Journal Pre-proofs

Degradation of polymer banknotes through handling, and effect on fingermark visualisation

B.J. Jones, J.W. Cammidge, C. Evan, G. Scott, P.B. Sherriffs, F. Breen, P.M.B. Andersen, K.T. Popov, J. O'Hara

PII:	S1355-0306(22)00107-1
DOI:	https://doi.org/10.1016/j.scijus.2022.08.007
Reference:	SCIJUS 1070
To appear in:	*Science & Justice*
Received Date:	10 March 2022
Revised Date:	12 July 2022
Accepted Date:	29 August 2022

Please cite this article as: B.J. Jones, J.W. Cammidge, C. Evan, G. Scott, P.B. Sherriffs, F. Breen, P.M.B. Andersen, K.T. Popov, J. O'Hara, Degradation of polymer banknotes through handling, and effect on fingermark visualisation, *Science & Justice* (2022), doi: https://doi.org/10.1016/j.scijus.2022.08.007

Degradation of polymer banknotes through handling, and effect on fingermark visualisation

B.J.Jones[1,2,3], J.W. Cammidge[1], C. Evans[2,4], G. Scott[2], P.B. Sherriffs[2], F. Breen[2,5], P.M.B. Andersen[2], K.T.Popov[2], J.O'Hara[6]

1. School of Applied Sciences, University of Huddersfield, HD1 3DH, UK
2. Psychology & Forensic Science, School of Applied Sciences, Abertay University, Dundee, DD1 1HG, UK
3. School of Materials, University of Manchester, M13 9PL, UK
4. Law, School of Social Science, University of Dundee, DD1 4HN
5. Key Forensic Services Ltd., Coventry, West Midlands, CV4 7EZ, UK
6. West Yorkshire Police, Yorkshire and the Humber Regional Scientific Support Services, Calder Park, Wakefield, WF2 7BJ

Acknowledgements

Thanks to Clydesdale Bank for facilitating supply of samples, Dr Della Wilkinson for early discussions, Dr Arne Jansson for technical support, Shannon Gibson for additional exploratory work, and Dr Kevin Farrugia for early discussions of the text. This work has been part-funded by the Scottish Institute for Policing Research as part of the Future of Policing grant scheme, SIPR: FOP-21-06.

Author Contributions

BJJ: Conceptualization, investigation, resources, formal analysis, supervision, visualization, writing; JWC: Investigation (study 1), writing – original draft; CE, GS: Investigation (study 2), writing – original draft; CE & GS contributed equally to this work; PBS: Formal Analysis, writing – review; FB: Formal Analysis; KTP: writing – review; PMBA: Investigation (AFM), writing – review; JO'H: Resources, investigation (study 1).

Degradation of polymer banknotes through handling, and effect on fingermark visualisation

Highlights

1. Vacuum metal deposition is the optimum method for fingermarks on handled banknotes
2. Performance of each fingermark visualisation technique varies with issuing bank
3. Handling of polymer banknotes causes surface cracking and degradation of printing

Degradation of polymer banknotes through handling, and effect on fingermark visualisation

Abstract

The surface structure of mint (as-issued) and handled polymer five pounds sterling banknotes was studied by atomic force microscopy and laser scanning confocal microscopy. A total of 1856 fingermarks on mint and handled banknotes from four different issuing banks (Bank of England, Bank of Scotland, Royal Bank of Scotland and Clydesdale Bank) were visualised with Vacuum Metal Deposition (VMD), Cyanoacrylate Fuming (CAF) and, on Clydesdale Bank notes, magnetic fluorescent powder. VMD was significantly more effective in developing fingermarks on handled banknotes, across all the banks studied, although effectiveness varied with issuing bank. For example, on handled Bank of England notes 45% of marks showed ridge detail with VMD development and 28% with CAF; for Bank of Scotland handled notes success rates were 17% with VMD and 1% with CAF. Microscopy of degraded banknotes showed the loss of intaglio printing and the formation of a cracked surface structure in the handled notes. These features can lead to the trapping of powder, or contaminants, increasing quantity of development agent in fingermark background

between the ridges, decreasing contrast and decreasing performance of powder-based fingermark development techniques. These same features can restrict the migration of

material and thus reducing potential formation of empty prints, so that VMD development is not adversely affected.

Keywords

Banknote; Latent fingerprints; Currency Bills; Vacuum Metal Deposition; Cyanoacrylate; Surface Structure

Highlights

4. Vacuum metal deposition is the optimum method for fingermarks on handled banknotes
5. Performance of each fingermark visualisation technique varies with issuing bank
6. Handling of polymer banknotes causes surface cracking and degradation of printing

1. Introduction

In the field of forensic fingermark detection the development of fingermarks on polymer banknotes is evolving, as the number and types of circulating polymer banknotes increase. Launching polymer banknotes in 1988, The Reserve Bank of Australia released a new series of polymer banknotes during 2016-2020 with new designs and enhanced security features. The Bank of Canada launched a new series of polymer notes over 2011-2013, with additional issues of commemorative notes in 2015-2018. The UK had an extended process of switching from ‘paper’ to polymer banknotes with staggered release during 2015-2021 with examples of both types currently in circulation in 2015-2022. Unusually, in the UK in addition to the Central Bank (The Bank of England) some commercial banks are authorised to issue banknotes. In Scotland circulating notes are primarily issued by four banks, which have been converting to polymer notes over this period with a staggered release of a new issue; designs and release dates vary with denomination, issue and issuing bank. Polymer banknotes are designed to last two-and-a-half times longer than previous materials, and

[1-3].

Fingermarks (or latent fingerprints) and their visualisation are strongly affected by the donor, the ageing of the mark, and by the substrate [4-10]. The choice of methodology for visualising the deposited mark is informed by the nature of the substrate, usually classified as porous, semi-porous or non-porous. “Paper” banknotes are porous and techniques such as amino acid stains, for example ninhydrin, may be optimal. Polymers are non-porous (or in some cases, semi-porous) and further consideration of the substrate is needed. In the case of polymer banknotes the substrate includes the type of the polymer itself, the pigmentation, lacquering, intaglio (raised) printing and surface texture, as well as some additional security features. Therefore, the polymer banknote surface provides a new set of challenges, and the behaviour of deposited fingermarks and development processes may not always be transferable between different issuing banks, or even different designs of notes. The importance of surface properties for fingermark development quality was highlighted in a study of counterfeit paper US dollar bills [11] which were tested for fingermarks using the standard techniques used for paper banknotes; however, due to the nature of the counterfeit sample notes the standard techniques were unsuccessful due to the effects of the differing surface. Other studies have variation in efficacy of development, and in the optimum choice of technique, among the different surfaces within a single classification such as light polymer, thermal paper or adhesive tape [4,5,8,9,10,12,13].

1.1 Surface texture

The effect of polymer substrate texture on a fingermark and its subsequent development has been discussed by Jones et al [5]. The research investigated three different polymeric surfaces, classified as “smooth, light coloured” leading to the same recommended treatment processes through reference to the UK Home Office Centre for Applied Science and Technology (CAST) manual [6]. Atomic Force Microscopy (AFM) images of the virgin surfaces were used to assess the texture and Scanning Electron Microscopy (SEM) images of the surface with developed fingermarks showed how the surface characteristics affected the mark visualisation. In addition to the numerical magnitude of the surface roughness, classified for example with R_a values, it was seen that the shape of the features, characterised by kurtosis and skewness, as well ‘lay’ of the surface, which is the direction of linear features such as ridges and scratches, had a significant effect on the development of fingermarks. This may be due to the migration of deposited fingermark material, which is affected by substrate texture and surface energy [7] or by interaction with the developing agent for example trapping applied powders [5]. This links to the topography of polymer banknotes due to the variability of the surface including the polymer, security features and intaglio printing.

1.2 Polymer and additives

Studies into the influence of polymer type on the quality of marks developed using gold/zinc Vacuum Metal Deposition (VMD) varied the quantity of gold and precursor treatments [8,9]. Five different polymers were examined and there was no single optimal condition that was effective across all of the polymers used, or even for two substrates with the same polymer base layer. Bacon et al. [10] showed variability in fingermark development on light coloured polymers related to differences in type and local concentration of surface and sub-surface pigment, with proximity of titania based pigmentation increasing adherence of fingerprint

In addition to variation in development efficacy between issuing banks, these findings could elucidate differences in fingermark behaviour or development of fingermarks across a banknote. This may be due to the difference between a clear or opaque section of a note, integration of surface and sub-surface security features, or two printed areas with different structures caused by the pigmentation.

1.3 Developing fingermarks on polymer banknotes

Various techniques, including vacuum metal deposition (VMD), cyanoacrylate fuming (CAF), powders and powder suspensions, have been found to work with differing degrees of success on several polymer banknotes [14-20].

Studies on the detection of fingermarks on Canadian polymer banknotes [15,16] focused on determining the most suitable sequential process for the development of latent fingermarks. The work recommended a combination of CAF, VMD and dye staining; VMD has been shown to enhance CAF development through nanodecoration improving contrast [21], as well as increase fingermark detection.

Other studies have investigated the use of copper VMD as well as IR and near-IR active powders to remove background interference from polymer banknotes [8,18,19]. An extensive study by CAST provided an initial insight for the development of latent fingermarks on the Bank of England £5 polymer banknote [20] although only examined mint, uncirculated notes; an iron oxide based powder suspension is now routinely used. In spite of the tendency of textured surfaces with negative skewness to capture powders thus reducing fingermark contrast [5], fluorescent powders have been shown to be effective on

[22]. Work investigating the enhancement of marks on mint £5 and £10 polymer notes from Clydesdale Bank and Royal Bank of Scotland found that a CAF process of PolyCyano UV followed by black magnetic powder was the most effective series of processes and this is now being implemented on these notes in Scotland [17]. This was conducted on a relatively small sample size of only three people, therefore the inter-donor variability could have an impact on the wider interpretation of these results [23].

