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The first plant bast fibre technology: identifying splicing in archaeological textiles

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Abstract
Recent research into plant bast fibre technology points to a Neolithic European tradition of working fibres into threads by splicing, rather than draft spinning. The major issue now is the ability of textile specialists and archaeobotanists to distinguish the technology of splicing from draft-spun fibres. This paper defines the major types of splicing and proposes an explicit method to observe, identify and interpret spliced thread technology. The identification of spliced yarns is evaluated through the examination of textiles from Europe, Egypt and the Near East. Through the application of this method, we propose that the switch from splicing to draft spinning plant fibres occurred much later than previously thought. The ramifications of this shift in plant processing have profound implications for understanding the *chaîne opératoire* of this ubiquitous and time-consuming technology, which will have to be factored into social and economic reconstructions of the past.

Keywords Plant bast fibre · Splicing · Spinning · Technology · SEM · Identification method

Introduction

Fibre technologies: from plant to thread

Plant bast fibre products, such as linen textiles, have a complex and time-consuming *chaîne opératoire*. Bast fibres are collected from the phloem (inner bark) surrounding the stem of certain dicotyledonous plants, such as flax, hemp, nettle and lime tree. Before such fibres can be worked into a textile, they have to be extracted, prepared and formed into a thread. The latter process has been generally assumed to be a sequence of operations (retting, bracking, scutching and heckling) in preparation for draft spinning using a spindle, which is a tool usually composed of a rod and a flywheel known as a spindle whorl (see Barber 1991, 41–44 on draft spinning). During the last 25 years, however, research into a different yarn-making technology has developed based on the Pharaonic Egyptian textile finds—it is known as splicing, a term that in fact subsumes a variety of related techniques (Leuzinger and Rast-Eicher 2011). Although suggested by Fox over 100 years ago (Fox 1910), the idea that in Pharaonic Egypt the threads were made by splicing was only fully accepted relatively recently.

Splicing is fundamentally different from draft spinning. In draft spinning, retted (by partially rotting the stems to separate the fibres) and generally well-processed fibres are drawn out from a mass of fluffed up fibres usually arranged on a distaff and twisted continuously using a rotating spindle. In splicing, strips of fibres are joined in individually, often after having been stripped from the plant stalk directly and without or with only minimal retting. The techniques can be separated into two main types: (1) Those where fibre strips are added in continuously (Cooke et al. 1991, 21, fig. 5b; Médard 2003, 83; Granger-Taylor 2003; Tiedemann and Jakes 2006, 295, fig. 1); (2) Those where fibre strips are joined end-to-end, by either twisting (Barber 1991, 47–8, fig. 2.9; Cooke et al. 1991, 21, fig. 5a; Van Rooij and Vogelsang-Eastwood 1994, 17, fig. 2a; Granger-Taylor 1998,103–104) or twisting and turning back (Van Rooij and Vogelsang-Eastwood 1994, 17, fig. 2a-c). Definitions and descriptions of these techniques by

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the various scholars who researched them extensively are summarised in Table 3. These two types of splicing, which for the sake of simplicity we will call continuous and end-to-end splicing, can be worked at different scales and using a variety of techniques.

Although beyond the scope of the present paper, it should be pointed out that numerous bast fibre splicing techniques have been used in East Asia and Pacific and many of them survive and are still being practiced for example by the indigenous communities in Korea, China, Japan and the Philippines. These provide important ethnographic data on splicing (e.g. Nagano and Hiroi 1999; Hamilton and Milgram 2007). Here, we concentrate on Europe, with references to the Near East, including Egypt from the late Neolithic to the Archaic period (c.3400–500 BC).

Based on the final appearance of the threads (rather than the specific technique used), the general description of the two splicing methods is proposed in Table 1 and illustrated in Fig. 1. The end-to-end splicing likely developed from continuous splicing (Granger-Taylor 1998, 105).

Identifying splicing in archaeological material is not straightforward. The aim of this paper is to set out clear identification criteria based on macroscopic and microscopic indicators systematically observed in archaeological textiles from different chronological periods and geographical areas. In thoroughly reviewing previous work on the terminology, technique, visible appearance and provenance of splicing (Table 3) and presenting new results, this paper seeks to provide a secure and rigorous basis from which to analyse and identify splicing technology. In such handcrafted materials, a range of physical outcomes is to be expected. In order to counter this, we have analysed threads from a wide geographical and temporal range. The significance of the research is that it provides a unique collated and expanded identification key (including extensive SEM micrographs from across Europe and the Near East, terminology, flow chart and diagrams) with which to investigate plant bast fibre splicing technology that is suitable for textile specialists and archaeobotanists with the relevant laboratory skills.

Materials and methods

Materials

Since 2011, textiles from chronological periods spanning from the Neolithic to the Archaic period (ca. 4000–500 BC) and over 30 different sites in the UK, Spain, Italy, Greece, Turkey, Iraq and Egypt were examined by the authors, of which 8 representative case studies are presented here. The contextual data is provided subsequently, and technical textile data is summarised in Table 2. The textiles are shown in Fig. 2.

When annotating a spliced thread structure, an asterisk (*) is inserted before the single to differentiate the construction technique as suggested by Rast-Eicher and Dietrich (2015, 36). For example, a thread composed of two draft spun singles of z-direction, plied in an S direction, is annotated as S2z. The thread composed of two spliced yarn of z-direction, plied in an S direction, is annotated S2*z. Often, in spliced threads, the singles have little or no discernible twist—in this case, two spliced rovings, plied in an S direction, are annotated S2*. Where the twist in the singles is very loose, the letter may be in brackets S2*(z).

Tarkhan, Egypt, Neolithic (3482–3102 cal BC)

Linen textiles, including a dress known as the world's oldest woven garment, were excavated by Flinders Petrie in 1913 and, according to his report, were found in a 1st Dynasty tomb (Landi and Hall 1979). Recent radiocarbon dating has confirmed the early date of the dress (Stevenson and Dee 2016). The textiles were preserved in arid conditions. They are currently in the collections of the Petrie Museum of Egyptology, UCL, in London.

Cave of the Warrior, Israel, Late Chalcolithic (3900–3600 BC)

A skeleton of a male of 45–50 years old was discovered in a flexed position in a cave in the Judaean Desert near Jericho, in 1993 (Schick 1998). It was wrapped in a large linen shroud and placed on a plaited reed mat together with accompanying flint knife, a bow and arrows, a coiled basket bowl, a wooden

Table 1 Terminology to distinguish the two main types of splicing (see Fig. 1 for schematic diagrams)

Term	Technique
Continuous splicing	Individual fibre strips are added continuously into a twisting single thread. While the thread is twisted, new fibre strips are laid adjacent to fibre strips already caught into the thread, thereby becoming incorporated into the single thread. As part of the same procedure, two singles may be twisted together into a plied yarn which will be plied in the opposite direction to the singles (Fig. 1a). This is a single-stage process.
End-to-end splicing	The end of one fibre strip (or fibre ribbon) is joined to the end of a second fibre strip, which in turn is joined to a third and so on, creating a continuous thread. As the joins are inherently weak, two such spliced threads are typically then twisted together. This is a two-stage process of splicing the singles end-to-end, then plying them (Fig. 1b).

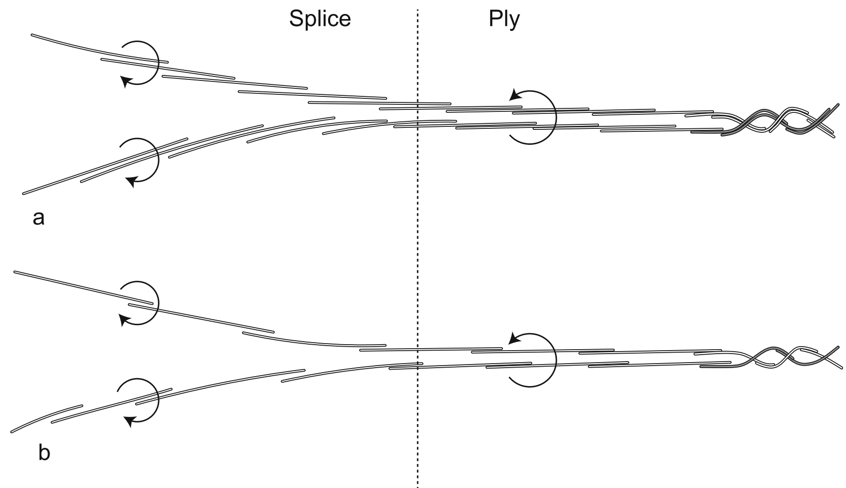


Fig. 1 Schematic diagram: (**a**) Continuous splicing; (**b**) end-to-end splicing (diagram by S. Harris, M. Gleba, V. Herring, adapted from Cooke et al. 1991, 21, fig. 5)

bowl, a pair of leather sandals and a stick. The shroud is a single-woven rectangular cloth, ca. 7 × 2 m, decorated with painted black asphalt bands and long fringes. Additionally, a kilt, made of a smaller textile was found. The textiles were preserved in arid conditions.

