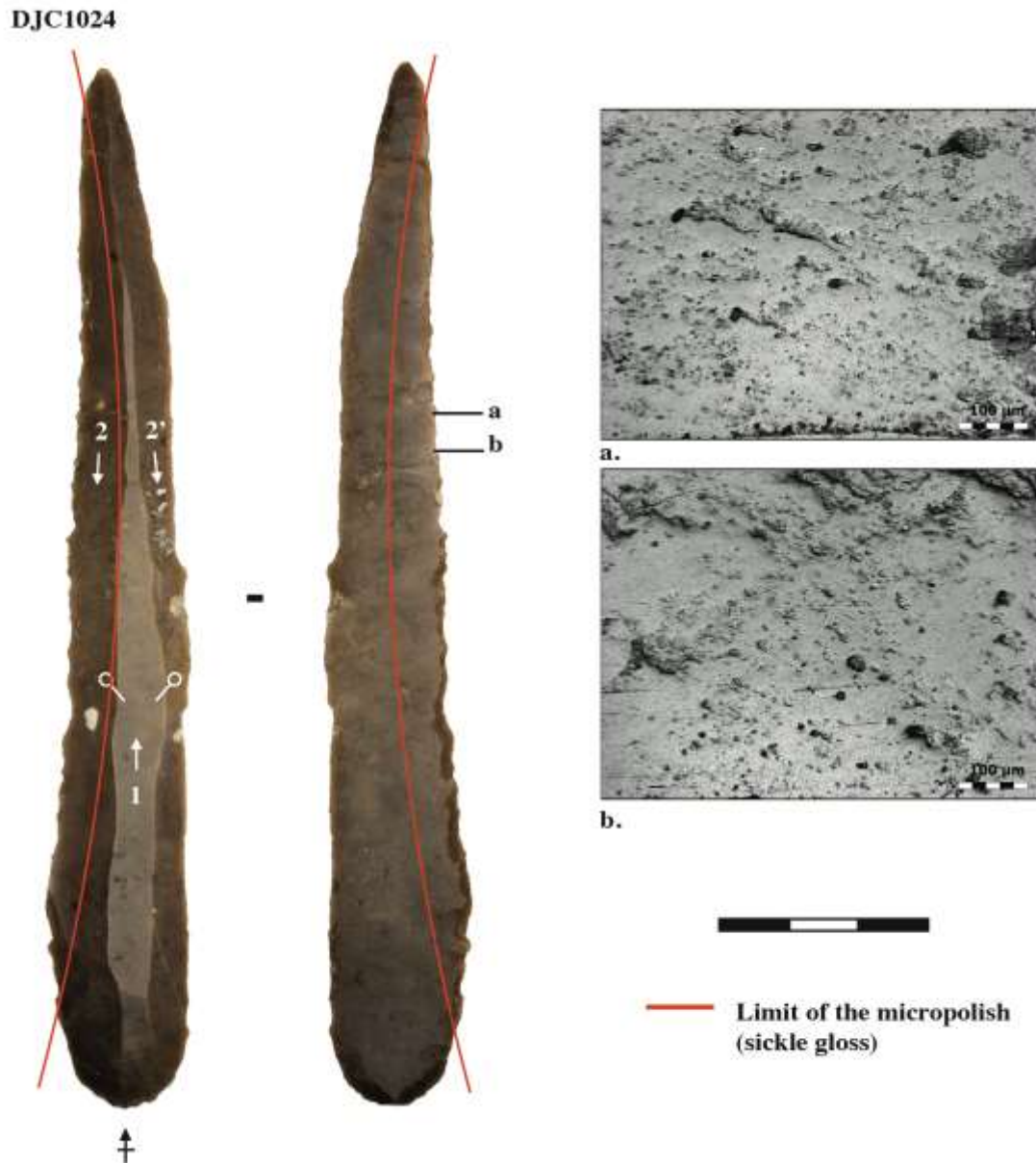


Fig. 12. Archaeological tool classified as used for harvesting ripe cereals. DJC92.