Crucially, these studies so far are on mint, or uncirculated notes. Work on polymer banknotes in Israel showed that the recommended protocols for enhancing marks only enhanced 4 latent marks on 224 circulated banknotes [14]. Work on polymer structure shows light mechanical action can damage the surface and alter the surface roughness [24]. A surface roughness increase can negatively affect the efficacy of fingermark development processes, particularly powder-based processes [5], and influences the spreading of the fingermark over the surface [7].

We examine both new and handled notes from four banks that have been converting to polymer notes with a new issue over a period of time, we have used this as an opportunity to compare the development of fingermarks on notes across banks, using a range of techniques such as VMD, CAF and Green Fluorescent Magnetic Powder (GFMP). The development efficacy is then related to the surface properties.

2. Methodology

2.1 Banknotes and Degradation

As-issued banknotes were supplied by, or sourced from, Clydesdale Bank (CB), Royal Bank of

Scotland (RBS), Bank of Scotland (BoS) and Bank of England (BoE) at or close to time of first issue. Notes were used as supplied ('mint') or were subjected to a light manual handling regime of approximately 2 minutes as a proxy for standard circulation of folding and crumpling ('handled'). No additional cleaning method was conducted; mint banknotes may have some cashier handling, although extra care was requested this was not monitored. Additional notes were subjected to extended repeated manual handling to mimic end-of-life state, with five repeats of the light handling process and storage on user in between process iterations.

Laser Scanning Confocal Microscopy (LSCM, Keyence VK-X200) was utilised to image five areas of the mint and the end-of-life banknotes. The LSCM has a minimal step of 10 nm between two adjacent focal plane scans which determine the Z-resolution. Atomic Force Microscopy (AFM, JPK Nanowizard III) was used to examine mint and handled banknotes. Silicon probes of resonant frequency approximately 300kHz were used in intermittent (tapping) mode, in air. Texture analysis enabled calculation of feature dimensions, as well as parameters such as average roughness, skewness and kurtosis as shown elsewhere [5].

The size of the fingermarks (~1 cm) is needfully different from that of areas of examination for surface texture by LSCM (~1 mm) or AFM (~100 µm). A fingermark may cover a range of different substrate surfaces which may affect the overall quality of developed ridges.

2.2 Fingermark study 1 Clydesdale Bank comparison of VMD and GFMP development

Prior to deposition of fingermarks, twenty Clydesdale Bank notes were subjected to a light

manual handling regime ("handled") by one person, as detailed in "degradation study" above. A further twenty were used as supplied ("mint"). See appendix A.1 for nomenclature.

A total of 320 natural fingermarks (those where the sebaceous secretions were not artificially increased through a grooming process) were deposited by 80 donation events by 76 individual donors over a two-day period. No instructions were given to donors except to request that they had not washed their hands for a period of 30 minutes prior to donation, aligned with the Home Office guidelines [25] and as used in other research for natural latent prints [4,5,13,21]. However, donor compliance was not monitored. Donors were limited to one donation per day. Banknotes were not physically cut or marked for deposition of fingermarks but were virtually divided into eight octants, in two rows of four (upper row labelled as A-D and lower row E-H), for ease of deposition and reference. The front (obverse) of the notes only was used. Donors deposited four marks, one from each of left and right index and middle fingers, onto individual octants of the supplied banknotes each donor placing latent marks onto two octants of a mint note and the matching octants of a handled note.

Notes were stored, lightly covered, in ambient conditions for a period of 11 – 13 days. Ten mint and ten handled notes were developed with vacuum metal deposition (VMD360, West Technologies Ltd) with standard gold-zinc procedure as applied by West Yorkshire Police and outlined elsewhere [12,21]. The remaining set of notes was developed with green fluorescent magnetic powder (GFMP, CSI Equipment UK) according to standard powdering methods. Marks were illuminated with white light and no viewing filter for VMD and UV / Blue light (340-413nm / 400-469nm) with a viewing filter (415nm / 476nm) for powder;

were developed with red fluorescent magnetic powder, with some successful marks but the visualisation with green was preferred by the grader; however, this may be related to physiology rather than technique performance, as seen in other comparison studies [22].

2.3 Fingermark study 2 Interbank comparison of VMD and CAF treatment

Twenty-four notes from each of Clydesdale Bank, Royal Bank of Scotland (RBS), Bank of Scotland (BoS) and Bank of England (BoE) were treated as supplied ('mint') and a similar set were subjected to a light manual handling regime ('handled') by two persons, as detailed in 'degradation study' above.

A total of 1536 fingermarks were used for this study. An approximately even mix of male and female donors, between the ages of 20-60 were asked to deposit natural fingermarks after having not washed their hands for at least 30 minutes prior to donating marks. To ensure an even distribution of secretions across the hands, donors were requested to rub their hands together and to then deposit marks using firm even pressure. Each collection of donated marks used sixteen donors, and sixteen notes (one of each condition from each bank for each development technique). The front (obverse) of the notes only was used. Each donor was attributed a specific area of handled or mint notes during each donation day, and a different finger was used between each note and each donor per donation day. This meant that each note would contain marks from eight different donors and eight different fingers, which were comparable among the eight different notes. The position on the note and finger used on each note was changed for each donor over a 10-week period

All banknotes with fingermark deposits were stored for eight days between donations and processing days. After donations, notes were lightly covered, deposit side-up and stored at room temperature before being processed. Half of the set of notes was treated with VMD and half with cyanoacrylate fuming and basic yellow 40 dye (CAF-BY40).

For cyanoacrylate fuming a CA30 chamber (Air Science) was used with 2 g of cyanoacrylate (Orapi 601). The humidity of the chamber was set to 80 % and after the chamber had reached this level of humidity, notes remained inside for a total of 45 minutes. After each run in the chamber the boat was measured to ensure that at least 90 % of the cyanoacrylate had evaporated. Once notes had been processed using CAF, they were dipped in a solution of Basic Yellow 40 dye (BY40) was prepared by dissolving 2g BY40 (Sirchie, LV507) in 1L of ethanol (Fisher CAS64-17-5) for a period of approximately 15 seconds. Each note was then individually rinsed with water and left to dry.

CAF-BY40 developed fingermarks were viewed using a Mason Vactron Quaser 2000/30 and illuminated with blue light or blue-green (400-469 nm or 400-519 nm) with a viewing filter (476 nm or 529 nm respectively); angle of view and lighting configuration were optimised for each mark, and captured using the Integrated Rapid Imaging System (IRIS, Media Cybernetics) with a Redlake Megaplus 4-2i camera.

VMD development was achieved using a West Technology Forensics VMD360 system where molybdenum boats were heated to evaporate 3 mm of 0.25 mm diameter gold wire followed by heating a zinc pellet until development was observed. This adhered to both the fingermark visualisation manual [6] and the guidelines provided by the manufacturer [26].

Tungsten (white) lamps and captured using the IRIS and camera system as before.

2.4 Grading fingermarks

Marks were graded using the "Home Office" or "CAST" scale [25] of 0 (no evidence of a print) to 4 (over 2/3 of mark with good ridge detail), table 1. The boundary between sufficient and insufficient for identification is likely to be within grade 2, where some marks will have appropriate levels of detail, but other marks may have limited ridge detail or have insufficient minutiae evident [22]. Marks were graded on visualisation of ridge detail; marks with the same grade may have differing strength of contrast between mark and background; contrast and brightness are adjusted in the image, but no additional processing has been applied.

Table 1. Grading of fingermarks by amount of ridge detail present, using the Home Office or CAST grade [25]

Home Office Grade	Descriptor
0	No evidence of a mark
1	Evidence of a mark, no ridge detail
2	Ridge detail covering less than 1/3 print area
3	Ridge detail covering more than 1/3 print area but less than 2/3 print area
4	Ridge detail covering more than 2/3 print area

As fingermark grading is a classification, rather than a continuous or quasi-continuous measurement, taking an average grade is not mathematically robust. It is more appropriate to consider the number of marks in each grade, or the number that are, for example, at least a grade 3. We therefore use stacked bar charts to present the results, and Wilcoxon and Kruskal-Wallis tests for significance, as detailed elsewhere [27] instead of the equivalent t-test and Anova. The open source R statistical software was utilised to carry out all significance tests [28].

3. Results and Discussion

3.1 Surface degradation of the banknotes with handling

The Clydesdale £5 banknotes have been examined by Laser Scanning Confocal Microscopy (LSCM). Five small, relatively uniform areas were selected for LSCM examination for texture analysis, collectively representing the principal areas of the banknote. Surface parameters are shown in table 2. Roughness increased on handled notes on all areas (table 2), for example on £5 logo (opaque coloured polymer) from R_a of 0.9 µm to 6.3 µm and transparent area from R_a of 0.2 µm to 2.8 µm. Kurtosis, which reflects the sharpness of features, and skewness, which reflects predominance of peaks or troughs, moved closer to uniformity with handling of notes.

Table 2. Surface texture parameter values of mint and heavily handled Clydesdale £5 banknote assessed by Laser Scanning Confocal Microscope over different regions of the banknote.

	R_a / µm				Skewness		Kurtosis	
	Mint		Handled		Mint	Handled	Mint	Handled
Opaque colour polymer	0.9	±0.1	6.3	±3.9	0.3	-0.3	6.1	2.7
Intaglio Printing	2.8	±1.7	6.4	±2.9	0.7	-0.4	6.6	3.7
Pearlescent	0.5	±0.1	2.8	±1.2	-0.9	-0.1	15.7	5.6
White Print	1.0	±0.1	3.1	±1.4	0.3	0.2	4.8	3.1
Transparent	0.20	±0.05	2.8	±0.7	-44.5	0.2	3210	6.9

The LSCM examination of the heavily handled Clydesdale £5 banknote revealed the emergence of features such as cracking, up to 5 µm in depth, segmenting of the surface through a connected network of cracks on areas of coloured polymer, and scratch marks on transparent area as shown in figure 1.