Lucone di Polpennazze, Brescia, Italy, Early Bronze Age (2033 BC)

Linen textiles were recovered at the site in 1969, in the Early Bronze Age levels of Zona A (Baioni 2003; Bazzanella et al. 2003, 188–193). In 2008, a new textile fragment came to light and was recovered in situ embedded in a block of soil. The stratigraphic level in which the textile was found has been dendrochronologically dated to 2033 BC. The textile measures approximately 13 × 13 cm and preserves possible fringes and a part of a rep starting border. The textile was preserved through charring and subsequent waterlogging.

Over Barrow, Over, Cambridgeshire, UK, Early Bronze Age (1887–1696 cal BC)

A pit-pyre cremation of possibly two adults and an infant beneath a round barrow 2 in Over, Cambridgeshire, was excavated in 1998–2001 (Harris 2015). Numerous small charred textile fragments were found among the deposit of cremated bone and other materials in the primary cremation burial at the entrance of the barrow. Textiles were preserved through charring.

El Oficio, Cuevas de Almanzora, Almería, Spain, Early Bronze Age (2000–1500 BC)

The settlement belongs to the Early Bronze Age El Argar Culture of southern Iberia. Numerous textile fragments have been recovered from some of the 200 burials excavated at the site (Alfaro 1984, 123; Jover Maestre and López Padilla 2013,

Table 2 Technical textile data (see also Fig. 2 for textile appearance and Fig. 7 for detailed thread diameter data)

Site (inv. no.)	Date	Weave	Thread count in threads/cm warp/weft	Thread structure warp/weft	Thread diameter warp/weft (mm)
Tarkhan, Egypt (UC17030)	3482–3102 cal BC	Warp-dominant tabby	22–23/13–14	S2*s/S2*s	0.34–0.83/0.42–0.72
Cave of the Warrior, Israel (TexA)	3900–3600 BC	Warp-dominant tabby	17/10	S2*z/S2*z	0.4–0.71/0.46–0.82
Lucone di Polpennazze, Italy	2033 BC	Tabby	10–12/10–12	S2*/S2*	0.41–0.81/0.34–0.55
Over Barrow, UK (OVP00 (TD) Fragment 2)	1887–1696 cal BC	Tabby	12–13/12–13	S2*(z)/S2*(z)	0.76–1.62/0.92–1.46
El Oficio, Spain (T249.4)	2000–1500 BC	Tabby	13/13	Z2*/Z2*	0.64–0.97/0.46–1
Must Farm, UK (SF3070)	1000–800 BC	Tabby	22/23	S2*/S2*	0.16–0.31/0.19–0.32
Tarquinia, Italy (6326.C103)	730–720 BC	Warp-dominant tabby	22–32/10–12	S2*/S2*	0.33–0.74/0.31–0.57
Corinth, Greece	6th c. BC	Weft-dominant tabby	16/36	S2*/S2*	0.19–0.67/0.21–0.63

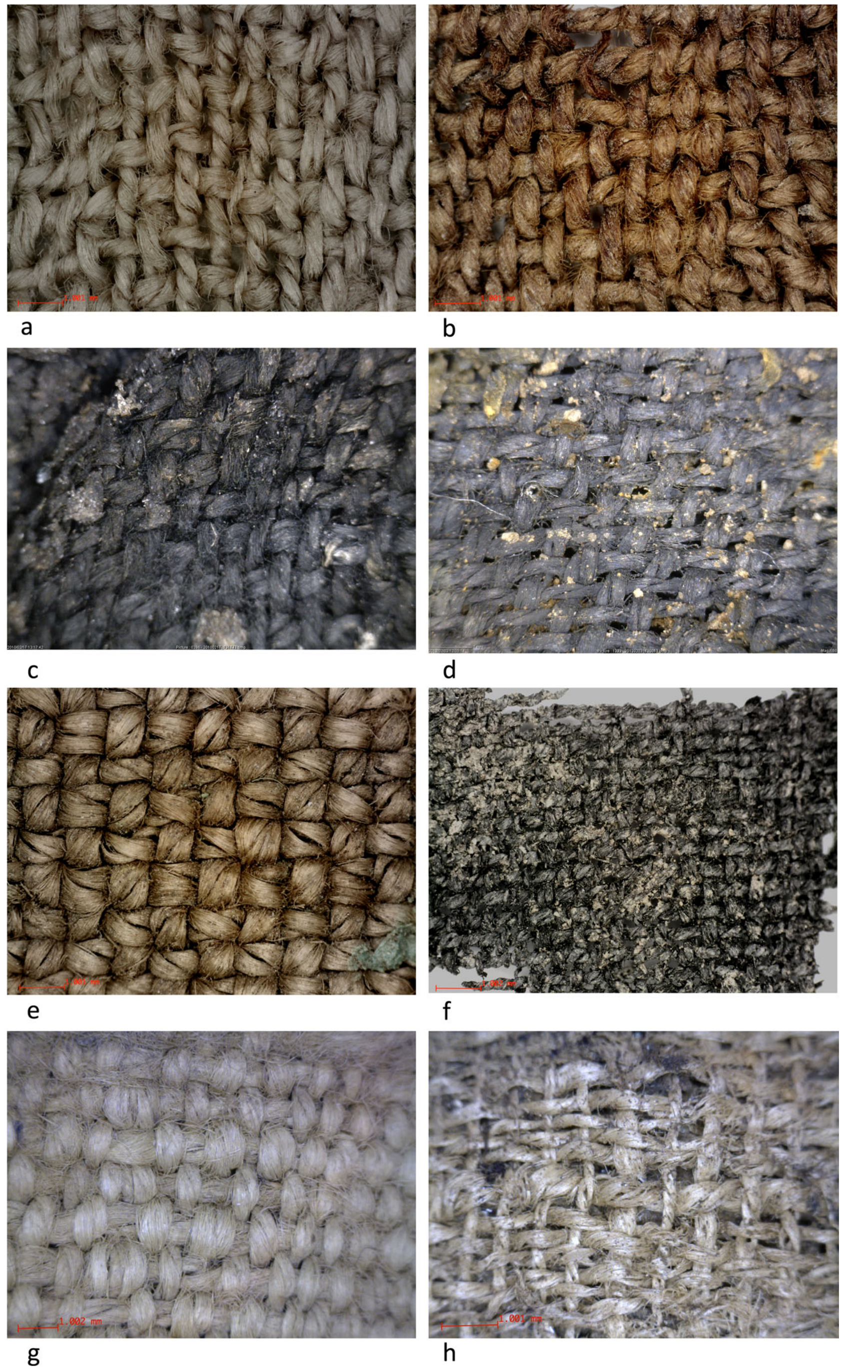


Fig. 2 Micrographs of the case study textiles: (**a**) Tarkhan, Egypt; (**b**) Cave of the Warrior, Israel; (**c**) Lucone di Polpennazze, Italy; (**d**) Over Barrow, UK; (**e**) El Oficio, Spain; (**f**) Must Farm, UK; (**g**) Tarquinia, Italy; (**h**) Corinth, Greece (images: M. Gleba, S. Harris)

167). Textiles were preserved through contact with bronze. The textile selected for the case study here comes from Tomb 249; it is typical for the culture and period.

Must Farm, Cambridgeshire, UK, Late Bronze Age/Early Iron Age (1000–800 BC)

The settlement of Must Farm built on a platform on piles over a river channel was excavated in 2006 and 2015–2016. The piles were destroyed by fire, causing the structures to collapse into the river, thereby preserving the contents in situ. Numerous examples of fibre, yarn and textile were recovered and are undergoing analysis. Textiles were preserved through charring and subsequent waterlogging.

Tarquinia, Monterozzi, Italy

The so-called Tomb of the Warrior was discovered in 1869 in the Monterozzi necropolis of the Etruscan city of Tarquinia, and the finds are currently in the collections of the Altes

Museum in Berlin, Germany (Babbi and Peltz 2013). Several undyed linen fragments have survived among the grave goods (Stauffer 2013). The textiles were likely preserved through contact with bronze.

Corinth, Greece, Archaic Period

Textile remains were found in an Archaic burial 839 excavated by the Corinth Ephorate in 2006 during the construction of a rail line. The stone sarcophagus housed a small wooden box that appears to have contained textiles, one of which was relatively well-preserved and white in colour.

Methods

The finds were analysed according to the standard procedure for textiles (Walton and Eastwood 1988). The analysis of splicing was carried out using visual observation, as well as digital microscopy (DinoLite portable microscope with magnifications ×20, ×50, ×230) and scanning electron microscopy (SEM). For SEM analysis, thread fragment samples 3–5 mm long and, where possible, larger textile fragments were examined. The small samples were placed on aluminium pin stubs covered with adhesive carbon tabs. Larger fragments were anchored in the microscope chamber using white tack.