Using all the samples (1145 3D images), we compared them with the experimental ones. Observing the position of the centroids of the groups, we obtained a first image of the degree of association of the tools from Dja'de III with the experimental groups (harvesting of domestic, wild cultivated or wild cereals, and reeds). The centroid of the tools from Dja'de III is close to the centroid for wild cultivated cereals (Figure 13).

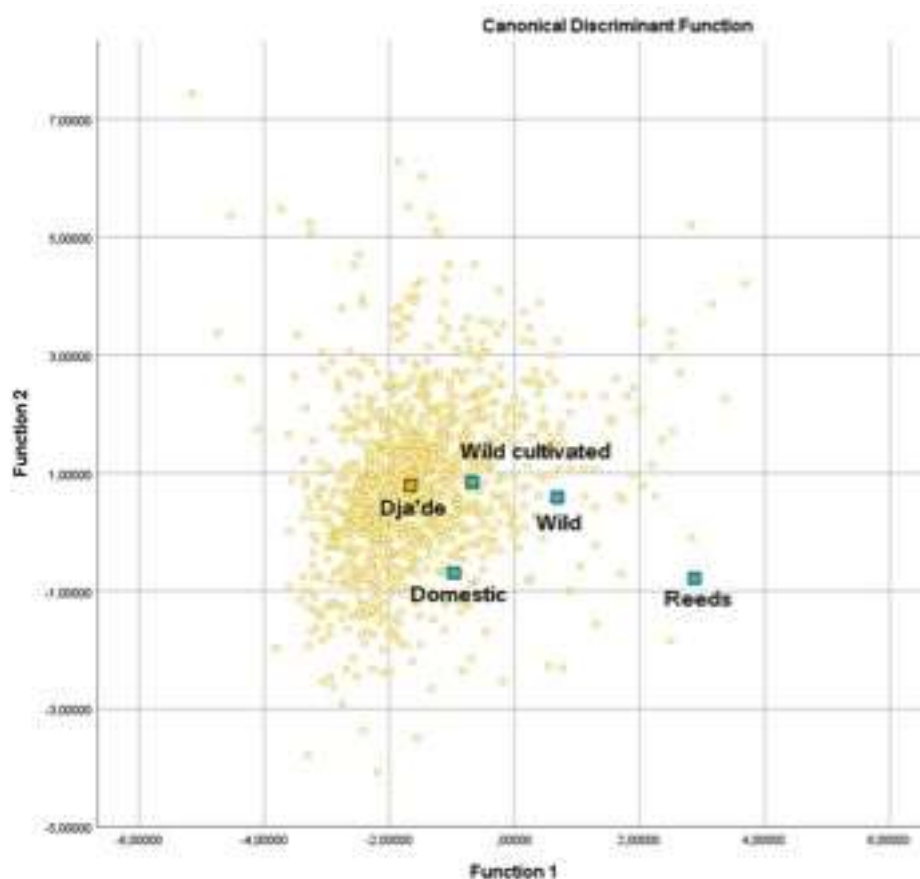


Fig. 13. Results of the quadratic discriminant analysis of the experimental tools used for wild cultivated cereals, wild cereals and domestic harvesting and reed cutting compared with the archaeological tools from the EPPNB levels of Dja'de III.

When more than 55% of the samples from each archaeological tool were classified in one group, the tool was considered as belonging to that group. When predicted membership classification in any of the four groups did not reach 55% of the samples, the tool was considered as unclassified. Taking into account each sickle tool, we obtain the following classification:

- 3 elements were classified as harvesting cereals in a green state, corresponding in the experimental program to wild cereals reaped in natural stands at the moment where stems of wild cereals were just yellowing and first grains had detached from the seed head;
- 26 elements were classified as harvesting cereals in a semi-ripe state, corresponding in the experimental program to wild cereals cultivated in Jalès (France) at the moment where stems of wild cultivated cereals were a mixture of yellow and green without a significant loss of the grains head;
- 8 elements were classified as harvesting cereals in a ripe state, corresponding in the experimental program to cutting domestic cereals at the moment where stems and ears of domestic plants were yellow;
- 11 elements obtained less 55% of the samples classified in one group, so they were considered as unclassified.