Intaglio printing, contributing to some text as well as shading of portraiture at a macro level, consists of raised areas approximately 15 ± 4 µm in height on the mint note. This is reduced or completely removed in places with handling of the notes. The principal degradation method appears to be at the adhesion between the printing and the polymer substrate, rather than the cohesion of the printing. The material breaks off, rather than gradually eroding.

The cracked network effect observed on opaque polymer regions on handled notes contributes the large increase in R_a roughness from 0.9 µm to 6.3 µm. This also explains the high levels of variation observed in the roughness measurement (± 3.9 µm) as the surface is composed of large cracks (up to 5 µm wide) that separate areas of relatively flat, undamaged polymer in this region of the degraded notes.

Prominent in the transparent region of the mint note are 'pin prick' holes which contribute to the high kurtosis and high negative skewness in this material. As the note is handled, scratches and creases appear and pin prick holes are filled or distorted, which is reflected in the reduction of texture parameters kurtosis and skewness to levels similar to those in other areas.

The pearlescent area (in the shape of a map of Scotland in the Clydesdale notes) initially comprises of flakes of reflectant material embedded at angles within a smooth polymer with R_a = 0.5 µm. This is degraded principally by the removal of polymer material covering the reflectant flakes, the roughness increases to R_a = 2.8 µm.

Lightly handled notes imaged within the AFM show the initiation of the degradation, proceeding in a similar way with the initiation of surface cracking, and some heavily cracked areas. Figure 2 shows (a) mint and (b, c) handled opaque regions of Bank of Scotland notes. The mint note shows no cracking, whereas all regions of the handled note observed some surface cracking, with some areas such as figure 2 (b) a few short cracks initiating, to figure 2 (c) where the surface cracking becomes the dominant feature.

3.2

development

The quality of detected fingermarks developed from Clydesdale £5 banknotes in each of the handling states and development methods, is summarised in figure 3 and figure 4, example images of fingermarks are shown in figure 5. The data is presented as the Home Office scale grades 0-4 a description of which can be found in Table 1. Figure 3 outlines the grades given to detected fingermarks on both the mint and handled Clydesdale banknotes with each development method (VMD and GFMP). This shows that VMD is a more effective technique, this process developed 55 % and 65 % of fingermarks to grades 3 or 4, an identifiable standard, on handled and mint notes respectively, whilst GFMP developed 1 % and 39 % of marks to an identifiable standard on handled and mint notes respectively ($p<0.0001$, see supplementary information A2 for statistic parameters). These results also clearly show that the handling process has a detrimental effect on the subsequent enhancement of fingermarks; however, this effect is greater for GFMP ($r = 0.57$, $p<0.001$) than it is for VMD ($r=0.17$, $p=0.029$). This is expected to be due to the GFMP becoming trapped and building up in the cracks and scratches, produced through the handling of the notes which can be seen in Figure 1, similar to that observed in a study on texture effects on fingermark development on polymers [5].

The comparison of VMD development to that with GFMP and influence of substrate surface is observed strongly when the quality of detected marks is considered for each of the eight

The variation in quality of detected fingermarks between the eight regions of the mint banknotes seen in figure 4 is consistent with the wide variability in the surface texture and material. Each of the eight regions of the banknote used for each fingermark deposition is not uniform but contains more than one of the five main materials/surfaces examined by LSCM. Higher grades of fingermarks as seen in figure 4 are more likely in regions D, E, H corresponding to three of four corners, and areas of lower roughness and uniformity. The multiple components, such as intaglio printing and pearlescent components, in the fourth corner (region A) may lead to lower development efficacy. The intaglio printing is also likely to have reduced the efficacy of development in region G, this raised text is at a sufficient height (approximately 15 µm) to cause interference with the deposition of the fingermark components. The surface material, chemistry and energy will also have effects on the behaviour of the fingermark deposit and the development process. Figure 5d,e show differential quality of development of areas of individual fingermarks dependent on substrate surface.

The variation in development quality may not be only due to the different substrate characteristics, but also due to the donor variation of the fingermarks deposited. Inter and intra donor variations on equivalent areas of mint banknotes result in some high quality marks, but also empty prints, for example figure 5a, which is consistent with other studies of fingermark development on polymers [14,29]. However, the number of donors should allow this variability to be averaged out over the study, therefore mitigating the impact of this variable on any conclusions that are drawn.

Banknote handling reduces intaglio (raised) features which are a major structure in areas C and G; and fills 'pin prick' holes, and introduces surface scratching in transparent areas A and E; and introduces surface cracking in the opaque polymer, which is the predominant material in region H, segmenting of the surface, with similar effects in parts of regions A,B,D,E,F. All these features can affect spreading of fingermark components and the development quality. It is known from previous studies [5,7] that scratches, narrow valleys, narrow ridges or cracks limit fingermark components spreading when parallel to the fingermark ridges but increase the spreading when they are on an angle towards them. For the degradation seen on the opaque polymer segments the surface at a scale of approximately 20 µm, see figure 1, this is below the ridge width (~100 µm) and will therefore likely improve the retention of the fingermark ridges in their deposited position and limit any spreading of the mark, good quality marks on handled notes in regions of opaque polymer can be seen in figure 5c,e. VMD development has been suggested to be affected by layers of deposited material 3 nm thick [30] and fingermarks have been shown to exhibit migrating layers of material of approximately 3-4nm, spreading tens of microns from the fingermark ridge [7]. This cracking may therefore act to stabilise or improve the VMD development on these regions of the handled notes.

3.3 Fingermark study 2 Interbank comparison of VMD and CAF treatment

In study 2, the efficacy of VMD and cyanoacrylate fuming was assessed on mint and handled banknotes issued by four different banks. These have different designs, leading to different surface features in each octant and different proportions of coverage by these variable features. Example images of developed fingermarks are shown in figure 6 and 7 for VMD

Collated results presented in Figure 8a show the performance of the techniques in developing fingermarks on mint banknotes. It is clear that the techniques are relatively comparable in terms of effectiveness and quality of fingermark development, and there are no significant differences between VMD and CAF development for any issuing bank, the effect size is very small for RBS, BoE and BoS and small (in favour of VMD) for Clydesdale, see supplementary information A2. The effectiveness of each technique varied among banks ($P<0.05$) for example, on notes from RBS approximately 30% of marks were enhanced to grade 3 or 4, an identifiable standard, with either technique. On Clydesdale 50% with VMD and 41% with CAF were developed to this standard.

The effect on fingermark development of the stressing of notes to simulate circulation can clearly be seen in figure 8a and b by the decrease in grades achieved by fingermarks developed by both techniques.

Figure 8b shows that VMD is more effective than CAF for enhancing latent fingermarks on the handled polymer notes, irrespective of bank of origin (Clydesdale, BoS, RBS $p<0.001$; BoE $p<0.05$). The effectiveness of the methods did vary between the banks, however, with approximately 15% and 18% respectively of marks developed to an identifiable standard using VMD on notes issued by the Bank of England and Clydesdale Bank. In comparison, fewer than 5% of marks on notes from both the Royal Bank of Scotland and Bank of Scotland were developed to a grade 3 or 4 standard with VMD, although 19% and 17% respectively showed some ridge detail. This is still significantly more effective than CAF on the same type of notes where 1% and 0% of marks for RBS and BoS respectively were enhanced to identifiable standard, and 6% and 1% showed some ridge detail. The handling

visualisation.

The variation between banks may be related to differences in the design of the notes, as the designs have different distributions of intaglio printing, transparent regions and pearlescent features. As was observed on the Clydesdale notes, the various regions comprised of a combination of different features, such as transparent, opaque or reflective areas, as well as intaglio printing. These differences in region composition are also apparent for banknotes produced by the other issuing banks. For example with VMD development, in figure 6a on mint RBS note, and corresponding area on handled note (figure 6b) fingermarks show clear ridge detail on opaque polymer region (left) but poorer on transparent, pearlescent and interface regions. Similar effects are shown on a BoE note (figure 6c). This suggests an additional technique in sequence could be beneficial in improving the visualisation on (parts of) fingermarks on substrate areas not well visualised with VMD. Donor effects also contribute to mark variation; figure 6d shows a predominantly empty print on opaque polymer with some ridge detail at edge. Areas of high variation in background structure can still exhibit marks, Figure 6e shows a high-quality mark, although with some distortion, on a heavy intaglio region. Figure 6f shows ridge detail but heavily obscured by handling and substrate background, suggesting post processing or additional visualisation process may be beneficial.

Figure 7a shows a handled BoE note and Figurer 7b the corresponding region on mint note showing variation in development with substrate surface. Figure 7c shows excellent ridge detail and contrast with CAF on transparent and metallic region but reduced on opaque polymer region. This suggests, along with the VMD results, that a combination in sequence

figure 7d, although high quality ridge detail is also observed e.g. figure 7e,f although background staining and pattern interference affect contrast, suggesting a one-step approach such as Lumicyano or PolycyanoUV may produce better visualised marks in some cases [17].