Most of the samples were analysed using Hitachi TM3000 TableTop SEM at the McDonald Institute for Archaeological Research, University of Cambridge. The following instrumental settings were used: analytical condition mode at 15.00 kV accelerating voltage, compositional imaging and working distance of 5–10 mm. Samples from Tarkhan, Over Barrow and Cave of the Warrior were analysed using Hitachi S 3200 N SEM at the Wolfson Archaeological Science Laboratories, Institute of Archaeology, University College London under 15.00 kV accelerating voltage, 60 Pa and working distance of ca.10 mm. Samples from Must Farm were analysed using Quanta 200F SEM at the ISSAC facility, University of Glasgow, under 10.00 kV accelerating voltage and working distance of 10 mm.

Results

Criteria for identifying splicing in archaeological specimens

A systematic observation using different macro- and microscopic techniques permitted the identification of splicing in all the archaeological textiles analysed. We propose the following criteria for splicing identification in archaeological specimens, which are illustrated by our case studies. It should be noted that an absence of one or more of the potential splicing characteristics described subsequently does not exclude the possibility of splicing, and the caveats are discussed in the "Caveats" section.

Plying

The initial indicator of spliced yarn is plying, which is a result of twisting two or more single threads into one (Fig. 3). Plying is not necessary with draft-spun yarns, and until more recent textile history, most spun yarns were used as singles. Spliced fibres, on the other hand, *must* be plied. In fact, as noted by Granger-Taylor, "it is the plying one sees, not the splicing as such" (Granger-Taylor 1998, 105). Unlike draft-spun yarn, spliced yarn is inherently unstable and is weaker at the splice point. It therefore needs to be stabilised by giving it a twist and/or plying it with another yarn (see discussion in Kemp and Vogelsang-Eastwood 2001, 74–77). In most of the plant bast fibre textiles we have examined to date, this plying appears to usually be in counter-clockwise, or S-direction, possibly exploiting the natural s-fibrillar orientation of flax fibres (Bergfjord and Holst 2010). It has even been suggested that the Egyptians preferred s-direction for splicing, twisting and plying, which made the thread to appear more homogeneous, to the point that, if executed well, the thread appears single-twisted at a glance (Kemp and Vogelsang-Eastwood 2001, 76 and fig. 3.10). Nevertheless, clockwise or Z-plying is known for example in the Bronze Age textiles from Switzerland (Rast-Eicher and Dietrich 2015) and is common for Bronze Age Spain (Alfaro 1984; Jover Maestre and López Padilla 2013).

In end-to-end splicing, the place where the fibre ribbons are twisted together (the splice) will have an *enhanced plied appearance* (term suggested by Hero Granger-Taylor). The splices have been noted in Egyptian and Levantine textiles (Fig. 4; Kemp and Vogelsang-Eastwood 2001, 68 fig. 3.12).

The spliced and plied threads are in stark contrast to the draft-spun plant fibre threads that become common from the second half of the first millennium BC onwards: they are almost always single, with a preference for z-twist in the European regions, while s-twisted yarn is more common in Egypt and the Near East (Barber 1991, 65–68; Bender Jørgensen 2017, 237–238). It is not until much later that draft-spun and plied linen yarn becomes common in textiles.

Variation in thread diameter

There is often a considerable variation in thread diameter in adjacent yarns of spliced textiles. We have measured between 10 and 15 thread diameters in warp and weft in all our case studies, and the results are presented in Fig. 5. The coarsest threads from Lucone di Polpenazze have the widest range; conversely, the finest threads from the Must farm have the

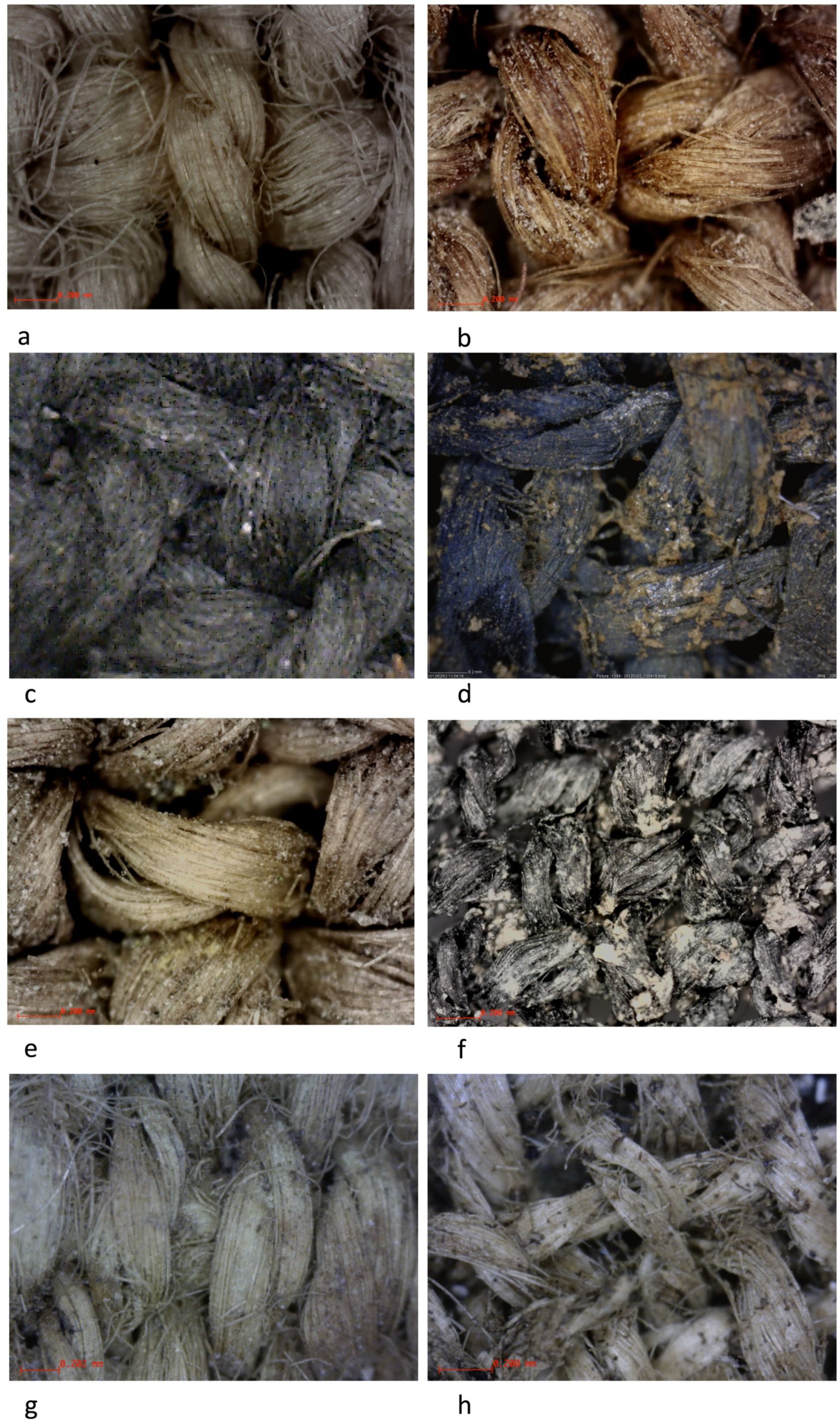


Fig. 3 SEM micrographs of textiles showing the absence or minimal twist in single-thread elements: (**a**) Tarkhan, Egypt; (**b**) Cave of the Warrior, Israel; (**c**) Lucone di Polpennazze, Italy; (**d**) Over Barrow, UK; (**e**) El Oficio, Spain; (**f**) Must Farm, UK; (**g**) Tarquinia, Italy; (**h**) Corinth, Greece (images: M. Gleba, S. Harris)

narrowest range. Nevertheless, initial analyses show that the maximum measurement in each range is at least double or more of the minimum measurement. It has been suggested that this variation could reflect the differences between the diameters of plant stalks used to produce the yarns (Kemp and Vogelsang-Eastwood 2001, 73). However, it may also be due to the differential width of fibre strips removed as ribbons from the plant stem: at the base of the stem, the ribbon will be proportionally wider than at the tip. This will cause a variable diameter even within the same thread. In order to reduce this variation, the craftspeople of East Asia add an overall twist to the spliced thread (Nagano and Hiroi 1999, 350). In fact, in East Asia “textiles incorporating tree- and grass-bast fibers preserve the direction from base (at the roots) to tip (towards the end) of the original plants” (Nagano and Hiroi 1999, 354). None of the investigations carried out to date on the archaeological textiles have been able to identify this characteristic, but we should be aware of the possibility.

