Technical Research Bulletin

Volume 8
2014

The British Museum

Microscopical examination of fibres used in Ming dynasty paper money

Caroline R. Cartwright, Christina M. Duffy and Helen Wang

SUMMARY The paper money of Kublai Khan and the Chinese Yuan dynasty (AD 1271–1368) is well known, largely thanks to the accounts by Marco Polo. The succeeding Ming dynasty also issued paper money, but this was less successful, and mismanagement, inflation and forgeries led to its demise. Many Ming notes have survived, but serious research on them is lacking. Traditionally, these notes were believed to be made from mulberry bark, although it has been unclear which of the Moraceae family could have been used, e.g. *Morus alba* (white mulberry), *Morus australis* (Chinese mulberry) or paper mulberry (*Broussonetia papyrifera* and *Broussonetia kazinoki*). Interest, partly generated by the radio series *A History of the World in 100 Objects*, prompted the scientific examination of the Ming notes in the British Museum and the British Library collections. The complementary techniques of variable pressure scanning electron microscopy and stand-alone digital microscopy revealed surprising results. While fibres from white mulberry and paper mulberry had been used, many different types of fibres and other plant cells were also present, including bamboo, rice straw, wheat straw, hibiscus and hemp (all identified by comparison with reference collection specimens, mostly from China and Japan). The results have important implications. First, this is the first combined microscopic examination of Ming paper money anywhere in the world. This pioneering study demands that the historical literature, specifically sources relating to the control of production of paper money, be revisited. Secondly, it provides unprecedented data for Ming dynasty papermaking, which is of immediate relevance to historians of Ming dynasty painting, book production and printmaking.

Introduction

In 2010, BBC Radio 4 broadcast the hugely successful series *A History of the World in 100 Objects*, a project developed with the British Museum [1]. One of those 100 objects was a Ming dynasty note (CIB,EA.260) dated to the Hongwu reign (AD 1368–1398) of the first Ming emperor, although the inscription remained unaltered under subsequent emperors. It is one of the most iconic objects in the history of Chinese money. But it is neither the earliest paper money in Chinese history, which dates to the Tang dynasty, AD 618–907 (although none has survived), nor the most famous Chinese paper money, which was issued by Kublai Khan during the Yuan dynasty, AD 1271–1368, and described so vividly by Marco Polo. It is certainly not the most successful note in history, as its demise served as a 400-year deterrent to government-issued paper currency. This note (CIB,EA.260) is not a unique object either, since Ming paper money was mass-produced and specimens survive in collections around the world; there are nine in the British Museum (BM), plus one reproduction and four later forgeries, and there are five in the British Library (BL).

"Telling history through things is what museums are for", wrote Neil MacGregor in his preface to the book that accompanied the radio series [1]. But object-based research takes time and depends not only on original sources and subsequent research, but also on the perspective of the researchers. Most studies relating to Ming notes are conducted by historians, who tend to undertake text-based research [2, 3], or numismatists, who typically focus on object-based research. The two disciplines also have different agendas and their combination is so rare that Peng Xinwei's *A Monetary History of China*, written in 1965 [4], remains a standard reference despite almost 50 years of unprecedented archaeological discoveries in China.

Table 1. Ming dynasty notes in the British Museum

British Museum No.	Dimensions (mm)	Remarks
1913,1011.30	338 × 220	With card frame pasted on back
1942,0805.1	341 × 222	
OR.9730	338 × 220	
CIB,EA.265	343 × 220	With decorative gold detail (applied later?)
CIB,EA.260	340 × 218	
CIB,EA.261	340 × 220	
CIB,EA.262	341 × 220	
CIB,EA.263	340 × 220	
CIB,EA.264	340 × 220	
1984,0605.8637	261 × 174	Forgery
2002,1015.8	250 × 152	Forgery
2002,1015.9	248 × 144	Forgery
2002,1015.10	251 × 146	Forgery
1986,0925.1	347 × 227	Reproduction (made by Thomas Leech in 1986)

Note: The BM registration numbers indicate the year of acquisition (1913, 1942, 1986) or the original collection (those prefixed CIB,EA came on loan to the BM as part of the East Asian section of the Chartered Institute of Bankers collection in 1987, and were formally donated by the ifs School of Finance in 2009).

In short, Ming notes might be iconic objects, but there is much work to be done before their history can be told fully.

It is known that Ming paper money was issued by the Secretariat (*Zhongshusheng*) between 1375 and 1380, and thereafter by the Ministry of Revenue (*Hubu*), with the involvement of the Supervisorate of Paper Money (*baochao tijusi*), the Currency Supply Service (*chaozhiju*) and the Plate Engraving Service (*yinchaoju*) [5]. The dark colours and limp appearance of the notes seen today have been attributed to the processing of fibres from mulberry bark, but it was not clear which kind of mulberry: *Morus alba* (white mulberry); *Morus australis*, formerly known as *Morus bombycis* (Chinese mulberry); *Broussonetia papyrifera* (paper mulberry); or *Broussonetia kazinoki* (Japanese paper mulberry or *chu*).

Early papermaking originated in China and later spread throughout Asia. Although the methods of ancient paper-making varied according to the location and availability of materials, the basic processes employed throughout the centuries were similar. Disintegrated cloth and rags were used to produce the first paper in China, but it was not long before bark and other plant materials such as mulberry, hemp and China grass were introduced as raw materials [6]. The demands of the papermaking process required mills to locate near mountains, where raw materials such as wood, stones and mud could easily be obtained for the construction of buildings, and near a stream to give access to a supply of water [7]. Tools were required for cutting bark and bamboo shoots and for digging pools in the ground where materials could be mixed. Other necessities included ropes for tying wooden boards together to press water from the paper mixture and tweezers to lift single sheets from the mass when dried. In the first stage of preparation, raw material was soaked, pounded, washed and steamed or boiled to a pulp. Bark paper, including mulberry bark paper, was produced by mixing bark with smaller amounts of cut bamboo and rice stalks. These were soaked in an alkaline solution containing, for example, lime or wood ash to remove non-cellulosic materials. Adhesives and other insoluble materials were sometimes added to the pulp to improve the physical and chemical qualities of the paper. The dilute suspension of beaten material was allowed to drain through a screen, usually made of a cloth sieve attached to a frame. The pulp was then pressed to remove excess water, before being placed to dry on a heated wall. This process laid down a mat of randomly interwoven fibres that formed a sheet of paper when fully dried. The dried paper was further processed by treatments such as sizing, loading, dyeing, colouring and coating to protect it from degradation, or for aesthetic purposes. Asian papers were typically soft, pliable and absorbent, with the choice of materials and their relative quantities based on the purpose of the paper. Later traditional papers were made specifically with the calligrapher in mind and were light with a transparent quality. An old proverb in the paper trade claims that "a sheet of paper does not come easily; it takes 72 steps to make" [7]. While this may be a generous number, it is clear that the raw materials in paper have been greatly altered from their natural state.

Materials analysed

Table 1 contains the details of the British Museum notes: nine originals, one reproduction and four later forgeries. When taking samples from these notes, considerable effort was made to keep the amount of material removed to an absolute minimum (*c*.1 × 1 mm) and to avoid sampling any areas with pigments or inks, macroscopically visible adhesives, adhering modern fibres or conservation consolidants that might affect identification. Figure 1a shows a Ming note from the British Museum (1942,0805.1), the Chinese text along the top of which reads *Da Ming tongxing baochao* and translates as 'Great Ming Circulating Treasure Note'. The denomination is written in two characters *yi guan* ('one string'), below which is a depiction of a string of 1000 coins, arranged in 10 groups of 100 coins. Beneath the bottom four sets of 10 coins are the instructions for use of the note and a threat to punish forgers.

The British Library holds five Ming dynasty notes (ORB 40/861–865) measuring 220 × 330 mm, two of which were removed from their glass casing (ORB 40/862 and 863) for examination and the taking of minute samples. The notes do not appear to be printed from the same block; Figure 1b shows one of the notes from the British Library collection (ORB 40/863).