3.4 Comparison of studies

Both studies show a decrease in effectiveness of fingermark development techniques with handling of banknotes, however, this decrease is less pronounced for development by VMD. The scratches and cracks observed in the banknotes by LCSM on extensively handled Clydesdale Bank notes, and by AFM on lightly handled banknotes across banks, will reduce the potential for the fingermark components to spread, potentially favourable for VMD development effectiveness. These same features will also adversely affect the GFMP development efficacy due to the trapping of the powder particles within the cracks and scratches which were observed in the earlier study [5], this is evident in the reduction in numbers of grade 3 or 4 marks from 39 % to 1 % seen with GFMP development on banknotes that have been handled. Surface features such as these have also been shown to cause background development with CAF processes [10]. Reasons for low quality of mark visualisation in some cases, e.g. figure 6f, 7f, may be background interference in the visualisation processes (enhanced by BY40 dyeing for example, or requirement for incident light wavelength that enhances intensity of security or material features) and this may be rectified by approaches that use infra-red or anti-stokes development techniques, or posthoc image processing [19,20]. However, in many cases the background trapping of development agent within surface structures, has reduced the contrast. Other marks

7d, which may be related to the action of the fingermark components on the substrate surface, which if residue is (still) present in a ridge pattern, may require an alternative process or sequence of techniques.

There was a significant drop in the efficacy of the VMD technique in developing fingermarks on Clydesdale notes between studies 1 and 2. This is approximately 15% on mint notes and 20% on handled notes. This difference is likely due to a range of factors which includes: differences in banknote material or structure with issue date, donor secretion composition [29,31], duration and environmental differences such as humidity during storage, variation in the VMD operator and differences in the grader of developed marks [32]. The trends are the same in both studies, with VMD effective on mint and handled banknotes.

4. Conclusions

Handling of these polymer banknotes causes changes in surface texture. In Clydesdale Bank £5 banknotes, LCSM shows the surface roughness increases while Kurtosis (sharpness of features) and Skewness (predominance of peaks or troughs), move closer to uniformity. The handling causes areas of cracking of the opaque polymer, with a network of interconnected cracks up to 5 µm in depth, that segment the surface. The intaglio printing fails in adhesion with the substrate. AFM shows the initialization and development of these features across issuing banks on the lightly handled notes.

Development efficacy of techniques varies between banks. In this study, GFMP or CAF techniques are only effective for mint banknotes, while handling of the banknotes reduces

exhibit ridge detail on mint notes, but only 1% on handled notes. On Bank of England notes the same technique develops 73% of marks on mint notes, and 28% on handled notes. On Clydesdale Bank notes, GFMP develops 50% of marks with ridge detail on mint notes, and 5% on handled notes. The changes to the surface with handling are likely to cause traps for contamination and applied development reagents, decreasing the effectiveness of CAF and powder-based techniques. The differences between banks may be linked to the surface structure variation, as the efficiency of the techniques is strongly substrate material dependent, as observed when a fingermark covers multiple surfaces within these notes.

Development by VMD is less affected by the handling of the banknotes. The surface changes are likely to reduce the deposited fingermark material spreading, potentially improving VMD development. On Bank of England notes VMD develops 61% of marks with ridge detail on mint notes and 45% on handled notes. In study one on Clydesdale Bank notes VMD developed 83% of marks with ridge detail on mint notes and 65% on handled notes; in study two, this is 73% and 39% respectively. VMD is effective for both mint and handled banknotes, in these studies, performing significantly better than other techniques on handled notes for all banks.

References

[1]. Committee of Scottish Bankers (no date) Polymer Banknotes available at https://www.scotbanks.org.uk/banknotes/polymer-banknotes.html (Accessed 1 April 2021)
[2]. Bank of England (2016) The new fiver is issued today [Press release] 13 September
[3]. Bank of England (2021) The new £50 note unveiled [Press release] 25 March

visualisation with iron oxide powder suspension: the variable effectiveness of iron (II/III) oxide powders, and Tween® 20 as an alternative to Triton™ X-100. Forensic Sci. Int., 292, 190-203.
[5]. B.J. Jones, R. Downham, V.G. Sears, Effect of substrate surface topography on forensic development of latent fingerprints with iron oxide powder suspension, Surf. Interface Anal. 42 (2010) 438–442. doi:10.1002/sia.3311.
[6]. Centre for Applied Science and Technology (CAST), Fingermark Visualisation Manual, Home Office, 2014.
[7]. K.T. Popov, V.G. Sears, B.J. Jones, Migration of latent fingermarks on non-porous surfaces: Observation technique and nanoscale variations, Forensic Sci. Int. 275 (2017) 44–56. doi:10.1016/j.forsciint.2017.02.015.
[8]. N. Jones, D. Mansour, M. Stoilovic, C. Lennard, C. Roux, The influence of polymer type, print donor and age on the quality of fingerprints developed on plastic substrates using vacuum metal deposition, Forensic Sci. Int. 124 (2001) 167–177.
[9]. N. Jones, M. Stoilovic, C. Lennard, C. Roux, Vacuum metal deposition: factors affecting normal and reverse development of latent Fingerprints on polyethylene substrates, Forensic Sci. Int. 115 (2001) 73–88.
[10]. S.R. Bacon, J.J. Ojeda, R. Downham, V.G. Sears, B.J. Jones, The effects of polymer pigmentation on fingermark development techniques, J. Forensic Sci. 58 (2013) 1486–1494. doi:10.1111/1556-4029.12206.
[11]. M. Azoury, D. Cohen, K. Himberg, P. Qvintus-Leino, T. Saari, J. Almog, Fingerprint Detection on Counterfeit US$ Banknotes: The Importance of Preliminary Paper Examination, J. Forensic Sci. 49 (2004) 1015–1017. doi:10.1520/JFS2003424.
[12]. P.B. Sherriffs, K.J. Farrugia, J.M. Fraser, B.J. Jones, The optimisation of fingermark enhancement by VMD and LumicyanoTM on thermal paper, Sci. Justice. 60 (2019) 160-168 doi:10.1016/j.scijus.2019.10.004.
[13]. B.J. Jones, A.J. Reynolds, M. Richardson, & V.G. Sears, Nano-scale composition of commercial white powders for development of latent fingerprints on adhesives. Sci. Justice, 50(3) (2010) 150-155. https://doi.org/10.1016/j.scijus.2009.08.001
[14]. R. Bengiat, Y. Liptz, N. Rajs, A. Bentolila, M. Levin-Elad, Time is Money or Money is Time? A Rapid Operational Sequence for Detecting Fingermarks on Polymer Banknotes, J. Forensic Sci. 65 (2020) 1465–1473. doi:10.1111/1556-4029.14479.
[15]. R. Lam, D. Wilkinson, T. Tse, and B. Pynn, Recommended protocols for fingerprint detection on Canadian polymer banknotes - Part I: Chemical development, J. Forensic. Identif., 64 (2014) 375-401.
[16]. R. Lam, Recommended protocols for fingerprint detection on Canadian polymer banknotes - Part II: Photography, lighting, and digital enhancement techniques, J. Forensic Identif., 64 (2014) 402-422.
[17]. C.A. Joannidis, P.R. Haddrill, K. Laing, Determination of the Most Effective Enhancement Process for Latent Fingermarks on Clydesdale Bank and Royal Bank of Scotland £5 and £10 Polymer Banknotes, 60 (2020) 160-168. doi:10.1016/j.forsciint.2020.110334.
[18]. R.S.P. King, P.M. Hallett, D. Foster, Seeing into the infrared: A novel IR fluorescent fingerprint powder, Forensic Sci. Int. 249 (2015) e21–e26. doi:10.1016/j.forsciint.2015.01.020.

[19]. R.S.P. King, P.M. Hallett, D. Foster, NIR-NIR fluorescence: A new genre of fingermark visualisation techniques, Forensic Sci. Int. 262 (2016) e28–e33. doi:10.1016/j.forsciint.2016.03.037.
[20]. R.P. Downham, E.R. Brewer, R.S.P. King, V.G. Sears, Sequential processing strategies for fingermark visualisation on uncirculated £10 (Bank of England) polymer banknotes, Forensic Sci. Int.

[21]. B.J. Jones, R. Downham, V.G. Sears, Nanoscale Analysis of the Interaction Between Cyanoacrylate and Vacuum Metal Deposition in the Development of Latent Fingermarks on Low-Density Polyethylene, J. Forensic Sci. 57 (2012) 196–200. doi:10.1111/j.1556-4029.2011.01952.x.
[22]. H. McMorris, K. Sturrock, D. Gentles, B.J. Jones, K.J. Farrugia, Environmental effects on magnetic fluorescent powder development of fingermarks on bird of prey feathers, Sci. Justice. 59 (2019) 117–124. doi:10.1016/j.scijus.2018.09.004.
[23]. International Fingerprint Research Group Guidelines for the assessment of fingermark detection techniques J. Forensic Identif., 64 (2) (2014) 174-200
[24]. Morales Muñoz, C. (2010) Surface modification of plasticized PVC by dry cleaning methods: Consequences for artworks Applied Surface Science, 256 (11), pp. 3567-3572
[25]. V.G. Sears, S.M. Bleay, H.L. Bandey, V.J. Bowman, A methodology for finger mark research, Sci. Justice. 52 (2012) 145–160. doi:10.1016/j.scijus.2011.10.006.
[26]. West Technology Forensics Ltd, VMD360 Operating Manual, 2017.
[27]. D Hockey, A Dove, T Kent, Guidelines for the use and statistical analysis of the Home Office fingermark grading scheme for comparing fingermark development techniques Forensic Sci. Int.,318, 2021, 110604, Doi: 10.1016/j.forsciint.2020.110604
[28]. R Core Team, R: A Language and Environment for Statistical Computing version 4.0.5 (2021) R Foundation for Statistical Computing, Vienna, Austria www.R-project.org
[29]. M.J. Bailey, N.J. Bright, R.S. Croxton, S. Francese, L.S. Ferguson, S. Hinder, S. Jickells, B.J. Jones, B.N. Jones, S.G. Kazarian, J.J. Ojeda, R.P. Webb, R. Wolstenholme, S. Bleay, Chemical Characterization of Latent Fingerprints by Matrix-Assisted Laser Desorption Ionization, ToF-SIMS, MeV SIMS, Gas Chromatography/Mass Spectrometry, X-ray Photoelectron Spectroscopy, and ATR-FTIR Spectroscopic Imaging: An Intercomparison, Anal. Chem. 84 (2012) 8514 - 8523. doi:10.1021/ac302441y
[30]. B. Scruton, B.W. Robins, B.H. Blott, The deposition of fingerprint films, J. Phys. D. Appl. Phys. 8 (1975) 714–723. doi:10.1088/0022-3727/8/6/016.
[31]. R.S. Croxton, S.M. Bleay, M. de Puit, Composition and properties of fingermarks, in: Fingerpr. Dev. Tech. Theory Appl. First Ed., John Wiley & Sons Ltd, 2018: pp. 35–68. doi:10.1002/9781119187400.
[32]. P. Fritz, A.A. Frick, W. Van Bronswijk, S.W. Lewis, A. Beaudoin, S. Bleay, C. Lennard, Variability and subjectivity in the grading process for evaluating the performance of latent fingermark detection techniques, J. Forensic Identif. 65 (2015) 851–867.