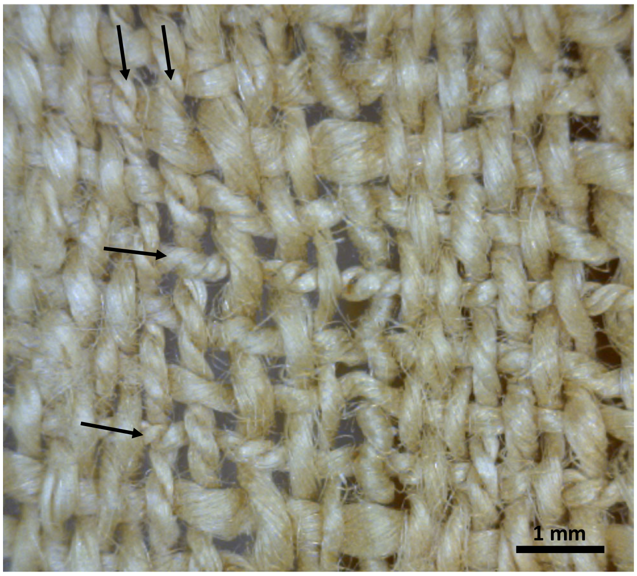


Fig. 4 Enhanced plied appearance of threads indicative of end-to-end splicing: Lahun, Egypt, UC 55054, Petrie Museum (image: M. Gleba, S. Harris)

Minimal twist

The next possible indicator of splicing is the absence of visible twist or minimal twist in the single-thread elements over significant portion of yarn length measured when plied and woven into a textile (Fig. 6). In spun threads, the angle of twist is typically between 10° (loose) to 45° (hard) (Emery 1966, 12) (Fig. 7). In single threads used for splicing, there is more propensity for less than 10° angle of twist (as measured from a line perpendicular to the outer edge of the thread) along much of the thread, with intermittent areas of tighter twist where splice occurs (Fig. 4). In order to be suitable for splicing, the fibres are removed in a bundle and therefore do not require a twist to hold them together in the way that separated fibres do in draft spinning, except at the point of the splice. This is visible, for example, in a weft thread from Cave of the Warrior, where one of the plied threads has no discernible twist, while the other has a clearly visible twist at the point where the two fibre bundles were joined together (Fig. 8). In modern East Asian splicing techniques, spliced threads have a twist only at the point where fibre bundles join and the twist is added to the threads afterwards (Nagano and Hiroi 1999, 350–351). According to the iconography, ancient Egyptians added the twist to the spliced thread using spindles (Granger-Taylor 1998, 104; Kemp and Vogelsang-Eastwood 2001, 76), but the subsequent plying may have resulted in the twist of the single threads unravelling or at least becoming less prominent. In continuous splicing (e.g. thigh spinning), the actions of rolling the two spliced threads together to ply them may undo the opposite twist imparted during the initial splicing.

Smooth threads with fibre strips and aligned dislocations

Since fibre processing differs depending on whether fibres are being prepared for draft spinning or for splicing, its

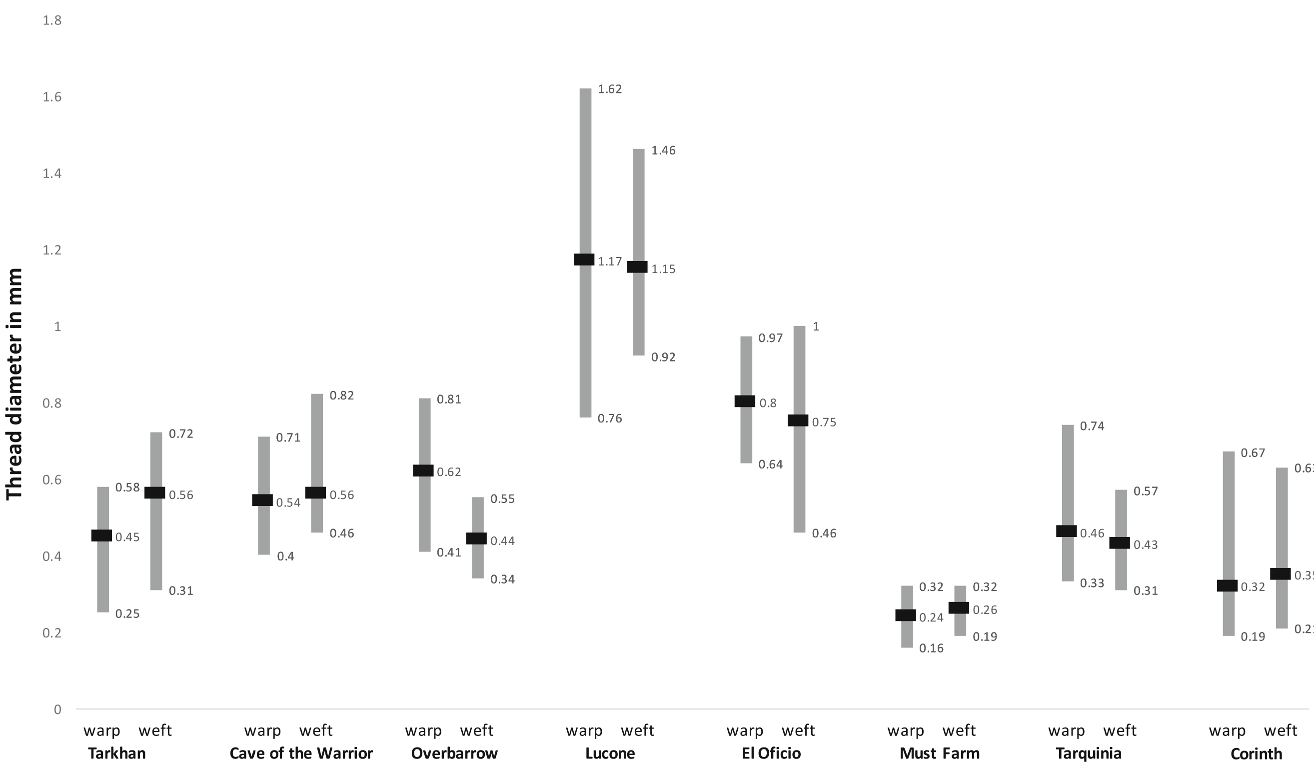


Fig. 5 Diameter variation chart with vertical grey bars representing the range of diameters and horizontal black bars the mean diameter