For this study, reference material associated with papermaking during the Ming dynasty was sourced from China and Japan. Bark, fibre and stem samples included: paper mulberry (*Broussonetia papyrifera*: Figure 2a); Japanese paper mulberry (*Broussonetia kazinoki*); white mulberry (*Morus alba*: Figure 2b); Chinese mulberry (*Morus australis*); snailseed vine (*Cocculus trilobus*: Figure 2c); and hibiscus/cotton rosemallow (*Hibiscus mutabilis*: Figure 2d). Samples from the British Museum's reference collection were also used, which included: stems and leaves from different types of bamboo (*Bambusa* sp.: Figure 2e); sandalwood bark (*Dalbergia* sp.); stems of rice (*Oryza sativa*: Figure 2f) and wheat (*Triticum* sp.); and fibres of cotton (*Gossypium* sp.), hemp (*Cannabis sativa*), ramie (*Boehmeria nivea*), jute (*Corchorus* sp.), rattan (*Calamus* sp.), flax (*Linum* sp.), gampi (*Wikstroemia canescens*), mitsumata (*Edgeworthia* sp.), abaca (*Musa textilis*) and silk (from mulberry silkworm, *Bombyx mori*, larvae cocoons).

Methods of analysis

The approach adopted was to use complementary microscopy techniques to examine the raw materials used in the papermaking process of Ming dynasty paper money in order to address current inconsistencies in the historical literature.

Digital microscopy

Images of Ming dynasty notes were captured *in situ* using a Keyence VHX 2000 E series stand-alone digital microscope. This system comprises a high-resolution camera (54-megapixel 3CCD) attached to a compact, high-performance zoom lens that allows images to be captured at magnifications ranging from ×20 to ×200 with a large depth of field. The microscope can be used either with illumination provided from the lens unit, using a dimmable 12 V, 100 W lamp that has a colour temperature of 3100 K at maximum light intensity, or in conjunction with transmitted light from an LED source in the microscope stage. The Keyence free-angle observation system allows the lens unit to be inclined or rotated and this oblique-axis motion allowed image capture at a wide range of angles without unnecessary handling of the notes. The microscope is also equipped with a motorized XY stage measuring 171 × 168 mm, which is controlled by a joystick. The notes were placed individually on the XY imaging stage and supported by a bespoke sheet of mount board. No fibres were removed from the notes for examination by visible microscopy. Due to the variation of material across the notes, individual images captured under the microscope do not always contain features that allow their location to be pinpointed, so a series of images was captured by moving the note with the XY stage and stitching the images together to provide a composite image that could be used to situate the material relative to the location of the text and seal markings. Once this image capture procedure is initiated, the XY stage automatically moves in a clockwise pattern around the selected origin point and captures images at each location.

Regions of interest were identified at which to produce images, so that an overall understanding could be provided of the fibres, fragments and pigments as individual components of the whole note, as well as to observe their relationship to each other. The microscopy images presented in Figures 3

a

b

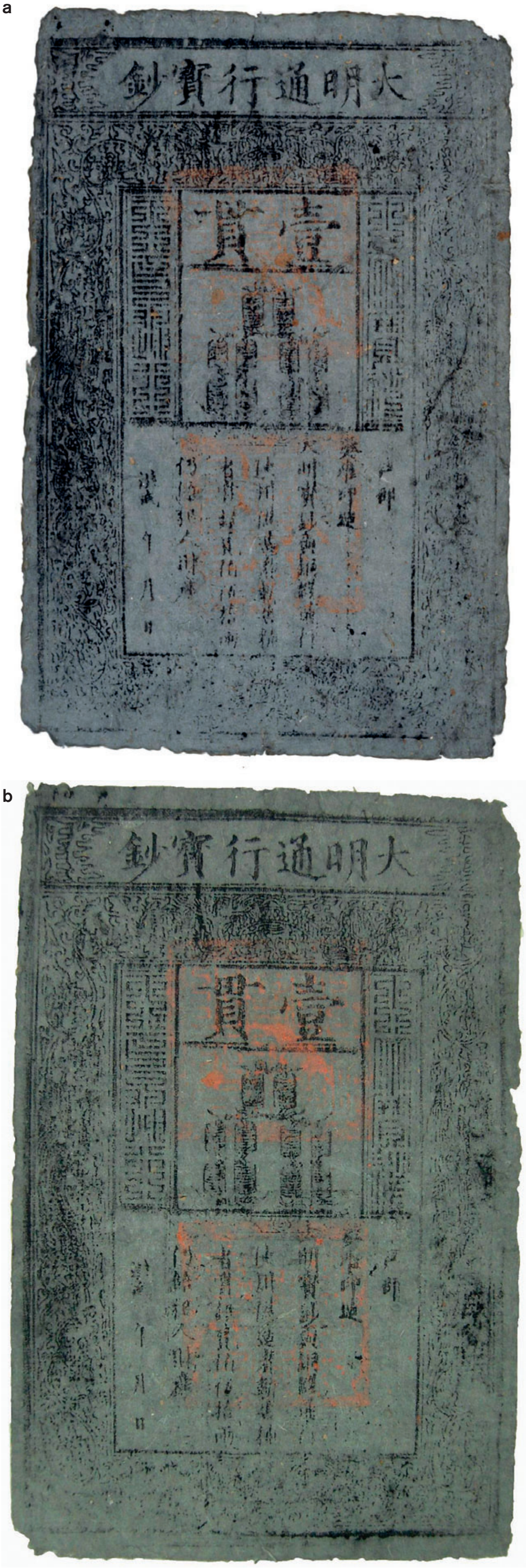

Figure 1. Ming dynasty notes: (a) British Museum note for one string of 1000 cash, 1942,0805.1; and (b) British Library note, ORB 40/863. Image: © The British Library Board