Appendices

A1. Nomenclature

We use a number of terms for the condition of banknotes: mint (as supplied by an issuing bank with no or minimal handling by cashiers), handled (a mint note subsequently subjected to a laboratory handling process), circulated (a note retrieved from retail after circulation), degraded (handled or circulated, visibly not mint).

We use the term ‘fingermark’ to mean a mark deposited primarily in endogenous compounds, for example at a crime scene, regularly shortened to ‘mark’. This is sometimes termed ‘latent fingerprint’ and is to contrast with a ‘fingerprint’, which is a deposit in ink or collected electronically, for example to use in comparison.

A number of terms are used for human interaction with the substrate

User: someone who touches a substrate (in this case a banknote), but does not deliberately leave a mark

Donor: someone who specifically deposits a fingermark under controlled conditions

Donation event: deposition of one fingermark, or a series, including depletions, with no replenishment of residue within this event. Although a donor may participate in a number of donation events over the course of a study, to avoid interactions between donation events donors will leave at least 30mins between donation events [12,23]. In the current study donors were limited to one donation event per day.

We use a number of terms for the condition of fingermarks: fresh (as deposited and under 24 hours old), aged (over 24hrs from deposition, usually with a stated number of days from

Observing the fingermarks also have a number of terms:

Development of fingermarks – the process of chemically or physically enhancing the appearance of a latent mark. A typical example is CAF+BY40.

Visualisation of fingermarks – the process of making a latent mark visible, this usually includes a development step, and may also include specific lighting and/or viewing processes. A typical example is CAF+BY40 illuminated with blue light and viewed with a 476nm filter.

In this study, banknotes were virtually divided into eight octants, in two rows of four (upper row labelled as, A-D and lower row E-H), for ease of deposition and reference, as shown in the schematic figure A1.

A2. Statistical parameters

[illegible] analysed with Wilcoxon rank sum test. Where no preferred method is indicated, the confidence in the significance of the difference between techniques is less than 95% and the effect size of changing technique is small or very small.

Bank	Condition	Development Options	Study	W	P	Za	r	Preferred Method
BoE	Mint	VMD/CAF	2	4343	0.4814	0.704	0.051	
BoE	Handled	VMD/CAF	2	5309	0.0373	2.082	0.150	VMD
RBS	Mint	VMD/CAF	2	4714	0.7773	0.283	0.020	
RBS	Handled	VMD/CAF	2	5467	0.0008	0.283	0.242	VMD
CB	Mint	VMD/CAF	2	5145	0.1507	1.437	0.104	
CB	Handled	VMD/CAF	2	6237	<0.0001	5.618	0.405	VMD
CB	Mint	VMD/MFP	1	4432	<0.0001	4.358	0.345	VMD
CB	Handled	VMD/MFP	1	5259	<0.0001	8.162	0.645	VMD
BoS	Mint	VMD/CAF	2	4744	0.7129	0.368	0.027	
BoS	Handled	VMD/CAF	2	5473	<0.0001	4.235	0.306	VMD

Table A2.2 Comparison of effect of condition with bank and development technique, fingermark grades analysed with Wilcoxon rank sum test.

Bank	Development	Condition Options	Study	W	P	Za	r
BoE	CAF	Handled/Mint	2	2112	<0.0001	6.861	0.495
RBS	CAF	Handled/Mint	2	2074	<0.0001	7.754	0.560
CB	CAF	Handled/Mint	2	1567	<0.0001	9.016	0.651
BoS	CAF	Handled/Mint	2	2151	<0.0001	8.113	0.586
BoE	VMD	Handled/Mint	2	2885	<0.0001	4.634	0.334
RBS	VMD	Handled/Mint	2	2587	<0.0001	5.756	0.415
CB	VMD	Handled/Mint	2	2398	<0.0001	5.981	0.432
BoS	VMD	Handled/Mint	2	2548	<0.0001	5.992	0.432
CB	VMD	Handled/Mint	1	2592	0.0291	2.182	0.173
CB	MFP	Handled/Mint	1	1425	<0.0001	7.250	0.573

Table A2.3 Interbank study Kruskal-Wallis test across banks for specific condition and development method

Condition	Development technique	Kruskal Wallis Chi-Sqr	P value
Handled	VMD	11.94	0.0178
Mint	VMD	12.275	0.0154
Handled	CAF	22.261	0.0002
Mint	CAF	10.329	0.0352

Figure Captions

Figure 1. Surface structures of heavily handled Clydesdale Bank £5 note studied by LCSM (a-c) mint and (d-f) handled note. (a) image and (b) corresponding height map of opaque area, with intaglio features in bottom right. (c) intaglio shading from portraiture. Height map scale is 25µm. Degradation with handling in (d) and (f) opaque polymer, and (e) showing removal of intaglio features, with degradation of polymer.

Figure 2. Atomic force microscopy (AFM) height map images of 100x100µm areas of Bank of Scotland £5 (a) mint and (b,c) lightly handled banknotes, showing development of surface cracking.

Figure 3. CAST grades of fingermarks developed on Clydesdale banknotes, study 1, showing GFMP and VMD development on handled and mint banknotes.

Figure 4. CAST grades of fingermarks developed in different regions of Clydesdale banknote, study 1, showing (a, b) Mint and (c, d) Handled notes on (a,c) VMD and (b,d) GFMP development. Banknotes are virtually divided into eight segments, two rows of four, for mark deposition, with regions A-D left to right on the upper row and E-H similarly on the lower row.

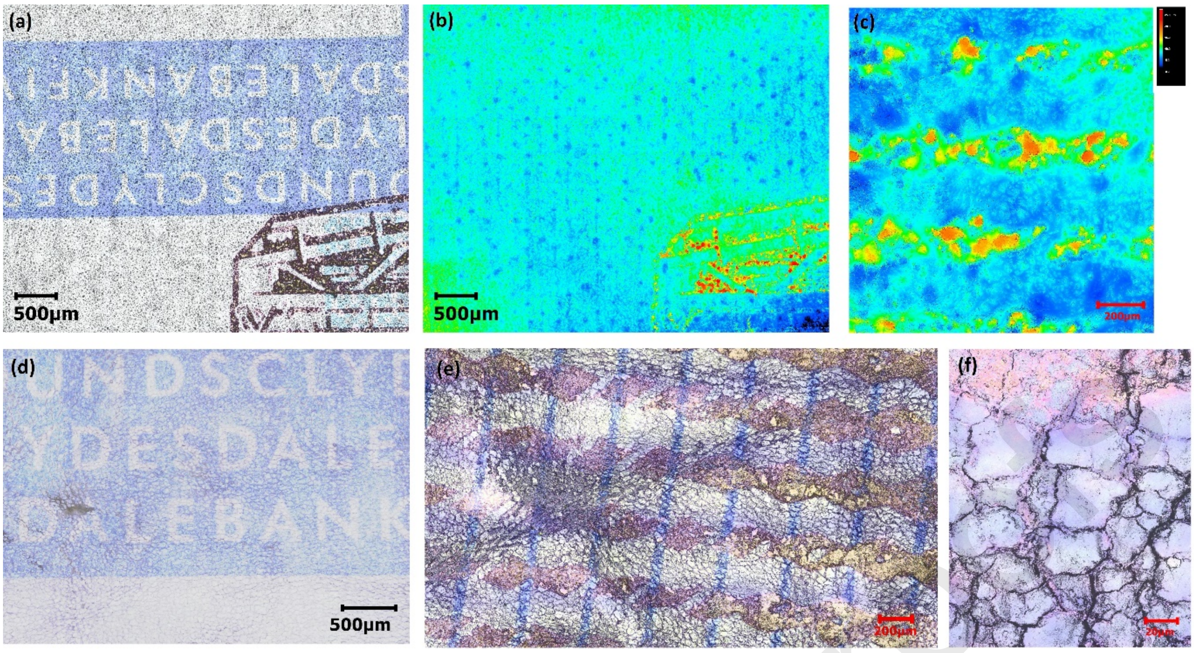
Figure5. Example fingermarks developed on Clydesdale Bank notes, study 1, showing (a) empty print on mint note opaque area; (b) high quality mark on mint note, with some obstruction from intaglio printing; (c) high quality mark across handled region of opaque polymer; (d) partial print on mint note showing some ridge detail, and substantial background obstruction; (e) high quality mark across different materials; (f) GFMP developed with some background obstruction.