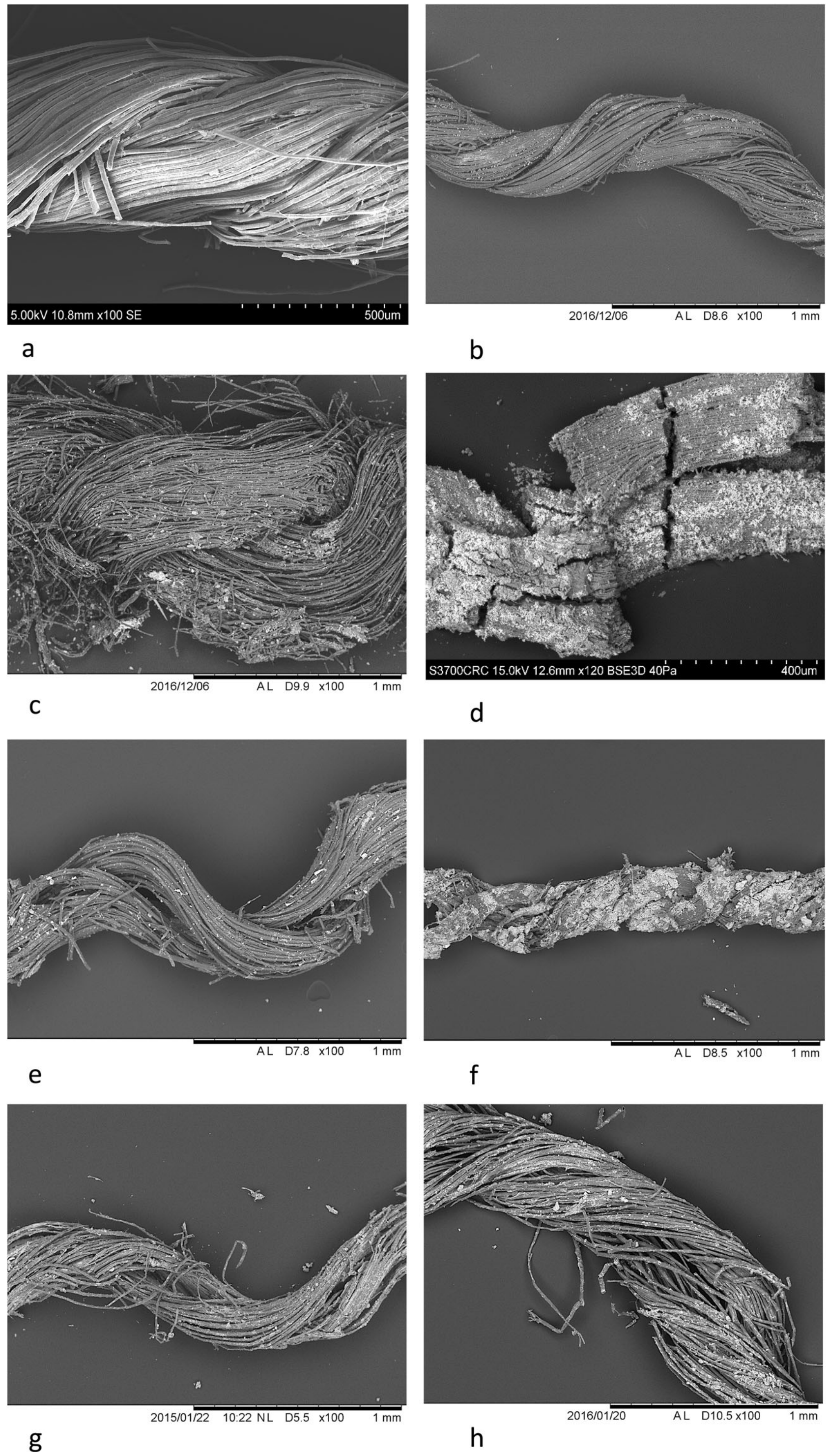


Fig. 6 Micrographs of textiles showing the plied appearance of the threads: (**a**) Tarkhan, Egypt; (**b**) Cave of the Warrior, Israel; (**c**) Lucone di Polpennazze, Italy; (**d**) Over Barrow, UK; (**e**) El Oficio, Spain; (**f**) Must Farm, UK; (**g**) Tarquinia, Italy; (**h**) Corinth, Greece (images: M. Gleba, S. Harris)

various stages will also leave distinctive characteristics. Draft spinning requires fibres to be carefully processed into unaligned fibres resulting in a fluffy or hairy yarn with individual fibres sticking out (Fig. 9) (see Cooke et al. 1991, 22). In a spun linen yarn, adjacent fibres likely come from many different flax plants as they were mixed during heckling. During splicing, the fibre strips or ribbons are removed from an individual flax fibre without fibres being separated into ultimate fibres or mixed with fibres from other plants (see Cooke et al. 1991, 22; Granger-Taylor 1998, 104; Kemp and Vogelsang-Eastwood 2001, 31), resulting in a very smooth and clean yarn (Fig. 10). As the fibre bundles are incorporated into thread, the disloca-tions or nodes (characteristic of bast fibre anatomy) remain

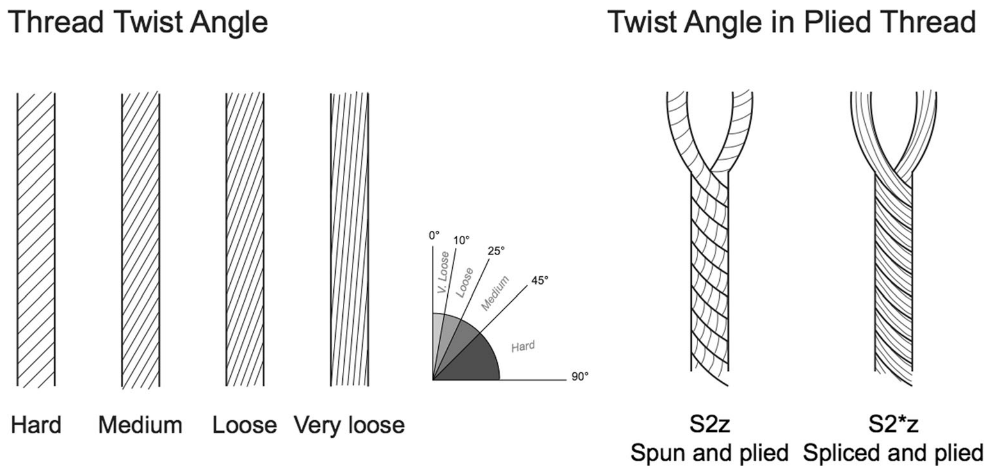


Fig. 7 Diagram of twist angles (diagram by S. Harris, M. Gleba, V. Herring)

adjacent to each other (see also Cooke et al. 1991, 21; Granger-Taylor 1998, 105). The fibre bundles or ribbons with adjacent dislocations thus constitute another important characteristic of spliced threads (Fig. 11).

Evidence of less thorough retting and processing

Retting requires partial rotting of the plant stem to loosen the fibres before extraction. Thorough retting is a necessary preparation for draft-spun fibres to produce a fluffy mass of fibres. Spliced fibre requires less thorough retting as it is preferable for fibre ultimates to remain together in strips or ribbons. Moreover, for the spliced fibres to hold together, a certain amount of adhesive substance is needed. In their experiments to replicate the splicing technique in the Egyptian yarns, Cooke et al. used an animal-based adhesive to join the fibre strips extracted from fully retted flax, which otherwise proved impossible to splice (Cooke et al. 1991, 22). They suggested that some kind of water-based adhesive may have been used to make ancient Egyptian yarns (Cooke et al. 1991, 21). Using saliva as a natural humidifier and adhesive was practiced in Egypt (Kemp and Vogelsang-Eastwood 2001, 71) and still is in East Asia, where the fibres are held in the mouth or licked. However, pectins and other gums present in plants can serve as a natural glue for the purpose, provided they have not been completely removed, which would have happened during full retting. A shorter retting process (Leuzinger and Rast-Eicher 2011, 537), or even absence thereof (Kemp and Vogelsang-Eastwood 2001, 30), would retain the plant pectins and gums, thereby facilitating the splicing process (Kemp and Vogelsang-Eastwood 2001, 31, 73). Extraction of fibres from dry, unretted stalks is known as "decortification" (Kemp and Vogelsang-Eastwood 2001, 30).

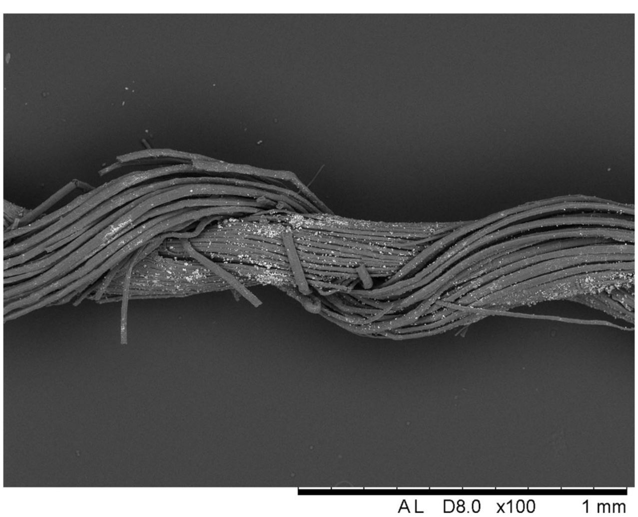
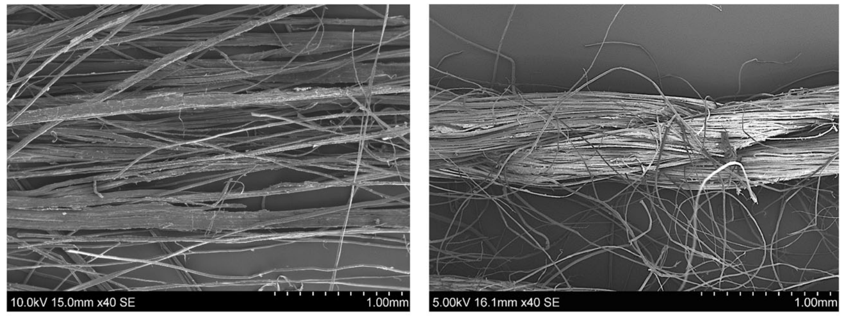


Fig. 8 SEM micrograph of a weft thread showing a splice in one of the single-thread elements, Cave of the Warrior, Israel (image: M. Gleba, S. Harris)

Since splicing does not require thorough retting and does not involve heckling to remove the outer layers of plant tissue, the presence of epidermal tissue adhering to the fibres is another indicator of the process (Fig. 12), as already noted in the case of the Swiss Neolithic finds (Rast-Eicher and Dietrich 2015, 32). Kemp and Vogelsang-Eastwood (2001, 30), who experimented with manually extracting ribbon-like fibre bundles from dry unretted flax, note that "It was difficult to remove the last tiny pieces of epidermis". Remnants of epidermal tissue are also not uncommon in Egyptian spliced textiles.

Caveats

Plying by itself is not an indicator of splicing as yarns plied of two or more spun threads have been used in later periods or for particular purposes. Variation in thread diameter may result from less careful or skilled spinning. Before the industrial processing of plant bast fibres, manual techniques



a b

Fig. 9 SEM micrographs of (**a**) manually processed flax (*Linum ussitattissimum*) with well-separated fibres that are intended for draft spinning on the left; (**b**) modern spun and plied thread on the right. Note fluffy appearance of the thread and pronounced single-thread twist angle (images: S. Harris, M. Gleba)

did not always achieve complete separation of fibres and removal of epidermal and parenchymal tissues (e.g. Fig. 9 left, where some fibres still cling together). For some types of fabrics, such as sails, it was also not necessary to completely remove the non-fibrous plant tissues. Therefore, spun threads from archaeological and historical contexts will occasionally have fibre bundles present. Conversely, the absence of the fibre strips with aligned dislocations and remnants of epidermal tissue is not necessarily an immediate disqualification for splicing. They could have disappeared during subsequent treatments such as washing (Granger-Taylor 1998, 104) or use, as in the case of nets (Rast-Eicher and Dietrich 2015, 33).