Just considering the 882 surfaces corresponding to 37 tools that were classified in one of the four plant cutting groups, 27,66% were classified in the group of ripe cereals, 61,99% in the group of semi-ripe cereals, 8% in the group of green cereals reaped in natural stands and 2,34% in the group of reeds.

These results confirmed the usewear traces variability observed with the metallographic microscope (i.e. in term of topography, in the degree of abrasion and in the quantity of striations), that we assumed to be related with the degree of humidity present on the stems at the moment of harvesting (Pichon 2017a; Pichon 2017b; Pichon 2019). The centroid of Dja'de is close to the centroid of wild cultivated cereals. These results are consistent with the archaeobotanical data, which indicate the evidence of a plant cultivation process on the site but still morphologically wild-type (Douché, Pichon 2018; Douché, Willcox 2019).

5.2. Comparison of the results from Dja'de III according to other neolithic sites from the Middle Euphrates area

These results from Dja'de III can be compared with 50 sickles coming from other sites located on the Middle Euphrates area that were analyzed following, basically, the same procedure (Ibáñez *et al.* 2016; Table 2): 4 tools from Abu Hureyra (Late Natufian), 27 tools from Mureybet (3 from Late Natufian/Epi-Natufian, 14 from PPNA and 10 from Early PPNB) and 19 tools from Halula (9 from Middle PPNB and 10 from Late PPNB).

Period	Sites	Chronology	Region	Tools
Late Natufian	Abu Hureyra	13th mill. cal BP	Middle Euphrates	4
Late Natufian/Epi-Natufian	Mureybet	Late 13th to Early 12th mill. cal BP	Middle Euphrates	3
PPNA	Mureybet	Mid 12th to Early 11th mill. cal BP	Middle Euphrates	14
EPPNB	Mureybet	Mid 11th mill. cal BP	Middle Euphrates	10
EPPNB	Dja'de III	Mid 11th mill. cal BP	Middle Euphrates	48
MPPNB	Halula	10th mill. cal BP	Middle Euphrates	9
LPPNB	Halula	Late 10th mill. cal BP	Middle Euphrates	10

Table 2. Archaeological tools from the Middle Euphrates.

In that paper (Ibáñez *et al.* 2016) we showed that green cereal cutting, associated to harvesting wild cereals in natural stands, was carried out in the Southern Levantine site of Hayonim Terrace, in the 14th millennium cal BP. Cereals were first cultivated in the Middle Euphrates during the 13th millennium cal BP, one millennium before it is acknowledged and two millennia before domestic cereals were exploited in the Middle Euphrates when cutting of ripe cereals is dominant for the first time in that region. Finally, we showed that harvesting unripe (green) cereals persisted up to the 10th millennium cal BP, probably indicating the occasional collection of cereals from wild stands, maybe at times of crop failure.

In that study (Ibáñez *et al.* 2016), all the tools were classified in the four groups of plant cutting activities. Later, those classified in the group of reeds were put aside and the rest was submitted to quadratic discriminant analysis between the three groups of cereal cutting activities (wild, wild cultivated and domestic). Thus the classification was made in two phases. However, in a later study (Ibáñez *et al.* 2019), we demonstrated that more precise results are obtained when the tools are discriminated between all the classificatory groups in only one step. Because of this, for this study, we changed of strategy and all the glossed tools are classified in the four groups in one step. In Ibáñez *et al.* 2016, the main part of the analysis of archaeological tools consisted in their classification in three experimental groups (green, semi-ripe and ripe cereal harvesting). When more than 60% of the samples were grouped in one of the three categories, the archaeological tool was considered as belonging to that group. In the present study, all the archaeological tools are classified in one step in four experimental groups (the three types of cereal cutting and reeds). Now, we use a threshold of 55% to classify archaeological tools in one group instead of 60%. Random classification for three groups would be around 33% while it will be of around 25% for four groups. Thus, as the risk of misclassification using a less demanding threshold is lower for four groups we use a threshold of 55%, so we reduce the number of unclassified tools. As we will see, the conclusions obtained with the current strategy of classification are basically the same than in the previous study.