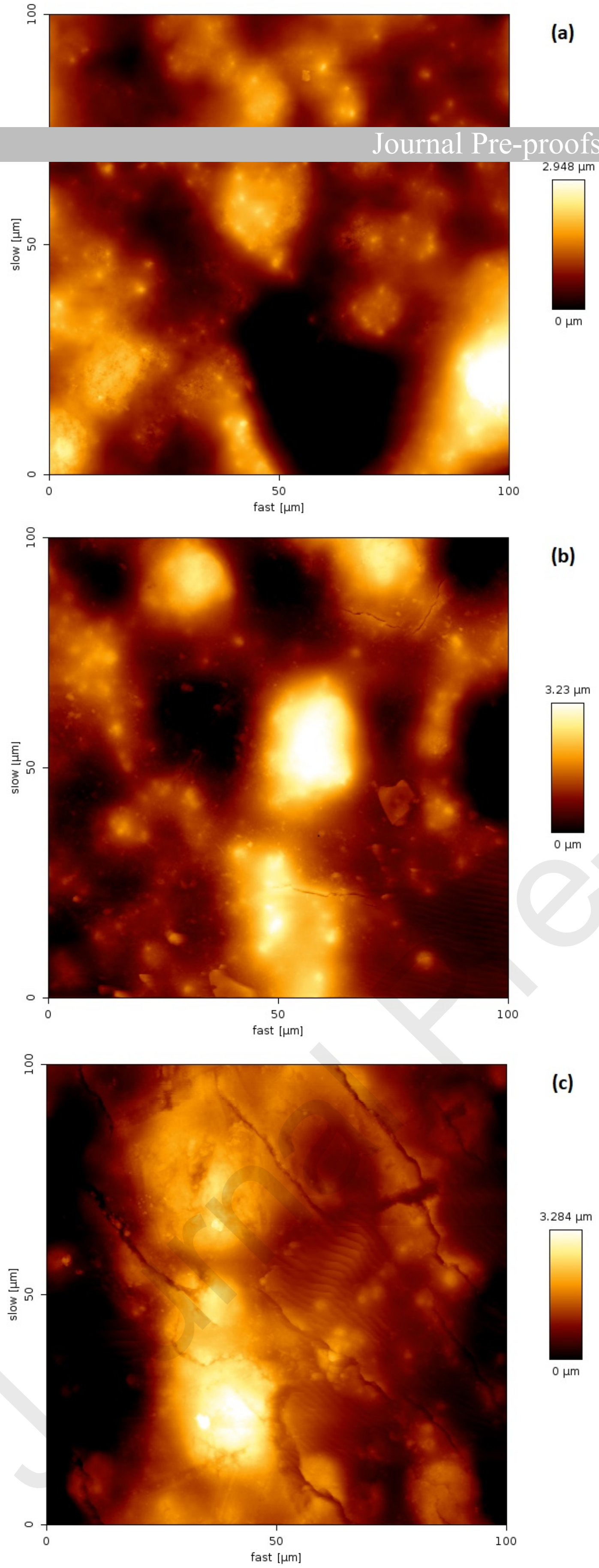
Figure 6. Example fingermarks developed with VMD on interbank study: (a,b) RBS, (c,d) BoE, (e) Clydesdale, (f) BoS. (a,b) Show high quality marks across opaque polymer with reduced visualisation on transparent region and boundary, on mint and handled notes respectively. (c) Mark on mint note well visualised on opaque region reduced clarity on foil and transparent areas. (d) Primarily empty print with some ridge detail on edge. (e) high quality development and visualisation of mark across heavily intaglio printed area although some distortion of ridges. (f) Handled note with high background interference with development.

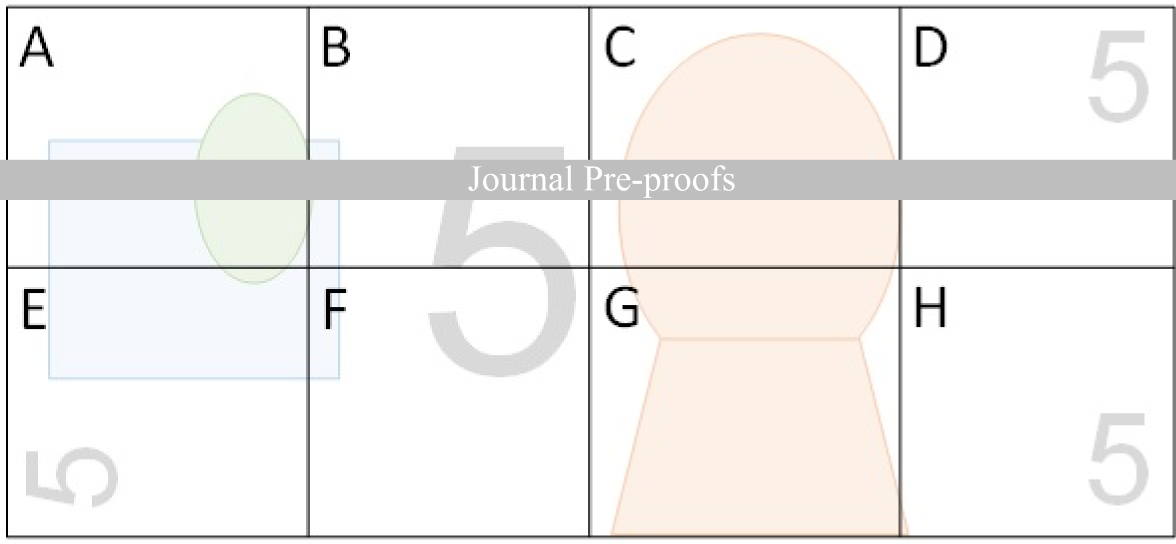
Figure 7. Example fingermarks developed with CAF on interbank study: (a,b,c) BoE, (d,e) BoS (f) RBS. (a) handled and (b,c) mint notes sharing variability of visualisation of ridge detail across different regions of the substrate. (d) small amount of ridge detail developed. Other areas (e,f) show excellent ridge detail development, although visualisation is affected by background pattern in some places (f).

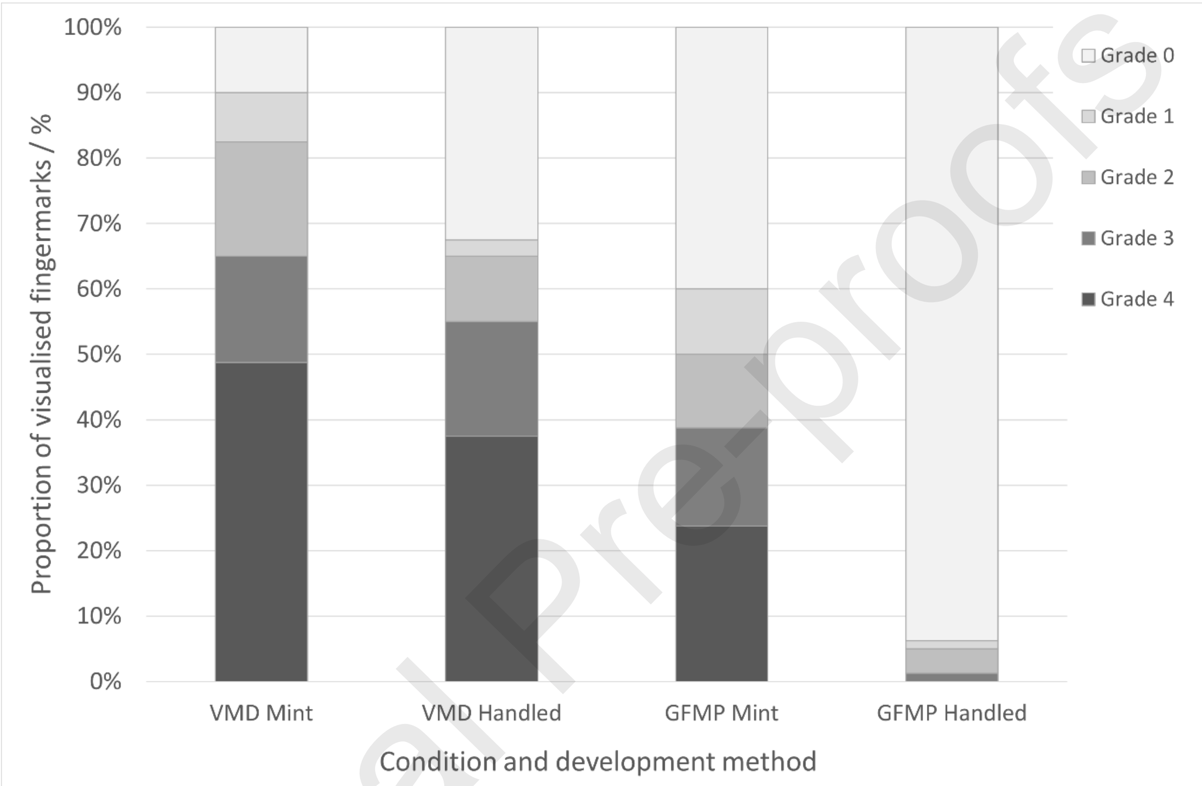
Figure 8. CAST grades of fingermarks developed on interbank study on (a) mint and (b) handled notes with VMD and CAF development across all banks.