Guide for identifying splicing in archaeological specimens

Based on the criteria described previously, we propose a flow chart to assist with the identification of splicing in archaeological textiles/threads (Fig. 13). Note that a combination of macro- and microscopic methods is necessary in order to observe the various features indicative of splicing. The use of this chart requires the analyst to have skills in fibre identification, an understanding of fibre ultimates and thread technology for textile production.

Working at low magnification (e.g. hand lens, stereomicroscope, digital microscope), it is possible to observe plied appearance and variation in thread diameters of adjacent threads in a textile.

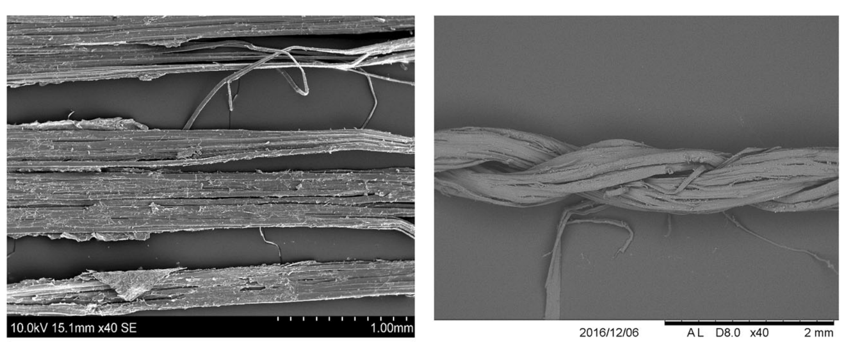
Working at low magnification (e.g. hand lens, stereomicroscope, digital microscope) or SEM (25–40× magnification) helps with the observation of twist degree in single-thread elements (low or absent in spliced threads); variation in individual thread diameter, which in end-to-end splicing will vary between the middle section and the ends of splices; enhanced plied appearance indicative of a splice (this will look like a plied section in one of the two singles, diagnostic of end-to-end splicing). In continuously spliced threads, the single-thread elements are similar to each other (i.e. unlike the irregularities of end-to-end splicing) and individual plied threads are more homogeneous (i.e. more regular diameter than in end-to-end splicing). Single threads are mostly loosely spun (low angle), with more pronounced angle of twist in some places.

Working at high magnification (SEM at 300–1000× magnification), aligned dislocations in the fibre bundles can be observed which indicate fibre strands or ribbons, indicative of fibre processing suitable for splicing, and the remnants of epidermal tissue.

Discussion

Splicing: the original thread technology

It has been long assumed that the technologies of making thread in plant bast fibres have been different in Europe/Near East and East Asia/Pacific: draft spinning in the first



a b

Fig. 10 SEM micrographs of (**a**) flax (*Linum ussitattissimum*) strips removed directly from the plant on the left; (**b**) spliced and plied hemp thread from Japan. Note smooth appearance of the thread and absence of twist in single threads (images: S. Harris, M. Gleba)

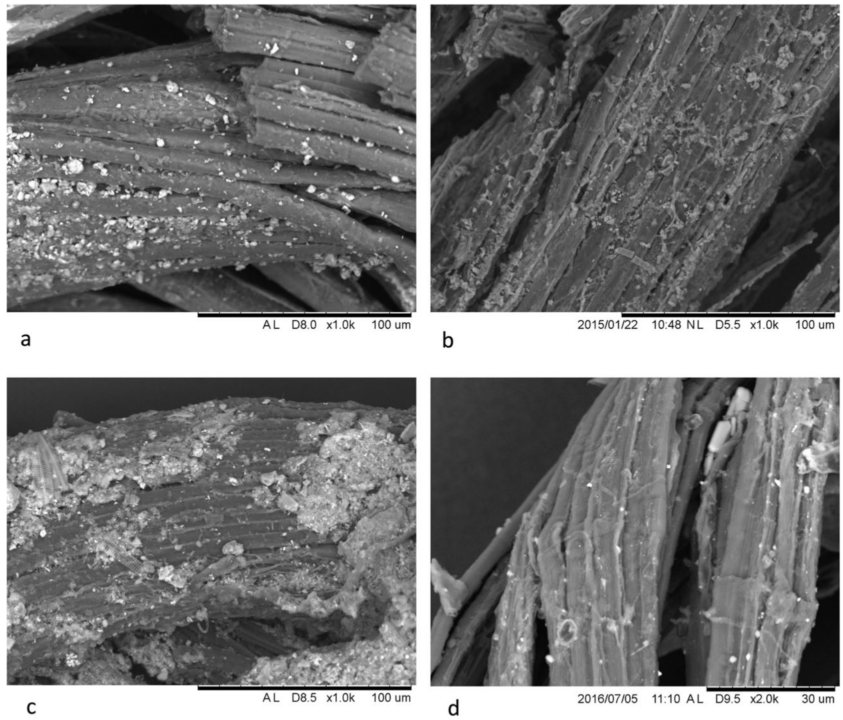


Fig. 11 SEM micrographs of fibre bundles in threads with dislocations adjacent: (**a**) Cave of the Warrior, Israel; (**b**) Tarquinia, Italy; (**c**,**d**) Must Farm, UK. Note adjacent dislocation viewed under higher magnification in (**d**) (images: M. Gleba, S. Harris)

case and splicing or knotting in the second (see Hamilton 2007, 32). Yet, the earliest textile finds from the Levant and Egypt, which are all made of plant bast fibre, are spliced. These include the linen thread attached to a comb from the 9th millennium BC Wadi Murabba'at (Schick 1995, 199) and the 7th millennium BC non-woven textiles from Nahal Hemar, Israel (Schick 1988), as well as woven textiles from Fayum, Egypt, dated to ca. 5000 BC (Granger-Taylor 1998, 106). The finds from Çatalhöyük in Turkey, dated 6500 cal BC, also appear spliced in published images (Burnham 1965; Fuller et al. 2014). According to Granger-Taylor, in Egypt, the technique switched from continuous to end-to-end splicing sometime around 3500 BC (Granger-Taylor 1998, 105). In Egypt and Sudan, splicing remained the primary technique of thread production at least until ca. 600 BC and, in fact, continued to be used in Lower Nubia into the Middle Ages (Wild and Wild 2014, 74).

Barber (1991, 47) previously discounted the possibility that early European textiles could be spliced due to the absence of obvious splices as seen in the Egyptian material (Barber 1991, 47, note 4). However, recent research by Rast-Eicher provided first evidence that in the Neolithic and Bronze Age lake dwellings of Switzerland plant bast fibre thread was also made by splicing (Rast-Eicher 2005, 121; Leuzinger and Rast-Eicher 2011; Rast-Eicher 2015, 16–17; Rast-Eicher and Dietrich 2015, 34–39). A recent textile find from Bell Beaker sanctuary in Brodek u Prostejova, Czech Republic, dated 2500–2200 BC, was also identified as spliced (Grömer et al. 2017).

When we look at the Bronze Age evidence, practically all of the European textiles made of plant bast fibre (mostly flax but occasionally in other species such as nettle and hemp) have been identified as woven with plied yarn. This is the case in Austria (Grömer 2012, 55), Germany (Möller-Wiering 2012, 134), Greece (Spantidaki and

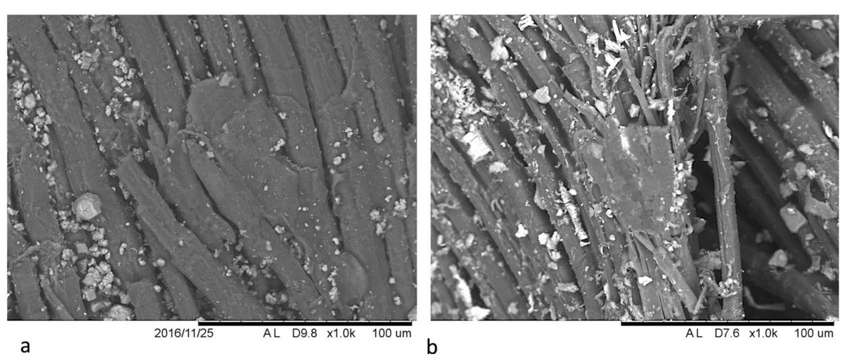


Fig. 12 SEM micrographs of epidermal tissue present: (**a**) Cave of the Warrior; (**b**) El Oficio, Spain (images: M. Gleba, S. Harris)