Following the new classification procedure (discrimination into the four groups in one step) and considering only the samples of the tools classified in one of the four groups (threshold of 55%), organized by period, the evolution through time in the characteristics of the harvested cereals can be evaluated. As not all the tools had the same quantity of surface samples, we pondered the results of the classification of the samples of each tool in base 10 (Table 3; Figure 14).

Period	Sites	Ripe	Semi-ripe	Green	Reeds
Late Natufian/Epi-Natufian	Mureybet/Abu Hureyra	10,51%	55,86%	29,45%	4,18%
PPNA	Mureybet	22,67%	34,00%	27,76%	15,58%
EPPNB	Dja'de III	28,30%	61,64%	7,78%	2,27%
EPPNB	Mureybet	42,39%	53,83%	2,94%	0,83%

MPPNB	Halula	70,40%	23,95%	5,00%	0,65%
LPPNB	Halula	59,56%	38,00%	2,45%	0,00%

Table 3. Classification of sample frequency according to the classification of the sample in each four groups. As not all the tools had the same quantity of surface samples, the results of the classification of the samples of each tool were pondered in base 10.

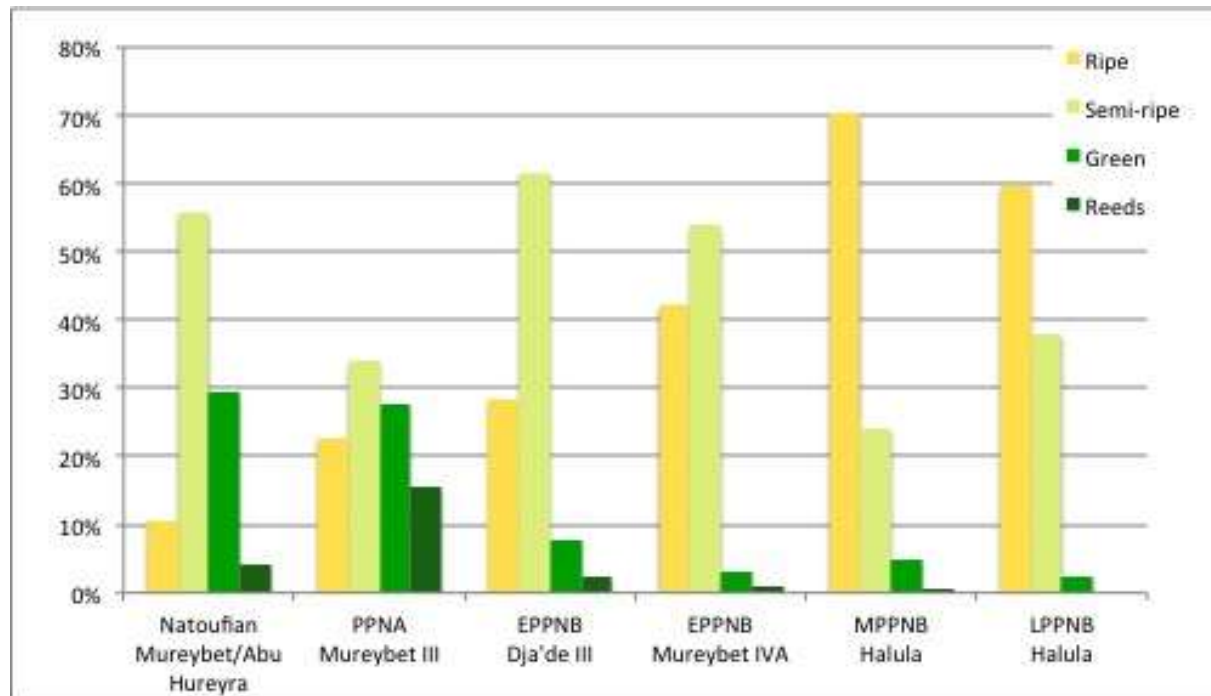


Fig.14. Classification of sample frequency according to the classification of the sample in each four groups.