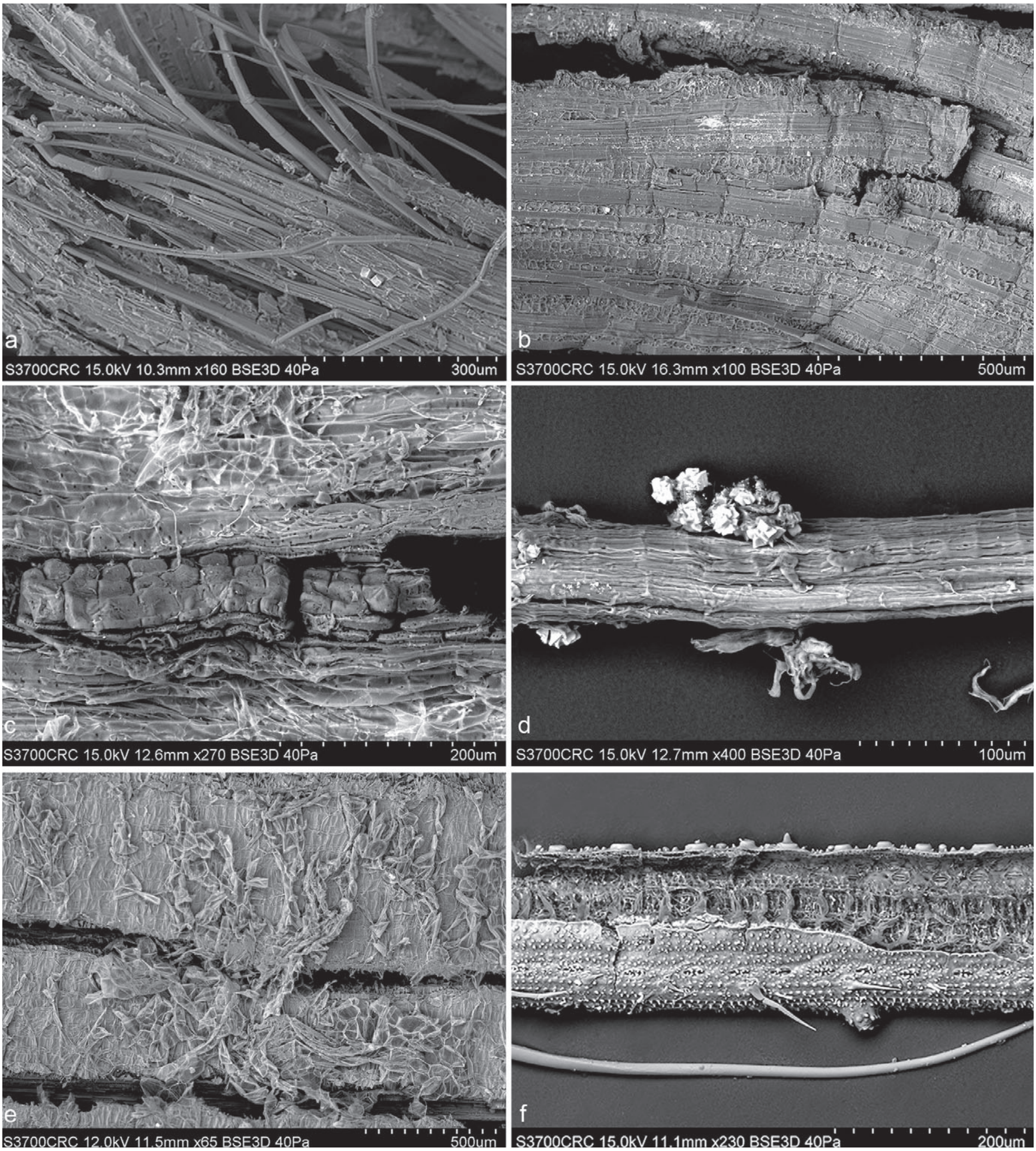

Figure 2. VP SEM images of selected reference specimens: (a) paper mulberry, *Broussonetia papyrifera*; (b) white mulberry, *Morus alba*; (c) snailseed vine, *Cocculus trilobus*; (d) hibiscus/cotton rosemallow, *Hibiscus mutabilis*; (e) bamboo, *Bambusa* sp.; and (f) rice, *Oryza sativa*

to 6 are a small selection of those captured. The reference material was examined separately, but to ensure the capture of *in situ* images comparable to those for the note material, no individual fibres were removed from reference material. Images were produced of features of the outer and inner bark where possible and of fibres already stripped from the bark.

To acquire images that captured a wide contrast range, the microscope was set to image in High Dynamic Range mode. In this mode a number of colour images are automatically captured at various shutter speeds, thereby increasing the range of different lightness levels that can be obtained. This mode generates images with the equivalent of a 16-bit depth from the series of 8-bit colour images captured by the camera, providing detailed images of the notes even in those areas that appear to show poor contrast. Offline measurements on collected images were made using the VHX-2000 Communication Software package for 2D/3D image playback, editing and 2D measurement.

The Ming dynasty notes presented some variation in surface topography due to the presence of larger inclusions of bark and other materials. It was possible to produce an image in which the whole surface was in focus by using the

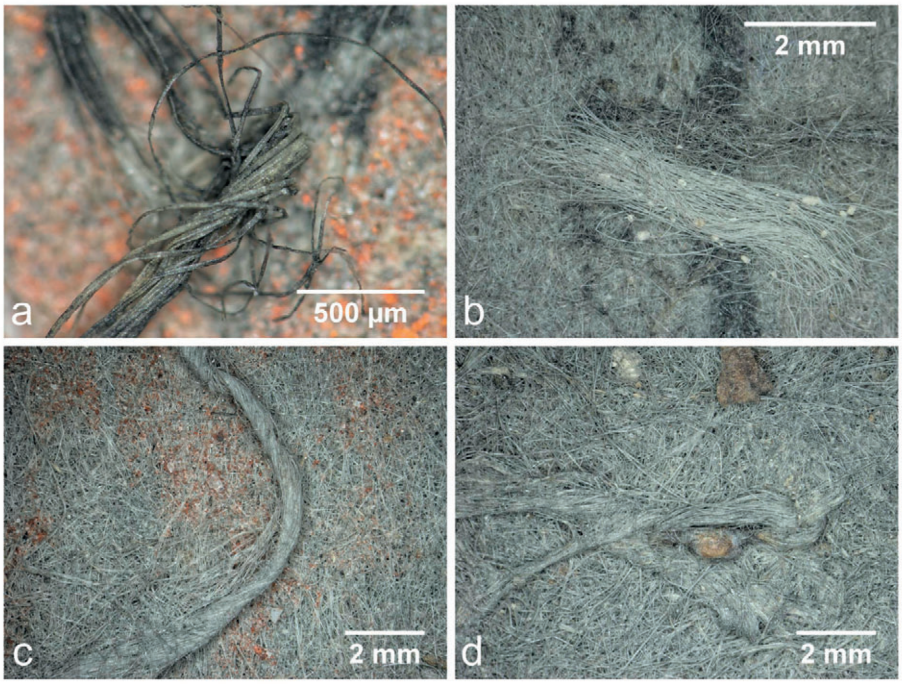

Figure 3. Images from digital microscopy of fibres from the Ming notes: (a) loose entangled fibres in BL ORB 40/862; (b) loose fibre bundle over black pigment in BM CIB,EA.264; (c) rolled fibre bundle in BM CIB,EA.264; and (d) interwoven fibre bundles in BL ORB 40/863

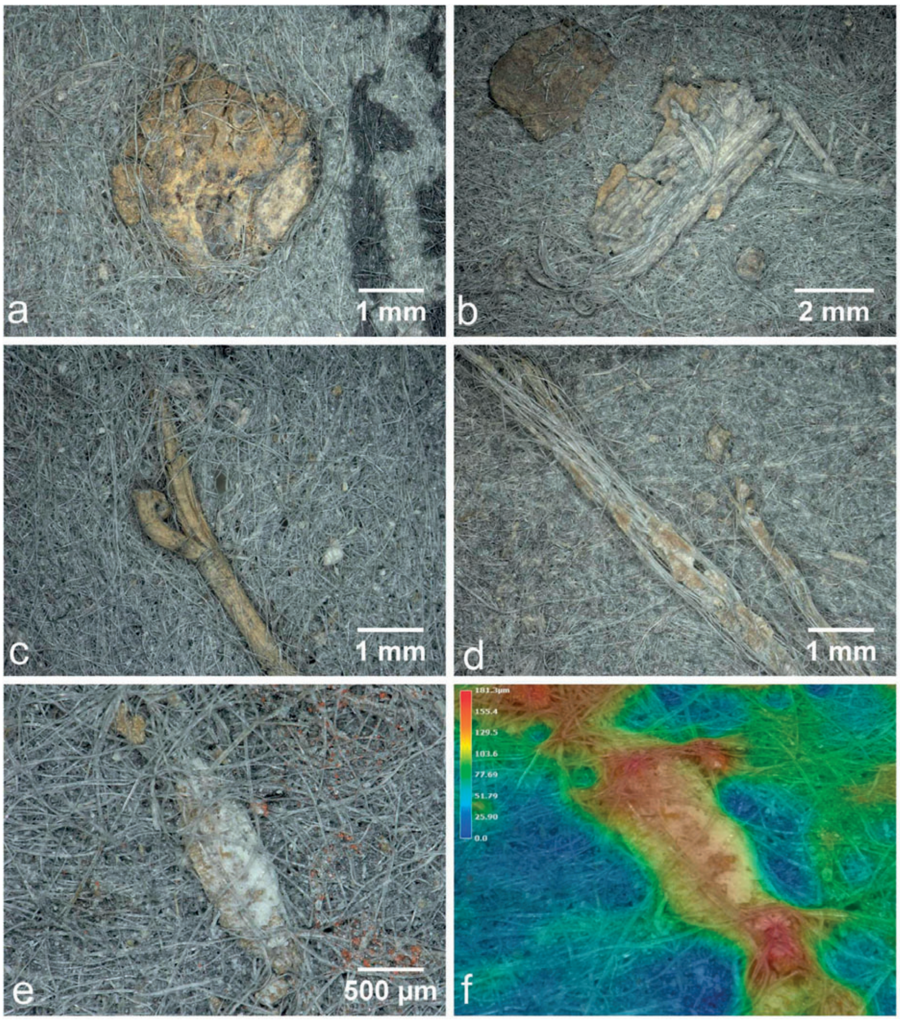

Figure 4. Images from digital microscopy of fragments from the Ming notes: (a) bark in BL ORB 40/862; (b) bark in BL ORB 40/863; (c) plant stem in BM 1942,0805.1; (d) bark fragment in BM 1942,0805.1; (e) detached fragment in BM CIB,EA.263; and (f) a 3D visualization of the region seen in Figure 4e