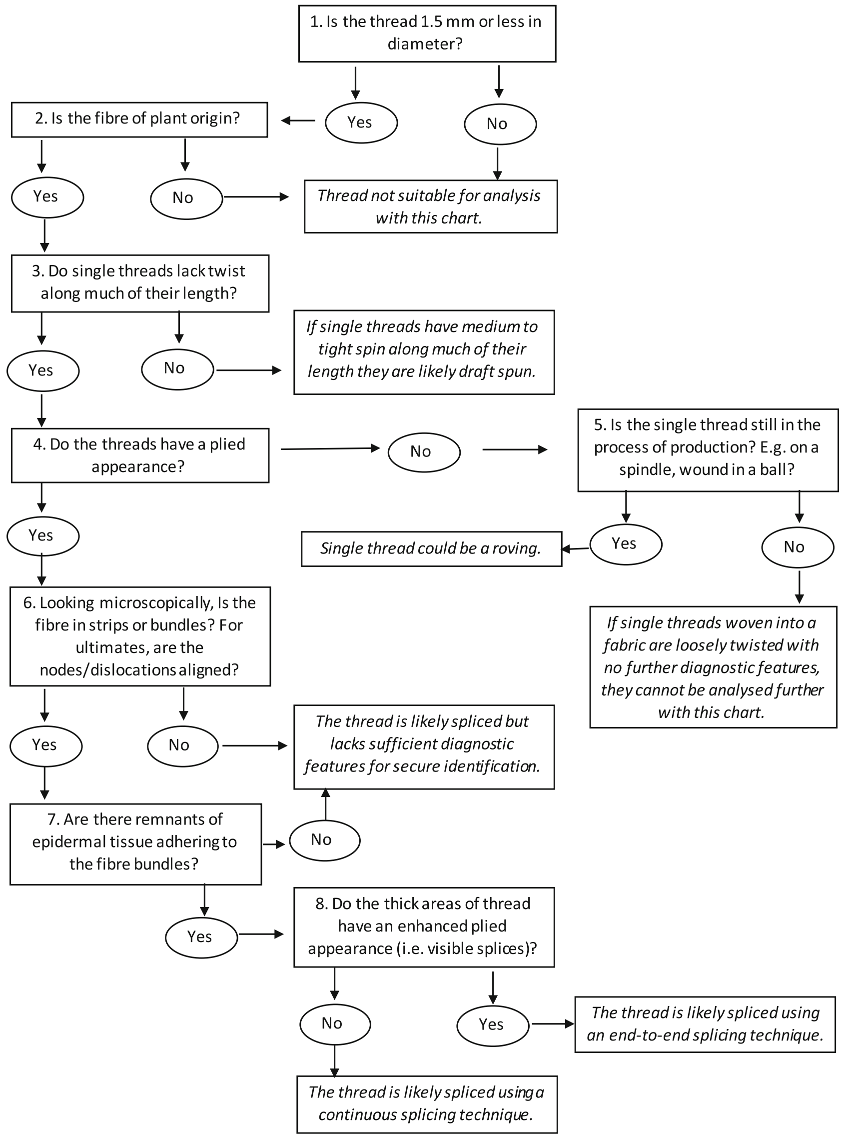


Fig. 13 Flow chart of the stages in the identification of splicing thread technology (S. Harris, M. Gleba)

Moulhérat 2012, 197), Italy (Bazzanella 2012, 207), Spain (Alfaro Giner 2012, 338–339), Ukraine (Gleba and Krupa 2012, 403) and the UK (DeRoche 2012, 446; Harris 2015; Wincott Heckett 2012, 432–433). Neolithic, Chalcolithic and Bronze Age textiles from across the Near East and Aegean have recently been reviewed by Skals et al. (2015, see Appendices A and B), and all plant bast fibre fabrics appear to be plied. Based on the criteria described here, this would hint that splicing, not draft spinning, was an important aspect of plant processing into fibres not just during the Neolithic but throughout the Bronze Age as well. To date, the only finds that do not fit this general pattern in the Bronze Age are two linen textiles from Hallstatt (HallTex 26 and 27), which are woven in single z-twisted yarn (Grömer et al. 2013, 250–252). However, these finds are unusual in terms of their structure (the earliest known other linen 2/1 twills date to the middle of the 1st millennium AD), and the dating is questionable as they were recovered in 1935 before the development of methodological excavation; no radiocarbon dating has been carried out to verify the attribution to the Bronze Age.

Our examination of a variety of plant bast fibre textiles across a wide chronological and geographical spectrum (both the case studies included in the present paper and over 20 others) resulted in the identification of splicing in all of them, including the multiple Iron Age examples from Italy and Greece. In the Near East, spliced textiles have recently been identified at the Iron Age Tell Shiukh Fawqâni in Syria (Breniquet in press), and our preliminary research also shows that they are present at contemporary Gordion in Turkey and Ur in Iraq. This indicates that in Europe and the Near East, splicing was used much more widely and much longer than previously recognised.

Beyond Europe and the Near East, splicing continued to be the primary technique for plant bast fibre thread production in the East Asia and the Pacific even longer, with many indigenous communities in Korea, China, Japan and the Philippines still practicing it, as already noted. Furthermore, recent research on early South American bast fibre textiles from La Yerba (6000 BP), using criteria proposed by us above, determined that these finds were spliced, too (Beresford-Jones et al. 2018). Splicing, thus, appears to be the earliest technique of thread production developed with the use of plant bast fibres across the world.

Why then has splicing not been recognised until recently in prehistoric textiles outside of Egypt and the Near East? There appear to be two reasons. One is that, for many years, it was assumed that, in ancient times, flax was processed into linen in exactly the same manner as in the nineteenth and twentieth century household industries of farming communities across Europe, well-known from historical sources, ethnography and craft work (Baines 1995; Flad 1984; Kezich et al. 2002, Vogt 1937, 46–47, abb 72). The other is that splicing is difficult to identify even in the well-preserved Egyptian material (Granger-Taylor 1998,103–4), but particularly in poorly preserved organic material, or material treated with waxy conservation treatments. This is hardly surprising since as Hamilton (2007, 34) points out, experienced modern craftspeople in east Asia "can join one fibre to the next with great speed, and so precisely that it is typically difficult to detect any knot, twist, or splice in the finished cloth without a magnifying device." The method presented in this paper is intended to change this situation, by providing researchers with the means to interrogate thread production technologies anew.

Extant prehistoric textiles must be carefully re-assessed following criteria proposed previously, but preliminary evidence suggests that splicing continued to be used for making plant bast fibre thread across Europe and the Near East at least through the seventh century BC, as in ancient Egypt (Granger-Taylor 1998, 106), and even later as in the case of a fifth century BC spliced yarn from Kerameikos in Athens (Spantidaki 2016, 29–40, 125 Fig. A.48). The switch from splicing to draft spinning plant fibres occurred much later than previously thought. This discovery has profound implications for our understanding of the *chaine opératoire* of thread and textile production and the economic and technological choices made by the past populations, although this is beyond the scope of the present paper and will be addressed elsewhere. For example, it will be important to readdress time calculations to process plant fibres and produce yarn, reconsider the mechanical and visual properties of plant fibres and re-evaluate the difference between animal and plant fibre thread production technologies. It also affects how we should interpret some of the less perishable evidence in prehistoric archaeological contexts, in particular spindle whorls.

In Europe and the Near East, spindle whorls become more common during the later Neolithic period and by the Bronze Age they are ubiquitous (Barber 1991; Becker et al. 2016). Presence of spindle whorls, however, is not evidence of draft spinning as they could have been used to impart the twist to the spliced yarn or to ply two or more spliced yarns together, as illustrated by the Egyptian iconographic evidence (see discussion in Kemp and Vogelsang-Eastwood 2001, 70–79). Neolithic and Early Bronze Age spindle whorls are generally heavy and have predominantly discoid or lenticular shape (e.g. Médard 2006, 61), which would have imparted slow but continuous rotation to the spindle due to high diameter to height ratio, particularly useful for plying. The appearance of other shapes, such as spherical and biconical, during the Bronze Age largely coincides with the advent of wool (Rast-Eicher 2005, 127). Previous debates as to the presence or absence of spindle whorls in prehistoric settlement sites hence remain pertinent (see for example Médard 2003, 83-5), with the added complexity of considering methods of splicing.

Conclusions

We have summarised insights on the identification of splicing from the key textile researchers and outlined possible indicators of splicing when analysing threads made of plant bast fibres. Identification of splicing requires careful observation of threads and fibres that have not been conserved with consolidants using both macro- and microscopic techniques. Successful identification of splicing is based on observing a combination of at least several characteristics, such as plying, smooth appearance of thread, absence of or low twist in single threads and presence of epidermal tissues and fibres still adhering to each other in bundles (Fig. 13).