Harvesting of semi-ripe cereals is dominant from the Late Natufian period in Abu Hureyra and Mureybet, suggesting that wild cereals were cultivated at that period. Cutting semi-ripe cereals continuous to be outstanding during the PPNA and PPNB periods of Mureybet, indicating the importance of pre-domestic cultivation at this site up to the end of the 11th millennium cal BP. Reaping of ripe cereals is dominant, for the first time, in the Middle PPNB levels of Tell Halula (mid 10th millennium cal BP), when domestic cereals are identified for the first time in the Middle Euphrates (Willcox *et al.* 2009) and continues to be dominant in the Late PPNB levels of this site. Green cereal cutting, experimentally associated to cutting wild cereals spontaneously growing, is relatively important during the Late Natufian period (near 30%) and decreases in the PPNA and Early PPNB levels of Mureybet, being marginal after that period.

The results of Dja'de 3 are similar to those of the EPPNB levels of Mureybet and are placed between the PPNA levels of Mureybet and the Middle PPNB levels of Tell Halula (Figure 14). These results also show the progressive increase in the group of samples classified as for cutting ripe cereals from the Late Natufian to the Early PPNB. The increase in the proportion of samples classified in the ripe group is abrupt in the Middle PPNB of Tell Halula with respect to the Early PPNB of Mureybet and Dja'de, coinciding with the exploitation of domestic cereals in Halula. The abrupt increase could also be linked to the interruption in the sequence of settlements in the Middle Euphrates valley ca. 10,200–9,800 cal BP showed by radiocarbon dates and analysis of PPN bidirectional blade production strategies throughout the northern Levant, that is followed by substantial cultural transformation (Borrell *et al.* 2015).

6. Discussion

The cultivation of wild wheat (*Triticum monoccocum*, *Triticum dicocum*) and barley (*Hordeum*) is attested in different places across the Levant (e.g. southern-central Levant and the Upper Euphrates area) since ca 11,500 cal BP (Weiss *et al.* 2006; Willcox *et al.* 2008; Willcox 2013; Arranz *et al.* 2016a). The higher temperature and rainfall and the development of more stable climatic conditions that characterize the beginning of the Holocene, affected the availability of food plants and led to cultivation as a reliable subsistence economy (Willcox 2012). The gradual increase of grain size over time, the presence of arable weeds, the introduction of founder crops

from elsewhere and the decrease of gathering are the main evidences towards a pre-domesticated cultivation (Colledge 2001; Willcox 2004; Fuller 2007; Willcox *et al.* 2008; Willcox 2012). The multiplication of large storage places and the presence of domestic house mouse (Kuijt, Finlayson 2009; Stordeur, Willcox 2009), sickle blades (Ibáñez *et al.* 2008; Pichon 2017a; Pichon 2017b; Pichon 2019) and ground stone tools (Dubreuil 2004) on Neolithic sites also suggest an intensification of agricultural practices (Arranz *et al.* 2016b).