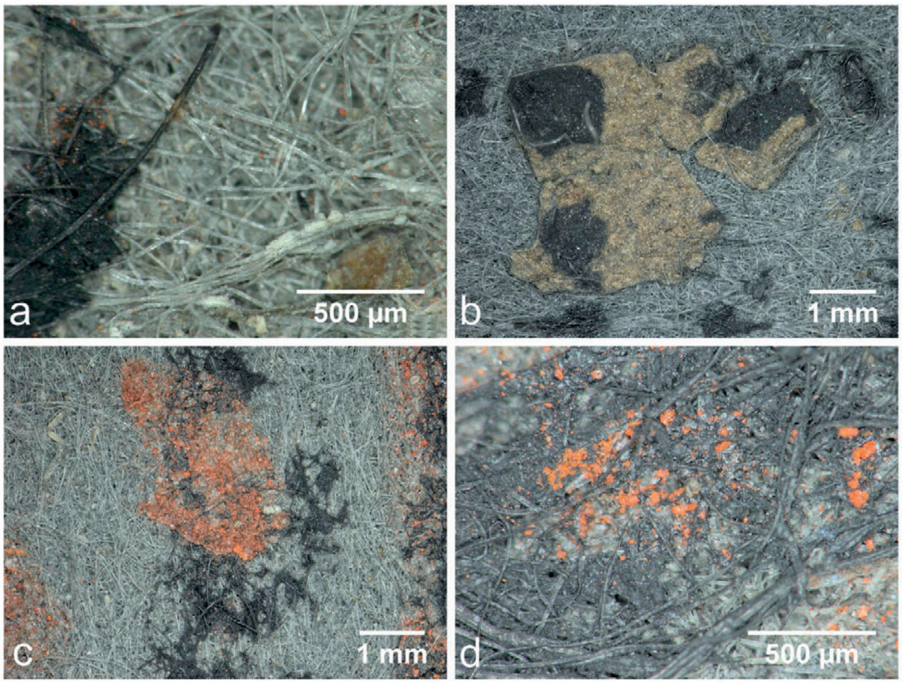

Figure 5. Images from digital microscopy of pigments from the Ming notes: (a) coated fibre in BL ORB 40/863; (b) coated fragment in BM 1942,0805.1; (c) red pigment over black pigment in BL ORB 40/863; and (d) particulate red pigment in BL ORB 40/863

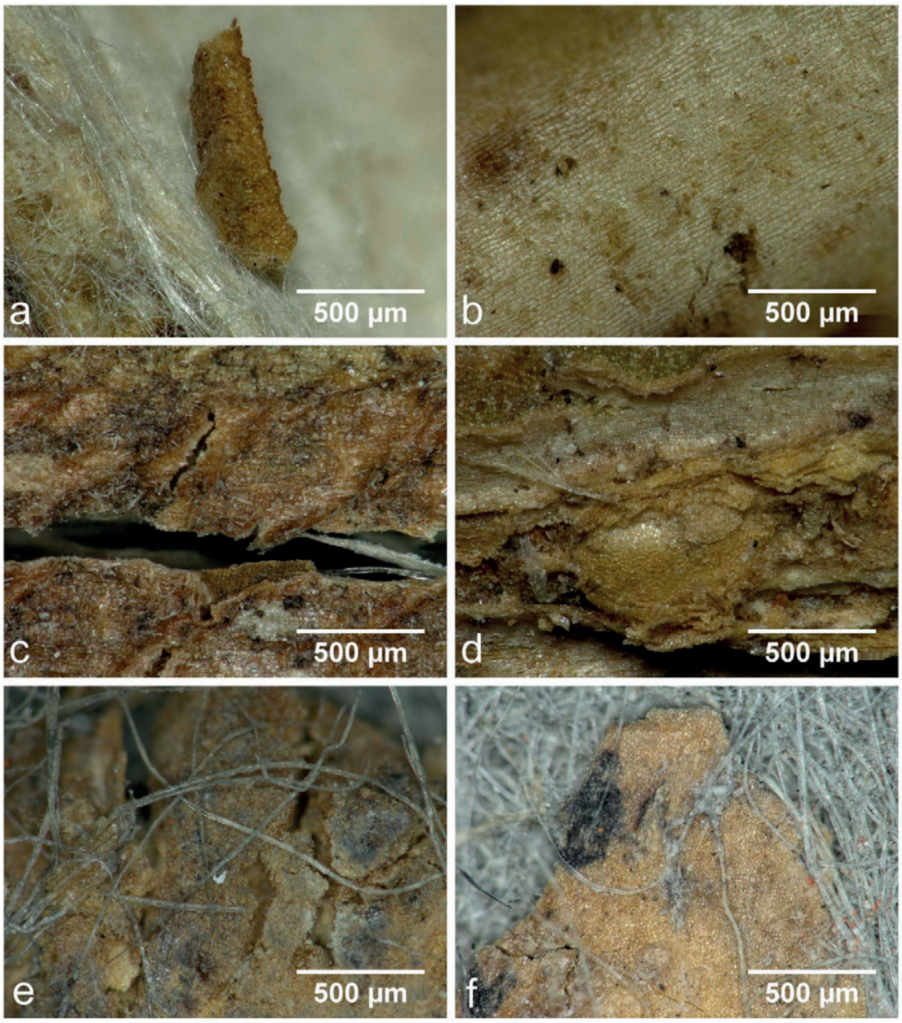

Figure 6. Images from digital microscopy of reference material: (a) white mulberry, *Morus alba*; (b) snailseed vine, *Cocculus trilobus*; (c) paper mulberry, *Broussonetia papyrifera*; (d) Chinese mulberry, *Morus australis* (syn. *M. bombycis*); (e) Ming note BL ORB 40/862; and (f) Ming note BM CIB,EA.264

microscope's 'quick depth' composition function that scans across the focal range for each pixel in the image and compiles a fully focused image for the region of the note being examined; 3D visualizations of some surface inclusions were constructed using the focal position data collected by this depth composition function.

While stereomicroscopes have a relatively good depth of field and can provide images that are helpful in determining the exact location of features, they have a much lower magnification limit than compound microscopes. In contrast, the inability to focus on targets with irregular surfaces is one of the major drawbacks of optical microscopy. In this study, the Keyence VHX 2000 combines the advantages and capabilities of both a conventional stereomicroscope and a compound microscope, the main additional benefit being that it is possible to inspect and measure the object from any angle due to its very large depth of field.

Scanning electron microscopy

Examination of the samples and comparative reference specimens was undertaken in the Hitachi S-3700N variable pressure scanning electron microscope (VP SEM) using the backscatter electron (BSE) detector, mostly at 12 kV but sometimes also at 10 or 15 kV, depending on the sample. The magnification ranged from ×25 to ×1500, while the preferred working distance was *c.*12 mm, although it was varied from 9.2 to 23.5 mm as required. As the samples were in various states of preservation, the SEM chamber was only partially evacuated, usually to 40 or sometimes 50 Pa. The BSE detector was used in 3D mode, in preference to Compositional mode, to maximize the opportunity to reveal diagnostic features for identification, as well as to highlight traces of wear and abrasion due to preparation and/or use, and also to show dirt, encrustations and fungal hyphae. The Oxford Instruments energy dispersive X-ray (EDX) analyser attached to the SEM was used to provide elemental identification and semi-quantitative compositional information where necessary, for example to determine whether crystals and inclusions were calcium oxalate or silica, as discussed below.