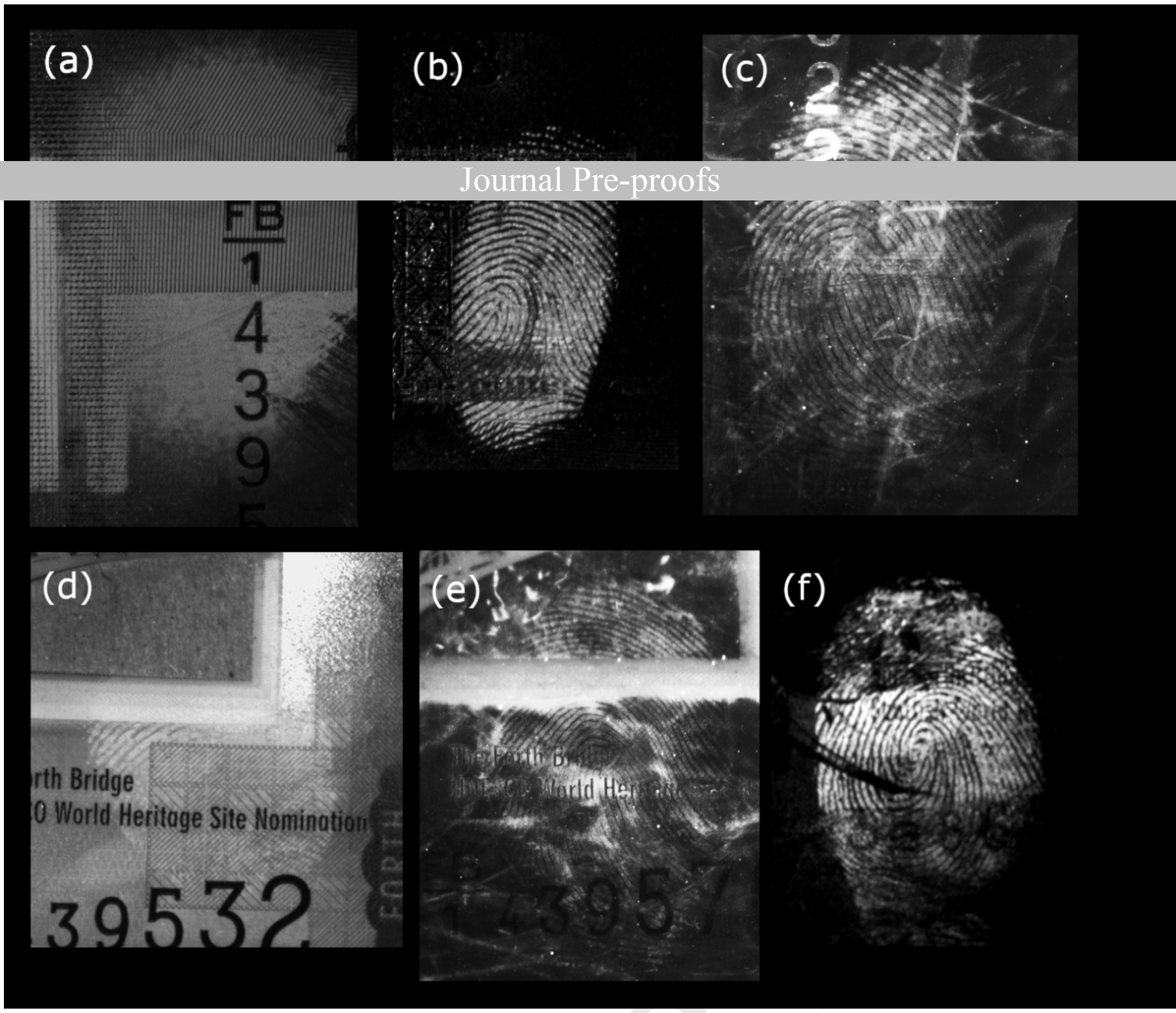
Figure A.1 Schematic of areas of banknote virtual divided for fingermark deposition, based on Clydesdale Bank five pounds sterling note. Different shaded regions reflect different substrate surface types.

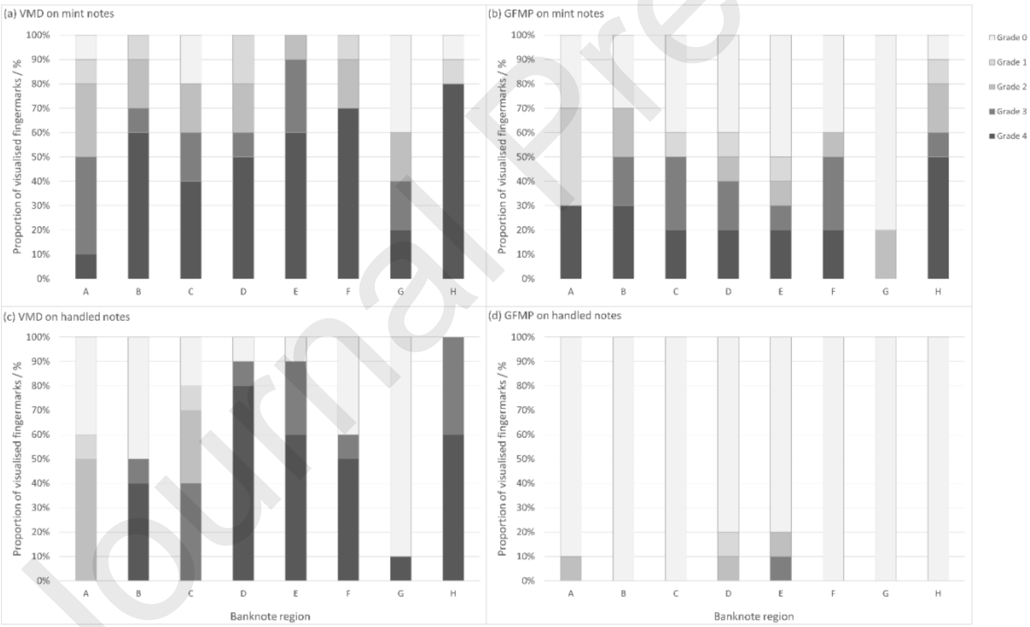


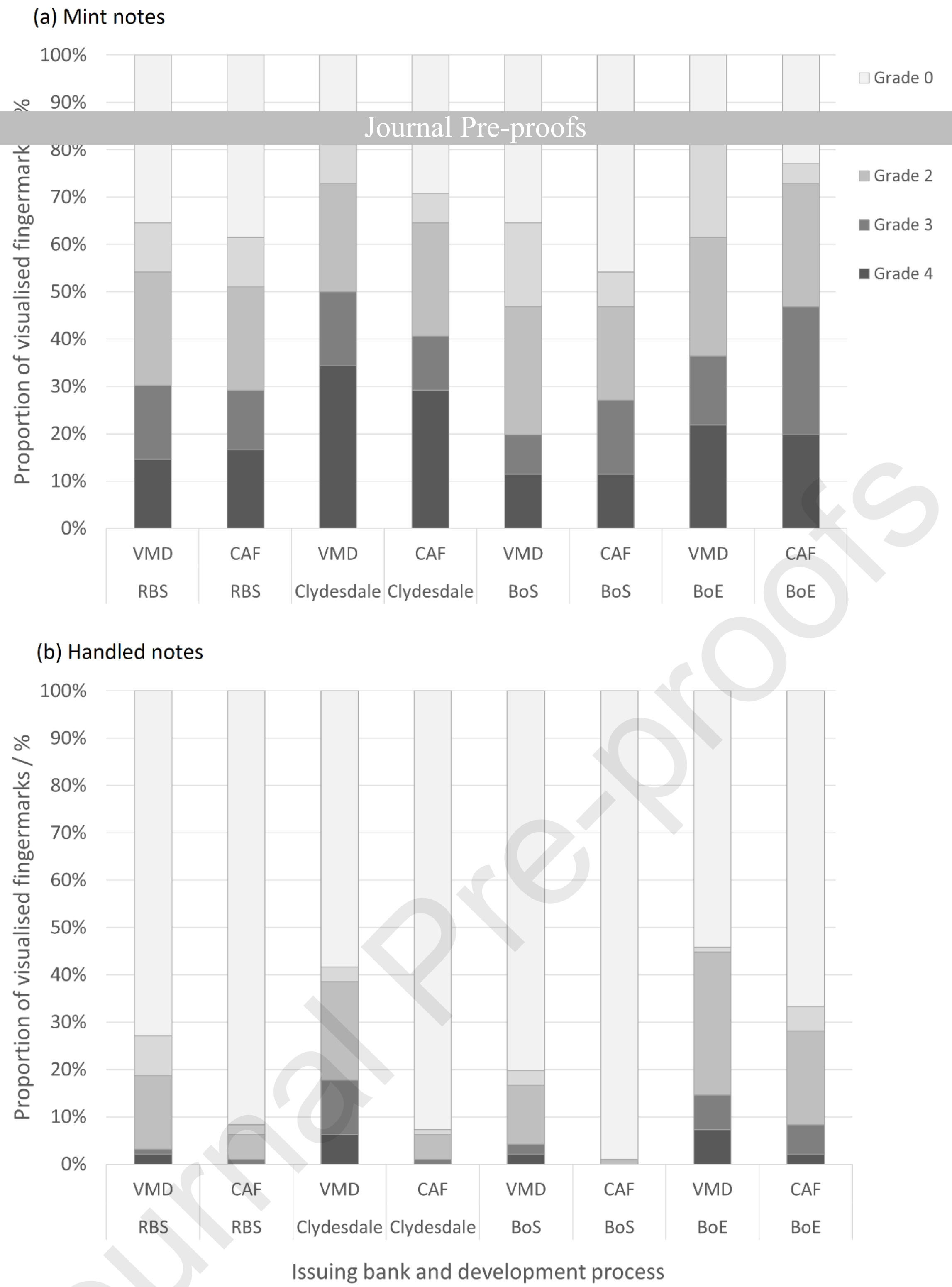

(a)
2.948 µm
0 µm
slow [µm]
fast [µm]
0
50
100
(b)
3.23 µm
0 µm
slow [µm]
fast [µm]
(c)
3.284 µm
0 µm
slow [µm]
fast [µm]