From the Early PPNB (10,800–10,200 cal BP), the first evidence of morphologically domestic cereals — with loss of the natural mechanism of dispersal (Fuller 2007; Willcox 2012; Zohary *et al.* 2012) — appears in significant proportion in the archaeobotanical record (ca. 30%) from the southern-central Levant, like barley at Tell Aswad (Douché, Willcox 2018) and emmer, einkorn, and barley at Tell Qarassa North (Arranz *et al.* 2016a). In Anatolia, first indications of solid cereals rachis are found at Cafer Höyük (Tanno, Willcox 2012). A few hundred years later, during the Middle and Late PPNB (10,200–8,900 cal BP), farming communities are clearly established and agricultural system based on established crop packages widespread across southwest Asia (Nesbitt 2002; Tanno, Willcox 2006; Tanno, Willcox 2012; Asouti, Fuller 2013; Zeder 2015). The archaeobotanical records include new cultivars such as naked wheat and an extinct variety of glume wheat (Willcox 2012). In central and southeast Anatolia, domesticated-type cereals (emmer, barley and one-grained einkorn) are found ca. 10,300–10,200 cal BP (Tanno, Willcox 2012). In the Middle Euphrates area, the situation evolves differently: first, exploitation of legumes (lentils, pea, vetch, grass pea) and small-seeded legumes is predominant (Arranz *et al.* 2016a; Douché, Willcox 2018); second, domesticated-type of cereals chaff accounts for more or less ca. 10% or even less indicating a continued exploitation of morphologically wild species (Willcox 2012; Arranz *et al.* 2016a; Douché, Willcox 2018). This is the period and region where we have to integrate the information generated in the present study about sickle blades. In the Middle Euphrates area, there is evidence of domesticated free-threshing wheat (*Triticum aestivum/durum*) ca. 9,800–9,300 cal BP at Tell Halula and Abu Hureyra 2 and domesticated hulled cereals ca. 9,300 cal BP (Willcox 2012). However, this is during the Late PPNB that well established crop packages became dominant among plant-based subsistence. This delay in the Middle Euphrates area could be explained by the break in the regional settlement pattern between the Early PPNB levels of Tell Mureybet and Dja'de el-Mughara and the newly established villages of Tell Halula and Abu Hureyra 2 (Borrell *et al.* 2015).

These last years, the original methodological approach, based on confocal microscopy, brought a new contribution to the knowledge of this transition from wild to domestic cereals (Ibáñez *et al.* 2013; Ibáñez *et al.* 2016). The data gathered by this research support the hypothesis of early cereal cultivation during the Younger Dryas and the protracted model of plant domestication, pointing to the Middle Euphrates in the northern Levant as one region where this process occurred (Ibáñez *et al.* 2016). However, the transition from the Early to the Middle PPNB is not fully understood (Willcox 2012). To obtain a more accurate image of the way agricultural practices evolve in the northern Levant, we applied this new method of analysis to sickles from the Middle Euphrates site of Dja'de el-Mughara (11th millennium cal BP), where cultivation of wild cereals is attested by archaeobotanical analysis (Douché, Pichon 2018; Douché, Willcox 2019). The new method of analysis applied on sickles from Dja'de el-Mughara (11th millennium cal BP) aimed to explain the variability - previously recognized - of usewear traces (Pichon 2017a; Pichon 2017b; Pichon 2019). By comparing the stage of maturity of the harvested cereals (green, semi-ripe or ripe) at Dja'de III with other Late Natufian and Early Neolithic sites, we wanted to understand how agricultural practices evolved in northern Levant. Additionally, results aimed to test previous hypothesis, claiming the existence of a continuous process between the 13th and the 9th millennium cal BP, towards the harvesting of more mature cereal in northern Levant (Ibáñez *et al.* 2016).

At Dja'de III, cereals were mostly reaped at a semi-ripe stage that corresponds to the results obtained by the experimental harvesting of wild cultivated cereals (Anderson *et al.* 1991; Ibáñez *et al.* 2016). These results are also confirmed by the archaeobotanical results, indicating the presence of cultivated wild cereals, mostly barley, at Dja'de (Douché, Pichon 2018; Douché, Willcox 2019). While archaeobotanical analysis showed similar results for the earliest occupation of the site (DJI), the domestication of plants did not occur during the two following phases of the Early PPNB occupation, even after one millennium of cultivation in the site. However, the possible arable weeds recovered in the assemblages of the three phases may reflect an intensification of agricultural practices. Thus, plant exploitation remained based on the cultivation of wild cereals, even if cereal exploitation evolved during the occupation of the site.