Most of the material examined was placed, uncoated, on adhesive carbon discs mounted onto aluminium SEM stubs; no other sample preparation was required. At a later stage, in an attempt to achieve greater clarity of information from material that was highly deteriorated, selected samples were sputter-coated with a platinum/palladium alloy (using a Cressington 208 HR sputter coater) to prevent charging by the electron beam in conventional SEM mode using the secondary electron (SE) detector at high vacuum.

Results

In describing the material in these Ming notes, it is worth noting that while, in plant anatomy, the term 'fibre' refers to a particular type of long, narrow cell in the bark and xylem that has the function of support, the term has been used more generally in the literature, which can be confusing. The term 'fibre' has been used throughout this article, even when the plant cells seen during examination include adjacent cells, including sclerenchyma cells (such as sclereids), parenchyma, collenchyma (from the cortex), phloem (from the innermost bark layer) and xylem (including tracheids and vessels). On those occasions when the fibre cells themselves have been extracted, adjacent cells (particularly parenchyma) often leave imprints or vestiges of their distinctly shaped cell walls on the surface of these fibre cells, which can sometimes appear to represent taxonomically diagnostic features. Accordingly, care must be taken not to base fibre identification on such vestiges.

Digital microscopy

Ming dynasty paper money is soft and loose-textured with fibres presenting in three main categories: a general fibre mass, loose surface-bound fibres, and partially or completely unprocessed fibre bundles, Figure 3. These categories sometimes contain synthetic fibres from conservation or contamination from handling in recent times.

The main mass fibres are a dull grey colour with no overall preferential orientation, Figure 1b. They provide a flat and monotone surface against which the more prominent features of loose fibres and fibre aggregates are apparent. Fibres that have become loose or detached from the main mass are often found to be self-entangled, Figure 3a. The vulnerability to loss and/or dissociation of these loosened fibres from the note depends on the proportion of the fibre that remains attached to the main mass. Bundles of co-aligned fibres range in length from several millimetres to over a centimetre and sometimes appear twisted and rolled, Figures 3b–3d. These bundles typically have a higher density of fibres than the loose entangled clusters.

Fragmented material, possibly periderm, presents as detrital surface features that are deeply embedded in, partially entangled within, or sitting over the main fibre mass, Figure 4. Fragments are distinguished from the general fibre mass by their different colour and larger size. In addition, when imaged, they appear in a different focal plane to that of the main fibre mass, allowing 3D depth maps to be generated. A colour height profile of a fragment in one of the British Museum notes (1942,0805.1: Figures 4e–4f), shows a *c.*180 μm protrusion from the main fibre mass. Fragments consist of wood bark (Figures 4a, 4b, 4d and 4e), and plant shoots, stalks or stems, Figure 4c. These fragments are dispersed throughout the note with random orientation and cell patterns are visible on most fragments.

The identification of the pigments found on the notes using Raman or XRF spectrometry was outside the scope of this phase of the project. Previous work on similar notes has identified the black pigment as amorphous carbon from soot and the red pigment as red lead (or minium, Pb_3O_4) [8]. The manner in which the black pigment used for the main note text adheres to the substrate differs between the fibres and fragments. For the fibres in regions of text, the black pigment appears to be well bound and only to coat the fibre surface. In some locations where there was no text, fibres entirely coated with black pigment were observed, Figure 5a. In contrast, the black pigment was found to have seeped into fragments (Figure 5b) although it did not penetrate through fragments into underlying fibres. The red pigment used for impressing seals was observed on both the main mass fibres and over regions of black text. Larger white particles were also found within the red areas, Figure 5c. The red pigment was not as well bound as the black with separate, individual particles distributed over the area in which the seal was impressed,

Table 2. Identifications of selected sampled Ming dynasty notes in the British Museum (BM) and British Library (BL) collections

Collection	Registration No.	*Broussonetia papyrifera*, paper mulberry	*Morus alba*, white mulberry	*Morus australis*, Chinese mulberry	Bambuseae tribe, bamboos	*Hibiscus mutabilis*, hibiscus/cotton rosemallow	*Oryza sativa*, rice	*Triticum* sp., wheat	*Cannabis sativa*, hemp
BM	1913,1011.30	✓	✓	✓	✓	✓			✓
BM	1942,0805.1	✓	✓						✓
BM	OR.9730	✓	✓	✓	✓				✓
BM	CIB,EA.260	✓	✓	✓	✓				✓
BM	CIB,EA.261	✓	✓			✓			
BM	CIB,EA.262	✓	✓			✓			
BM	CIB,EA.263	✓	✓					✓	
BM	CIB,EA.264	✓	✓	✓	✓	✓	✓	✓	✓
BM	CIB,EA.265	✓	✓	✓	✓				✓
BL	ORB 40/862	✓	✓	✓	✓				✓
BL	ORB 40/863	✓	✓						✓

Figure 5d. The intensity of the pigment varied with density of application, but the key feature was that the particles were located between the fibres rather than coating them as observed with the black pigment.

Digital microscopy of reference material revealed that, when viewed at magnifications of ×20 to ×200, the colour and cell distribution of the various components were similar. Even at ×200 magnification, certain taxa were indistinguishable with no specific characteristic features apparent, Figures 6a–6d. Similar cell surface patterns to those found on the reference material were observed in both the British Library and British Museum notes, Figures 6e and 6f.

Scanning electron microscopy

From the outset of the VP SEM examination, it was obvious that a complex array of different types of fibres (and other plant cells) was present in the samples taken from the original British Museum Ming notes listed in Table 1 and from two of the British Library examples. As these tiny samples were removed from a single specific location on each note, the identifications presented in Table 2 cannot be seen as being representative of all the fibre types used for the manufacture of this paper money. It also means that the identified taxa in Table 2 cannot be presented quantitatively or even semi-quantitatively, so that only their presence or absence has been noted.

Table 2 shows that while fibres from paper mulberry (Figure 7a: BL ORB 40/863 and Figure 7b: BM 1942,0805.1), white mulberry (Figure 7c: BM CIB,EA.265) and Chinese mulberry (Figure 7d: BM OR.9730) were used for the original Ming notes, many different types of fibres and other plant cells were also present, including bamboo (Figure 8a: BM 1913,1011.30), hibiscus (Figure 8b: BM CIB,EA.262), rice straw (Figures 9a–9b: BM CIB,EA.264), wheat straw and hemp (all identified by comparison with reference collection specimens, mostly from China and Japan). Although the British Museum's Ming note reproduction and the four later forgeries were also examined and imaged in the VP SEM, the results are not presented or described here.

Discussion

Digital microscopy

The presence of fibres (used in the general sense) in three broad forms (main fibre mass, loose surface-bound fibres and partially or completely unprocessed fibre bundles) indicates that the extent of processing during papermaking was varied and incomplete. Large bundles of co-aligned fibres appear entirely unprocessed. The presence of large plant stem and bark fragments with intact cells is an indicator that the beating process either did not last very long or was not sufficiently intensive to break up larger material. The lack of a particular orientation for the fibres and the random distribution of fragments suggest that the pulp, although not beaten to a great extent, was well mixed. There has been some suggestion that the variety of raw materials present and their apparent under-processed nature was part of an approach used to reduce the possibility of replication and forgery [7].