From a methodological point of view, we would like to advocate proper consideration of the following to the researchers analysing prehistoric plant bast fibre artefacts:

- Be wary of automatically assuming that ancient technologies, such as thread production, were the same as in the nineteenth century;
- Prehistoric thread technologies for plant bast fibres were varied—several forms of splicing are known today and they were likely more numerous in prehistoric times;
- Old assessments of thread technology need to be reviewed;
- If plant bast fibres are spliced, not draft spun, then production time assessments that are based on draft spun yarn need to be reviewed.
- Re-evaluate current understandings of the *chaîne opératoire* and technological choices surrounding fibre processing and thread production technologies.

Considering the survival of several forms of splicing until the present time, we would expect that a similar if not a much wider variety of methods existed in the past. Future studies into the specific methods of splicing in the past are therefore likely to demonstrate that thread production technology was varied (e.g. for fine yarns, cords, and according to time and place), which may explain variation in thread appearance.

The discovery of more widespread evidence for splicing than previously believed has a number of important implications for how we interpret the archaeological evidence of plant bast fibre technologies, textiles and other plant-based products, such as twined or looped materials.

It appears that splicing was not confined to the Neolithic and Bronze Age in Europe (Leuzinger and Rast-Eicher 2011), but continued much later, and many old identifications are wrong; the identification of splicing marks a major turning point in scholarship. It appears that draft spinning was a technological transfer, based on the skills and techniques learned from draft spinning sheep wool. According to Barber (1991, 50) and Granger-Taylor (1998, 106), this transfer happened in Egypt around 600 BC. Our research shows that in other parts of the Mediterranean, certainly in Italy and Greece, it happened at about the same time. The finds from the Must Farm in the UK and Lysehøj in Denmark (Bergfjord et al. 2012) indicate that at least in the early part of the first millennium BC, splicing was used in northern Europe as well. More data is needed for Central Europe, but if the two unusual linen twills woven in single-spun yarn from Hallstatt prove to be later in date, the pattern is likely to hold true in this area as well.

On the basis on Tiedemann and Jakes's (2006) study, which concluded that draft spinning was faster than splicing yarns, we suggest that the transition to draft spinning plant bast fibres may be based in a pressure to produce more yarn, faster. In comparison to draft spinning, the process of splicing is understudied by archaeologists and raises many questions which need further investigation. For example, Tiedemann and Jakes question whether to a competent person, splicing fibres into yarns could be as fast as draft spinning. Nevertheless, this is not the only technological difference between the two techniques. The extraction of fibre from the stem by braking, scutching and heckling in preparation for draft spinning is a mechanised process that can work multiple stems at the same time. It is likely that this was more time efficient than stripping fibres from individual plant stems in preparation for splicing. It is striking that similar technological transfer from camelid wool to plant bast fibres took place in South America, albeit much earlier due to the presence of cotton—a seed plant fibre, which, like animal hair, cannot be spliced (Beresford-Jones et al. 2018). In the Old World, the driving force behind the change was not a new raw material but the need for the intensification of textile production. The technological innovation of draft spinning plant bast fibres came at a crucial time in the development of urbanisation in the Mediterranean, when the production of goods, trade and transport powered by textile-driven sailing ships flourished. The new method of splicing identification proposed here is making these new insights possible.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Appendix

Table 3 Splicing in archaeological scientific reports: terminology, technical definitions, suggested technique and visual identification

Terminology	Technical definition	Technique	Visual appearance	Country and period	Source
–	"… a series of fibres had been placed parallel and twisted into a short thread; then, after twisting another set of similar fibres, one end of each set was overlapped, and both twisted together."	"This would mean the gradual building up of a continuous thread from a number of short sections, and only at the overlapping points would it be two-fold."	In places threads appear folded (double?), in other areas they appear single.	Egypt, 12th Dynasty	Fox (1910, 66)
Splicing/ultra-fine yarns from flax	a. "The splicing of ultimate bundles end to end, using moisture or adhesive to secure the join …" b. "… the overlap joining of ultimate bundles either with or without adhesive …" c. "… the wrapping of a sequence of bundles around a core made up of individual bundles, again either with or without adhesive."	Ribbons of flax bundles are stripped from the stalk and soaked in water for 24 h. Yarn is produced from a single ribbon of bast fibres that is spliced onto a similar ribbon. These ribbons are moulded into a circular form which may have required the use of a water-based adhesive or may have been processed while wet. In this process the ultimates (i.e. fibres) are not drafted. The stalks could have been stripped green leaving the natural pectins and gums in the stem to assist in the joining process.	"These yarns gave the appearance of changing from a singles, to a two fold yarn in the spliced section. Furthermore the singles sections were characterised by ultimates showing transverse impression marks running across the yarn surface …"	Egypt, 18th Dynasty	Cooke et al. (1991, 21, fig. 5)
Splicing	"Each strand consisted of lengths of fiber whose ends were overlapped by a few centimetres, and which then were twisted at the splice just enough to hold temporarily (fig. 2.9). Then three of these long single strands were twisted together, in such a way that the rather evenly-spaced splice points in one strand would come at different places in the final thread than the splices of each of the other strands"	Hand splicing the flax before twisting it with a spindle	Where there is a splice the yarn appears plied, as the twisted splice stands out from its paired roving. Where there is no splice the yarn may at first glance appear single.	Egypt, from 5th mill. BC to 11th Dynasty	Barber (1991, 47–8, fig. 2.9)
Long splicing	"… in which two, long lengths of thread are twisted together (fig. 2a). These lengths can vary from a few centimetres to fifty centimetres in some cases"	–	Two threads spliced together produce the effect of an S,2s ply	Egypt, Pharaonic	Van Rooij and Vogelsang-Eastwood (1994, 17, fig. 2a)
Short splicing	"Usually this form of splicing is where between one and two centimetres of thread are twisted together and then turned back on themselves and retwisted on the main thread (fig. 2b-c)."	–			Van Rooij and Vogelsang-Eastwood (1994, 17, fig. 2b&c)
Spliced and plied	1. "The rove consists of two elements which between the splices are separate or only very loosely twisted together. The elements are made of strips of fibre which within the splices are joined end to end,	1. Splicing and plying performed in one process possibly by thigh rolling to form a rove. 2. Rove then "twisted" on a spindle.	The spliced section is tightly twisted and about 5 cm long, separated by very loosely twisted sections about 35 cm long. Most Egyptian yarns are S "plied" with the	Egypt, Middle Kingdom	Granger-Taylor (1998, 103–4, fig. 1)

Table 3 (continued)

Terminology	Technical definition	Technique	Visual appearance	Country and period	Source
	the overlapping ends being first twisted on themselves in the Z direction—the "splicing" proper—and the two elements then twisted or "plied" together in the S-direction" […] 2. "Once the rove had been spliced together and wound up into a ball, the ball would have been placed in a bowl or jar and from there unwound again as further twist was added, this time to the rove's whole length, using a spindle"		splice in z direction. Splicing is difficult to distinguish after spinning and weaving.		
Twinned or simultaneous splicing	"This early type of linen yarn, which can be termed "twinned", was produced entirely without a spinde, by rubbing the elements together in the hand or against the thigh or against another surface" (Fayum style)	(1–2 as above) 3b. The splice and twist are carried out at the same time.	–	Egypt, prehistoric, before 2500 BC, e.g. Fayum	Granger-Taylor (2003; "Textile production and clothing")
–	Thread production without tools[a] producing extremely fine threads with diameter of 50 µ.	Spinning without the use of a tool consists of twisting the fibres between the two hands or between one hand and another part of the body (leg, thigh, cheek).	Extremely fine threads	Egypt, 18th Dynasty	Médard (2005, 19–20)
Spliced and twisted	Fibre strips are joined by splicing and twisting. "Two new strips were spliced end to end with the previous two strips the joins being separately twisted in the Z direction and the two joined elements then plied together in the S direction"	1. Flax/linen fibre is removed from the stem by stripping. 2. Wider strips are split lengthways according to required fineness of the yarn. 3. Approx. 5 cm fibres are joined end to end by twisting in a z direction. Two of these single elements are then plied together in a S direction	"On the Lahun roves, as in textiles of this period, the length of the splice is about 5 cm and the distance between splices c.35 cm. In these extant roves, between splices, there are always two lengths of strip visible side by side."	Egypt, Middle Kingdom, e.g. Lahun, c.1850–1750 BC	Granger-Taylor (2003; "Textile Production and Clothing")
Splicing	"the term "splicing" is used here to describe the addition of fibre bundles to produce a continuous thread [...]".	Following a short ret, the woody core of the plant is snapped and fibres are stripped from the wet stem. Two ends of wet fibre strips are twisted together end to end, then wrapped around a rigid spool to dry. Two of these dry, spliced yarns are then spun with a drop spindle.	Viewed microscopically: in fine linen thread the fibres in strips remain stuck together with parallel nodes, in lime bast the rays were still visible. Two single yarns plied together in S direction.	Switzerland & Austria, Late Neolithic to middle Bronze Age	Leuzinger and Rast-Eicher (2011, 537–41)

[a] Translated from the French by S. Harris: Thread production without tools ("Le filage sans instrument") (Médard 2005, 19)

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