Some tools were classified as resulting from cutting green cereals, associated to our experiments of harvesting wild cereals in natural stands. Thus, even if wild cereals were cultivated, natural fields were probably also exploited. Wild stands of barley are still visible in the local environment of the site (Weiss, Zohary 2011; Zohary *et al.* 2012). Wild einkorn is found farther north near the Turkish border in areas of annual precipitation between 300 and 350 mm (Willcox 2005; Weiss, Zohary 2011; Zohary *et al.* 2012), but it was also recognized on a volcanic massif at the east of Ain al Arab, around 25 km north-east from Dja'de (Coqueugniot 1998), while wild rye only grows considerably farther north at high altitudes (for example in the Karaça Dağ mountains). Given their ecological requirements, the presence of wild einkorn and wild rye in the plant economy during the

Neolithic at Dja'de raises the question of their availability in the environment close to the site at this period. Climate changes during the transition to agriculture could have impacted their distribution area (Willcox 2005). The persistence of cold conditions at the end of the Younger Dryas event and the beginning of the Holocene likely allowed these two species to continue to grow in the area and even farther south, but they were limited to rich soils with low pH (Willcox 2007). In this case, the closest potential natural habitats from the site could be the basalt outcrops located near the village of Sirrine between Dja'de and Jerf el-Ahmar (Willcox *et al.* 2009) and the Qara Perguel Dah volcanic massif on the left bank of the Euphrates, about 15 km south of the Turkish border (Willcox 2005; Willcox 2007). The predominance of barley in crop assemblages might reflect the ecological conditions around Dja'de because such plant is well tolerant to arid conditions and poor chalk and salty soils (Weiss, Zohary 2011). Occasionally, groups of harvesters collected wild cereals growing spontaneously either in the vicinity of the site or in more distant areas, but reachable in few days' walks.

Eight tools were classified in the group of harvesting ripe cereals, corresponding to our experiments of cutting domestic cereals. However, these results do not match with archaeobotanical analysis indicating that the proportion of domestic types chaff is really low at Dja'de III (ca 5%; see below). Therefore, this group of tools has to be interpreted as sickles used for cutting wild cereals in an advanced phase of maturity. Two possible hypotheses could explain the presence of ripe wild cereal cutting tools in the pre-domestication context.

First, cultivated wild cereals could have been reaped in a semi-ripe state of maturity trying to maximize the yield, as was tested in the experimental cultivation of wild cereals in Jalès (Anderson *et al.* 1991). This semi-ripe harvest could have been carried out high in the stem, in order to collect only the ears (for example directly with the hand or with a knife; Anderson *et al.* 1991). The drying stems leaving on the stand could have been reaped later with sickles in a cutting low way, in order to use them for different purposes, such as craft (basketry, mats confection) and architecture (fences, roofing houses, bedding and tempering in the mud walls) (Ertuğ 2006; Pichon 2017b; Douché, Pichon 2018). Straw could also have been used to feed livestock, as bovines were probably being domesticated during Dja'de III (Helmer *et al.* 2005).

As a second interpretation, maybe before domesticated cereals appeared during the Middle PPNB, wild cultivated cereals could have been progressively harvested in a more mature stage (Ibáñez *et al.* 2016), because of the homogenization in the maturation of the plants. The increase in size of barley grains at Jerf el-Ahmar and Dja'de III between the lower and upper levels (Willcox 2004; Douché, Willcox 2019; Douché, Willcox 2019) has been interpreted as resulting of changes in the wild cultivated populations in which higher proportions of grain reached full development (Willcox 2012). These "semi-domesticated" grains, retaining the brittle rachis, showed other changes associated with the shift towards domestication, such as the loss of wild-type germination inhibition and changes in seed size and shape (Fuller 2007). Riper harvesting would have diminished the quantity of immature grains (Fuller, Allaby 2009), so the yields would have increased, stimulating the process towards cereal domestication.

Conclusion

The texture quantification of sickle polish by confocal microscopy represents a major advance in the methodology of use-wear analysis of prehistoric tools. This achievement has demonstrated the enormous potential of the quantitative methodology for the identification of worked materials and for bringing new elements about the evolution of agricultural practices in the southwest Asia.