Individual fibres coated with black pigment, but found in regions where there is no text, suggest that the fibres can become loose but are not immediately susceptible to loss. The mechanical properties of a sheet of paper depend on the distribution of orientations of the cellulosic fibres, and paper made by the pulp screening process has a random arrangement of main mass fibres. Loose surface fibres on these notes appear to have moved, perhaps as a result of handling or storage, across

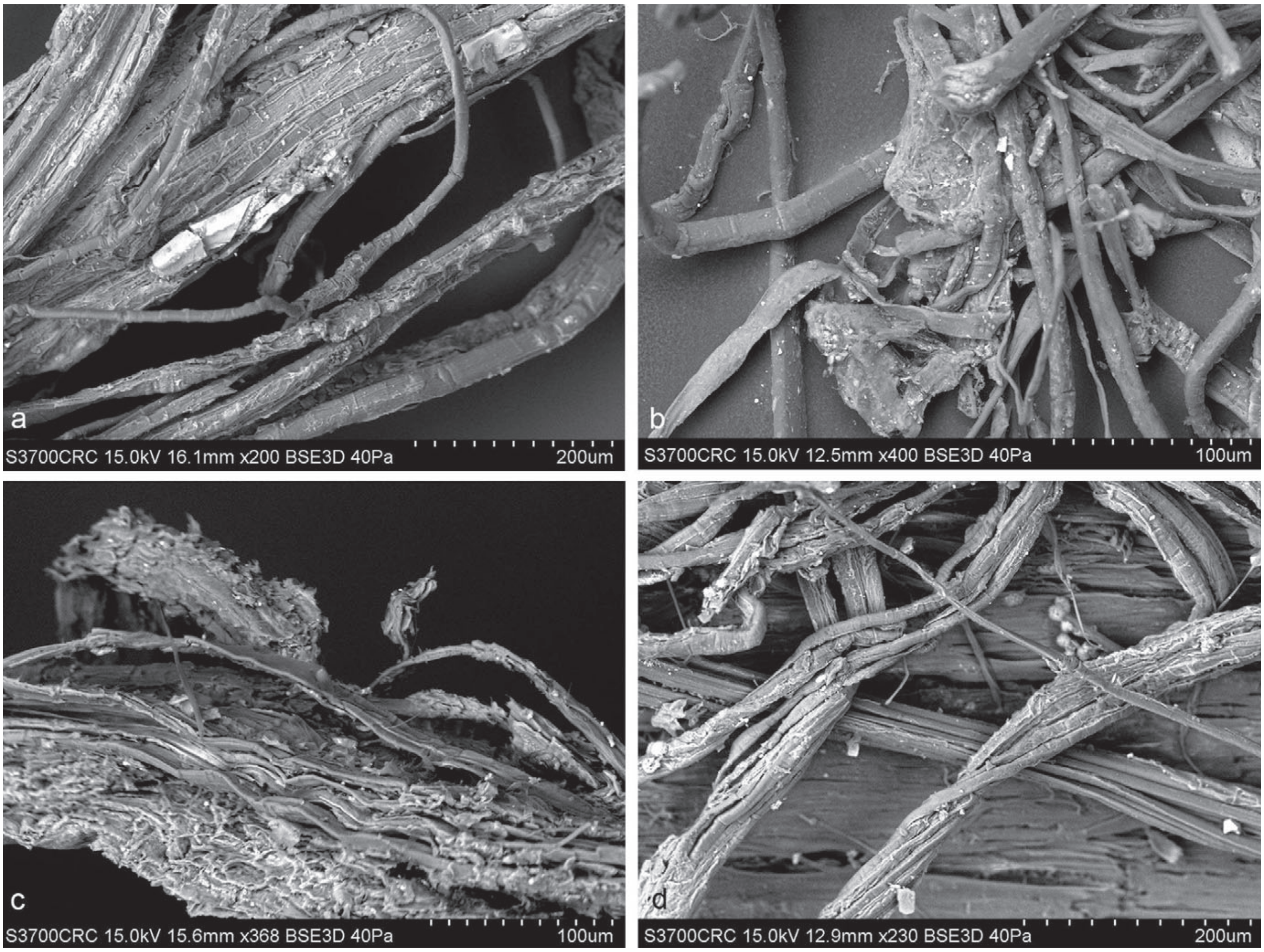

Figure 7. VP SEM images of fibres and other plant cells from the Ming notes: (a) paper mulberry, *Broussonetia papyrifera* from BL ORB 40/863; (b) paper mulberry from BM 1942,0805.1; (c) white mulberry, *Morus alba* from BM CIB,EA.265; and (d) Chinese mulberry, *Morus australis* from BM OR.9730

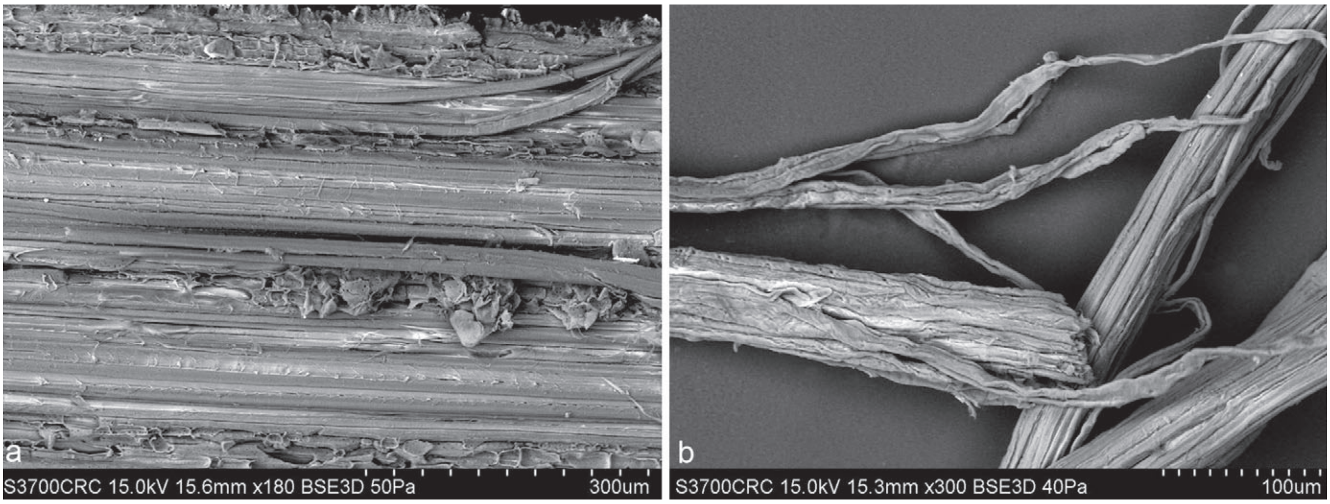

Figure 8. VP SEM images of fibres and other plant cells from the Ming notes: (a) bamboo (Bambuseae tribe) from BM 1913,1011.30; and (b) hibiscus, *Hibiscus mutabilis* from BM CIB,EA.262

the surface of the note in multiple directions; the same phenomenon was observed for the large bundles, which appear to have rolled across the surface. These migratory tendencies make it plausible that fibres from other sources, unrelated to the Ming dynasty notes, have found their way onto the paper money either during the papermaking process, where other papers were being manufactured, or during storage near other materials in their later history. Of greater concern is the detachment of fragments that often contain large areas of black pigment; if lost, there is a significant reduction in the legibility of the text.