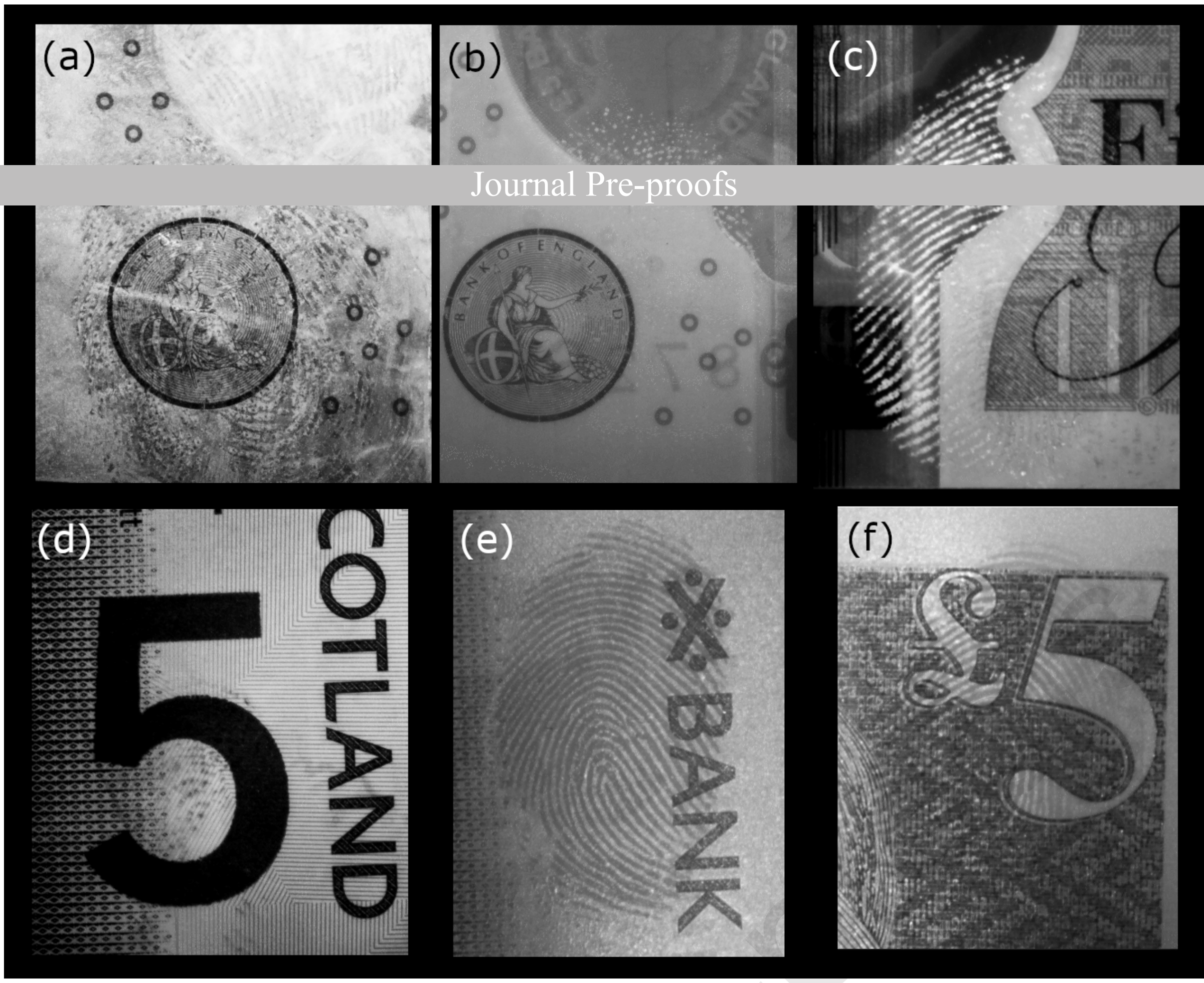

A
B
C
D
E
F
G
H

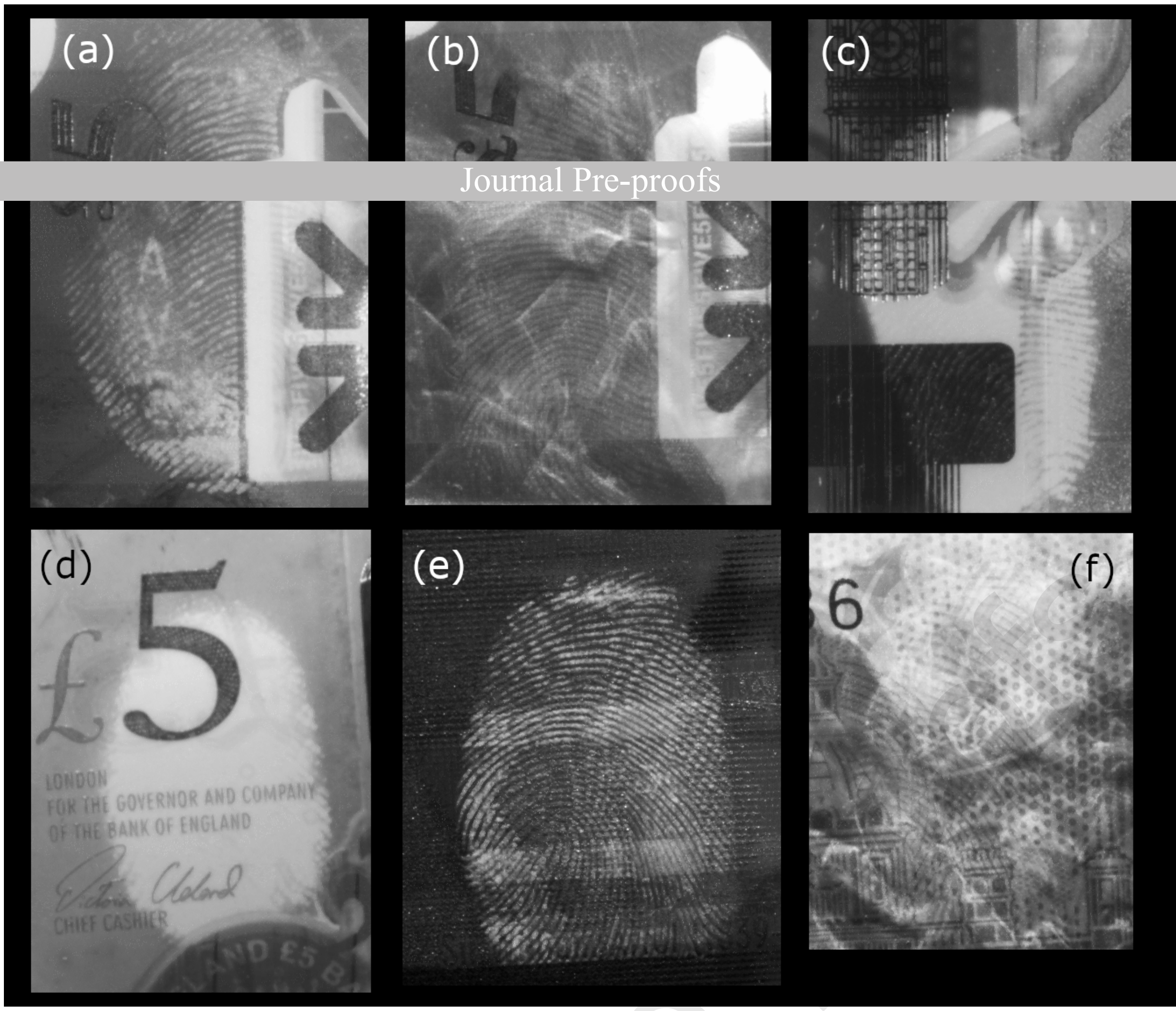

100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Proportion of visualised fingermarks / %
Grade 0
Grade 1
Grade 2
Grade 3
Grade 4
VMD Mint
VMD Handled
GFMP Mint
GFMP Handled
Condition and development method


(a)
(b)
(c)
(d)
(e)
(f)


(a) VMD on mint notes
(b) GFMP on mint notes
(c) VMD on handled notes
(d) GFMP on handled notes
Proportion of visualised fingermarks / %
Banknote region
A B C D E F G H
Grade 0
Grade 1
Grade 2
Grade 3
Grade 4


(a) Mint notes
Proportion of visualised fingermarks / %
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Grade 0
Grade 2
Grade 3
Grade 4
VMD RBS
CAF RBS
VMD Clydesdale
CAF Clydesdale
VMD BoS
CAF BoS
VMD BoE
CAF BoE
(b) Handled notes
Proportion of visualised fingermarks / %
Issuing bank and development process


(a)
(b)
(c)
(d)
5
COTLAND
(e)
BANK
(f)
£5



Degradation of polymer banknotes through handling, and effect on fingermark visualisation

Ancillary

This work has been approved by the Abertay University research ethics committee approval numbers EMS4230 and EMS4689.

All data available is included within the paper, appendices, supplementary information and linked publications.

Acknowledgements

Thanks to Clydesdale Bank for facilitating supply of samples, Dr Della Wilkinson for early discussions, Dr Arne Jansson for technical support, Shannon Gibson for additional exploratory work, and Dr Kevin Farrugia for early discussions of the text. This work has been [illegible] grant scheme, SIPR: FOP-21-06.

Author Contributions

BJJ: Conceptualization, investigation, resources, formal analysis, supervision, visualization, writing; JWC: Investigation (study 1), writing – original draft; CE, GS: Investigation (study 2), writing – original draft; CE & GS contributed equally to this work; PBS: Formal Analysis, writing – review; FB: Formal Analysis; KTP: writing – review; PMBA: Investigation (AFM), writing – review; JO'H: Resources, investigation (study 1).

Journal Pre-proofs