The analysis of 48 glossed tools from Dja'de III has shown the complexity of harvesting practices in the site, with tools used for cutting cereals in ripe, semi-ripe and green states. Semi-ripe harvesting, experimentally associated with cutting wild cultivated cereals, is dominant, what fits well with archaeobotanical information. Ripe cereals were also reaped, what can be interpreted as the secondary harvesting of ripe stems for using them in technological activities (roofing, basketry) or maybe as fodder. As other possible explanation, certain species of cultivated wild cereals could have been in an advanced moment in the process towards domestication, allowing the harvesting of the "semi-domesticated" crops when cereals were in an advanced state of maturity. Cereal reaping in a more and more advanced state of maturity would have allowed obtaining more productive crops.

The comparison of the texture analysis of sickles from Dja'de III with those obtained in other sites offers interesting perspectives about the process of cereal cultivation and domestication in the Middle Euphrates. Sickles from the Late Natufian and Epi-Natufian from Abu Hureyra and Mureybet (13th and beginning of the 12th millennium cal BP), were used for harvesting green and semi-ripe cereals. These results suggest that not only spontaneously growing cereals were exploited, but a certain proportion of cultivated wild cereals as well, as proposed by some botanical research (van Zeist, Bakker-Heeres 1984; Hillman 2000). From the PPNB and Early PPNB levels of Tell Mureybet and Dja'de, most of the tools were classified in the group of cutting semi-ripe cereals, suggesting that the cultivation of morphologically wild cereals was the main type of cereal exploitation. The cultivation of wild cereals in these levels of Tell Mureybet and Dja'de is confirmed by the cortege of weedy plants (Colledge 2002; Willcox 2008). Finally, most of the tools from the Middle and Late PPNB of Tell Halula

were classified in the group of ripe cereals. This period corresponds to the moment when morphologically domestic cereals appeared (Willcox *et al.* 2009). The persistence of harvesting cereals in a green stage up to the 10th millennium cal BP (Middle PPNB of Tell Halula) could indicate occasional collection from natural stands, even after the beginning of cultivation (times of crop failure?) or reflect a preference, like to prepare frikke (Al-Azm 2009). This could have caused hybridisation between wild and semi-domesticated cereal populations, which in turn would explain the long temporal extent of the process of domestication (Tanno, Willcox 2006).

Thus, in the Middle Euphrates, the evolution of crops allowing riper harvesting seems to be an *in situ* and continuous process in this area (Ibáñez *et al.* 2016). Prior to fixation of the solid rachis during the Middle PPNB, wild cultivated cereals were evolving traits allowing for more and more mature harvesting of the crops. This could be related to a progressive homogenisation in the moment of maturation of the wild cultivated plants, associated to others changes in the evolution towards domestication, as the loss of wild-type germination inhibitors and changes in seed size and shape (Willcox 2004; Willcox 2012; Fuller, 2007). Harvesting more mature crops would have permitted to maximise the yield, reducing the proportion of immature grains and, thus, stimulating the process of cereal domestication.

New data from Dja'de III fit adequately with this evolution, giving information about the mid and second half of the 11th millennium cal BP in the Middle Euphrates. The results from Dja'de III are very similar to those obtained in the Early PPNB levels of Tell Mureybet, which are contemporaneous to Dja'de III, and considerably reinforces previous studies. The analysis of Dja'de was made on a more extended collection of sickle elements (48 in Dja'de III and 10 in Tell Mureybet), providing consistent results. The similarity of results between the two nearby sites (ca 65 km away) suggests that the process of cereal cultivation and domestication evolved similarly in early Neolithic villages located in the same region. In both villages, cereals were mostly harvested at a semi-ripe stage of maturity, though some of the wild cultivated cereals were in an advanced state of maturity when reaped. At the same time in both villages wild cereals were occasionally exploited in natural stands. The diachronic image obtained from the texture analysis of sickle micropolish indicates that cereal cultivation took place during two millennia before domestication appeared in some areas of the Levant.

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