The particle size, structure and surface chemistry of the carbon black pigment have ensured its absorbance into the pulped fibres, resulting in good overall legibility. In contrast,

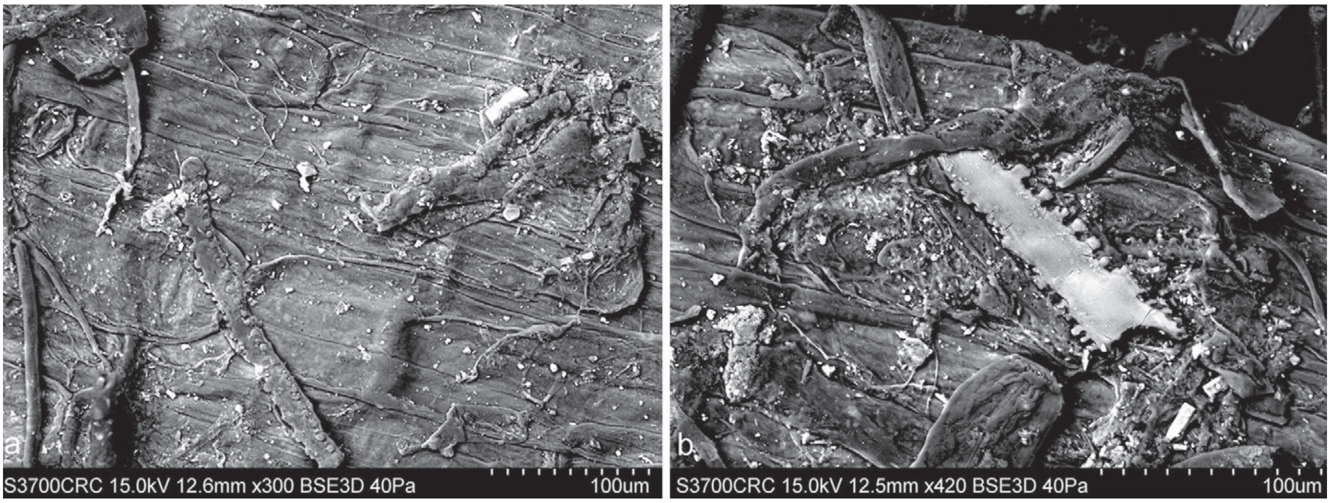

Figure 9. VP SEM images of fibres and other plant cells from the Ming notes: rice straw, *Oryza sativa*; paper mulberry, *Broussonetia papyrifera*; white mulberry, *Morus alba*; Chinese mulberry, *Morus australis*; bamboo (Bambuseae tribe); hibiscus, *Hibiscus mutabilis*; wheat straw, *Triticum* sp.; and hemp, *Cannabis sativa* from BM CIB,EA.264

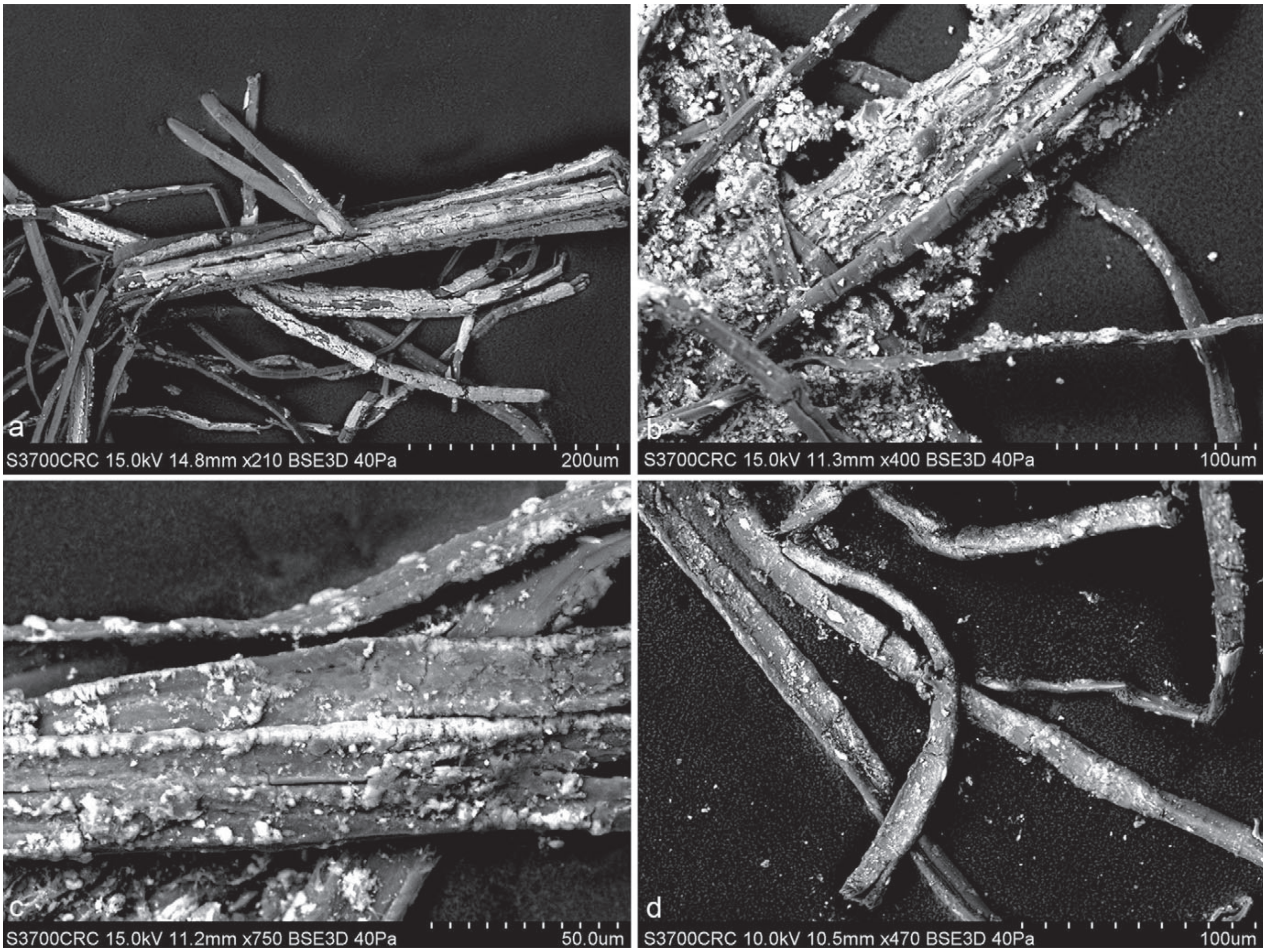

Figure 10. VP SEM images of fibres and other plant cells from the Ming notes: (a) encrustation on BL ORB 40/862; (b) encrustation on BM CIB,EA.260; (c) abrasion, wear and deterioration on BM CIB,EA.263; and (d) abrasion, wear and deterioration on BM OR.9730

the less well bound, more particulate red pigment does not coat the pulped fibres as readily, a consequence of which is that its legibility is reduced, even where it is impressed over regions of black pigment.

Very many notes were issued for general circulation during the Ming dynasty in a variety of denominations. Historical records refer to discrepancies in value between worn and new notes, to the exchange of worn notes for new and to the increasingly low value of Ming paper money. As today, it is likely that notes became worn through use and this may account for some looseness of fibres.

A comparison of reference material images using digital microscopy showed that at high magnification, common colour and cell distributions pervaded all taxa, which could be misleading for identification purposes; insufficient individual characteristic features were found at magnifications of ×20 to ×200 to indicate a particular taxon. The comparison of digital microscopy images of reference material with those of materials observed in the notes was thus inconclusive for identification purposes. This is generally the case when attempting to compare images from clean, modern fibres in printed and online fibre atlases with those in objects that have experienced a long history of processing, handling and ageing [9].

Scanning electron microscopy

Identification to taxon (i.e. to genus or genus plus species) was possible through the VP SEM examination of samples from the Ming notes. This technique revealed much key information, captured in a large archive of SEM images, of which only a small selection has been included here, Figures 7–10. A single SEM view was insufficient to characterize each sample or even each fibre type; between 10 and 30 SEM images were captured per sample. Some taxa, notably paper mulberry (*Broussonetia papyrifera*) comprise cells (see Figure 7b), which could appear to the inexperienced eye to be very similar to the flat, ribbon-like fibres of cotton (*Gossypium* sp.). Identification to taxon therefore required specialist expertise in plant fibre identification and was only possible where sufficient diagnostic features were present, and when these features were not camouflaged or compromised by fungal hyphae, dirt, pigments, encrustation or deterioration. Loose or displaced surface fibres were ignored as their age and association with the notes were uncertain, see above.

When identifying plant tissue, caution needs to be exercised not to rely on a single recognisable feature associated with plant cells, such as crystals. The presence of silica (silicon dioxide) and calcium compounds in plants has long been of interest to plant scientists, but the subject is complex, not least because the presence of both calcium compounds and silica in plant tissue is directly related to the chemical composition of the soil in which the plant is growing and the rate at which the plant may take up these materials. Nonetheless, many plant scientists and wood anatomists have paid attention to the presence and form (morphology) of silica bodies and calcium oxalate crystals in samples during the process of identification. For example, phytoliths, which are composed mainly of silica, can be representative of some plant families and their particular morphology can sometimes even allow identification to genus level [10]. Calcium oxalate crystals, whether prismatic in form (Figures 2a and 7a) or druses (Figure 2d), styloids or raphides, may be useful in characterizing some plant families [11]. Such crystals are mostly found in axial or ray parenchyma cells, not fibre cells. But the presence or absence of calcium oxalate crystals and/or silica bodies such as phytoliths should not be used alone as a prime identification criterion, but with discretion, in conjunction with key cellular anatomical features.

Taking the decision to examine most of the samples in the VP SEM without first cleaning and preparing them (for example, by obtaining casts or by thin-sectioning, embedding in resin and polishing) has yielded significant additional information about the condition of the fibres. Many display encrustation (Figures 10a and 10b), inactive fungal hyphae, loose particles of pigment, ink or dirt, abrasion, wear and deterioration, Figures 10c and 10d. Such information is useful for a number of reasons: it adds to the body of knowledge about the effects of processing fibres for papermaking and the use and storage of the completed notes. It can also inform active conservation and care of these objects in museum collections.

The presence in Ming notes of different fibres and plant cells from taxa other than white mulberry, paper mulberry or Chinese mulberry was noted in a letter from Thomas Rost of the Department of Botany at the University of California, Davis to Thomas Leech at the San Miguel paper workshop in Colorado Springs on 23 June 1986 [12]. The quantity of *Broussonetia papyrifera*, *Broussonetia kazinoki*, *Morus alba* or *Morus australis* fibres (or combinations of them) that needed to be included in the manufacture of Ming notes for them to be deemed to conform to required standards is not clear at this point and needs to be researched more fully. From the results of this study, it would seem that none of the Ming notes examined from the British Museum and the British Library contained single taxon fibres, for example solely paper mulberry, white mulberry or Chinese mulberry. The VP SEM results, while not indicative of the relative proportions of different taxa present, testify to an incontrovertible fact: all the Ming notes examined have fibres and other plant cells from more than two different plants/trees.

Further research is needed before it can be established whether the combined results show that the paper money was made of recycled materials, which may (or may not) explain the presence of black pigment on areas that were not printed, and why some plant materials are present more frequently than others. At this stage of the project there is no evidence to suggest that these notes are anything but Ming dynasty and thus date from the late fourteenth to the early fifteenth century.

Conclusions

Paper is manufactured from raw materials whose properties have been changed by maceration or disintegration, making their identification difficult. Ming dynasty notes display a wide variety of materials including fibres in isolation and in bundles on top of a main interwoven fibre mass. The presence of large fibre bundles and fragments of bark and stem indicate that the raw materials were not intensively processed during the papermaking stage; processes that would have included pounding, boiling and beating typically weaken bundle structures and result in a limited range of fibre sizes.

Pigment loss leading to illegibility is more associated with fragment loss than fibre loss, due to the preferential adhesion of the black pigment to bark and plant stems. Stand-alone digital microscopy has shown that the red seal was marked on the note later than the black text.

The lacklustre and diminished appearance of the red pigment seal is probably due to the production of galena lead(II) sulphide (PbS), the degradation product of red lead, which is present here in a poorly bound, particulate form [13].

Despite fully examining a range of reference material from China and Japan, digital microscopy at magnifications in the range ×20 to ×200 revealed that insufficient diagnostic features could be found to differentiate taxa; thus, the images obtained by this method should only be used at the very first level of fibre analysis. Finer differences are observable on chemically stained samples using an optical microscope with transmitted and polarized light, but introducing stains to the object is not permissible, rendering *in situ* microscopy impossible. Results from optical and digital microscopes are still significantly inferior and unreliable when compared to those achieved using VP SEM, although samples are required for this procedure as the notes are too large to be examined in the SEM chamber.

The results of the VP SEM examination showed clearly that while white mulberry and paper mulberry had been used in the manufacture of the Ming notes in the British Museum and British Library collections, many other raw material sources had also been exploited, such as bamboo, rice straw, wheat straw, hibiscus and hemp. As these notes were hitherto believed to be made from mulberry bark (taxon unspecified), these results have important implications and provide a reference point for ongoing research by specialist scholars from which new and challenging avenues of interest are expected to emerge. The results have provided unprecedented data for Ming dynasty papermaking, which are of immediate relevance to historians of Ming dynasty painting, book production and printmaking. Also, in the light of the results, the historical literature needs to be revisited, particularly in relation to the control of the production of paper money.

Acknowledgements

The authors first shared the results of their investigations into Ming notes in the British Museum and British Library collections at the Ming Banknote Workshop at the British Museum on 23 May 2013. They would like to thank those who attended the workshop, shared their own research and joined in the discussion. They also thank the former Curator of Chinese Collections at the British Library, Dr Frances Wood, for her expertise and for help accessing the collection.

Authors

Caroline R. Cartwright (ccartwright@thebritishmuseum.ac.uk) is a scientist in the Department of Conservation and Scientific Research and Helen Wang (hwang@thebritishmuseum.ac.uk) curator of East Asian money in the Department of Coins and Medals, both at the British Museum. Christina M. Duffy (christina.duffy@bl.uk) is the imaging scientist in the Conservation Science and Research Team at the British Library.

References

1. MacGregor, N., *A history of the world in 100 objects*, Allen Lane, London (2010).
2. von Glahn, R., *Fountain of fortune: money and monetary policy in China, 1000–1700*, University of California Press, Los Angeles (1996).
3. von Glahn, R., 'The origins of paper money in China', in *The origins of value: the financial innovations that created modern capital markets*, ed. W.N. Goetzmann and K.G. Rouwenhorst, Oxford University Press, New York (2005) 65–90.
4. Peng, Xinwei (translated E.H. Kaplan), *A monetary history of China*, 2 vols, Center for East Asian Studies, Western Washington University, Bellingham (1993) [Chinese title: *Zhongguo huobi shi* (3rd edn, 1965)].
5. Hucker, C.O., 'Ming government', in *The Cambridge history of China. Volume 8: The Ming dynasty 1368–1644, Part 2*, ed. D.C. Twitchett and F.W. Mote, Cambridge University Press, Cambridge (1998) 9–105.
6. Hunter, D., *Papermaking: the history and technique of an ancient craft*, Dover Publications, New York (1978) 201–223.
7. Tsien, T.H., *Science and civilization in China. Volume 5: Chemistry and chemical technology: part I, paper and printing*, ed. J. Needham, Cambridge University Press, Cambridge (1985).
8. Shi, J-l. and Li, T., 'Technical investigations of 15th and 19th century Chinese paper currencies: fiber use and pigment identification', *Journal of Raman Spectroscopy* 44 (2013) 892–898.
9. Cartwright, C.R. and King, J.C.H., 'Identification of hairs and fibres in Great Lakes objects from the eighteenth and nineteenth centuries using variable pressure scanning electron microscopy', *British Museum Technical Research Bulletin* 6 (2012) 69–81.
10. Piperno, D.R., *Phytoliths: a comprehensive guide for archaeologists and paleoecologists*, AltaMira Press, San Diego (2006).
11. Prychid, C.J. and Rudall, P.J., 'Calcium oxalate crystals in monocotyledons: a review of their structure and systematics', *Annals of Botany* 84 (1999) 725–739.
12. Thomas Leech, San Miguel paper workshop, Colorado Springs, personal communication (2 January 2014).
13. Miguel, C., Claro, A., Gonçalves, A.P., Muralha, V.S.F. and Melo, M.J., 'A study on red lead degradation in a Medieval manuscript *Lorvão Apocalypse* (1189)', *Journal of Raman Spectroscopy* 40 (2009) 1966–1973.