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A method for dating early books and prints using image analysis

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Many books and works of art printed over the centuries by hand-operated presses are undated or poorly dated. The use of classical methods of dating, such as matching watermarks in paper, has had limited success. Here, evidence is presented that the woodblocks and metal plates used in printing deteriorated at a constant rate, useful for time estimation. This change was measured in 2674 Renaissance prints. In successive editions, woodblock prints increased in the number of line breaks, whereas copperplate prints became paler. In both cases, the change was time dependent, not print dependent. For woodblocks, this can be explained by the aging of the wood, creating breaks in lines. For copperplates, image fading is a result of line thinning caused by surface erosion of the plate, not from compression by the printing press. The time dependency in copperplates is best explained by corrosion during plate storage, which was removed before each printing by polishing (erosion). The average rate of copperplate deterioration, 1–2 μm yr^{-1}, was estimated from the thinning rates of lines in two Italian prints and agrees with typical rates of atmospheric corrosion of copper. The print clock, if it applies generally, offers a relatively simple means of dating early books and prints.

Keywords: art; clock; copperplate; woodblock; corrosion; Renaissance

1. Introduction

The printing press was a catalyst of the Renaissance because it facilitated widespread communication of knowledge about the world. In conjunction with devices used for printing illustrations, such as woodblocks and metal plates, people other than the elite gained access to a wealth of information and art. The age of these printed works is a fundamental part of history and essential to understanding the development of ideas. Nonetheless, many of the thousands of different books and artwork printed over the centuries, prior to machine printing in the mid-nineteenth century, are undated or poorly dated. Included among those are works by Rembrandt (Ash & Fletcher 1998) and Shakespeare (Hunter 2001). Occasionally, marks in prints that resulted from defects or damage in woodblocks and copperplates have been used to establish the relative order of editions (Rasmussen

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2001). Watermarks in paper are more commonly used for dating, but they have limitations. For example, databases (Briquet 1907) contain only a small fraction of the different watermarks that were created, which may exceed a million (Schulte 1934), meaning that the chance of finding an exact match—necessary for dating—is low. Second, even if a match is found, the age of the paper may not correspond closely to the age of the print (Hunter 1947; Ash & Fletcher 1998).

In woodblock printing, the figures and lettering to be printed are raised areas which transfer ink to the paper. In printing from metal plates (usually copper), the artwork and lettering form depressions in the metal, and paper is pressed into the ink-filled grooves to obtain a print. The grooves in metal plates are created by engraving with a steel tool (burin) or etching the surface with acid. Because the woodblocks and copperplates were made by artists and were expensive to replace, they were commonly reused over decades to produce multiple editions of a book or print. The deterioration of printing devices during that time, which is the subject of this study, is seen in later editions as line breaks in woodblock prints, usually resulting from cracks in the wood, and image fading in the case of copperplate prints. The deterioration of the print itself in the centuries since it was printed, which is assumed to be negligible for these purposes (distribution of ink on the paper), is not considered here.

My initial observations of some Renaissance prints suggested that deterioration in successive editions was time-dependent, not print-dependent, and potentially useful as a means of dating old documents. To test this hypothesis, referred to here for simplicity as the 'print clock', detailed, quantitative analyses of prints were made, primarily from multiple editions of three sixteenth century books.

The woodblock analyses focused on Bordone's *Isolario* (Bordone 1528), with three dated editions (1528, 1534 and 1547), and one undated edition. The book is an atlas containing prints (maps) of islands. It was selected because it provided a large sample size (112 different prints in each book) and the three dated editions of the book permitted calibration of woodblock deterioration rate. Also, those dated editions were unevenly spaced in time, allowing the distinction of time- versus printing press-related deterioration. An undated edition of the book provided a test for the method.

The age of the undated book has been debated for nearly 200 years, with estimates ranging from 1537 to 1570 (Rich 1832; Harrisse 1866; Skelton 1966; Eco 2000), based on assumptions concerning the time of activity of the printer rather than direct physical evidence (see electronic supplementary material). In this study, the date of the undated *Isolario* was estimated with two independent print clocks: one based on prints within the *Isolario* and a second based on the printer's mark (=trademark), a small woodblock print located on the title page of the undated *Isolario* and other books by the printer. For comparison, a classical analysis of paper evidence (watermarks) was conducted.

The copperplate analyses focused on two books: Porcacchi's *L'isole più famose del mondo* (Porcacchi 1572) and Magini's *Geographiae* (Magini 1596). They were selected because the original plates were used, often without substantial alterations, through multiple editions and because those editions were unequally spaced in time, again permitting a comparison of time- versus printing press-related deterioration. Porcacchi's *L'isole più famose* was printed in six editions over five decades (1572, 1576, 1590, 1604, 1605 and 1620), whereas Magini's *Geographiae* was printed in three editions (1596, 1598 and 1621).

(*a*)
(*b*)

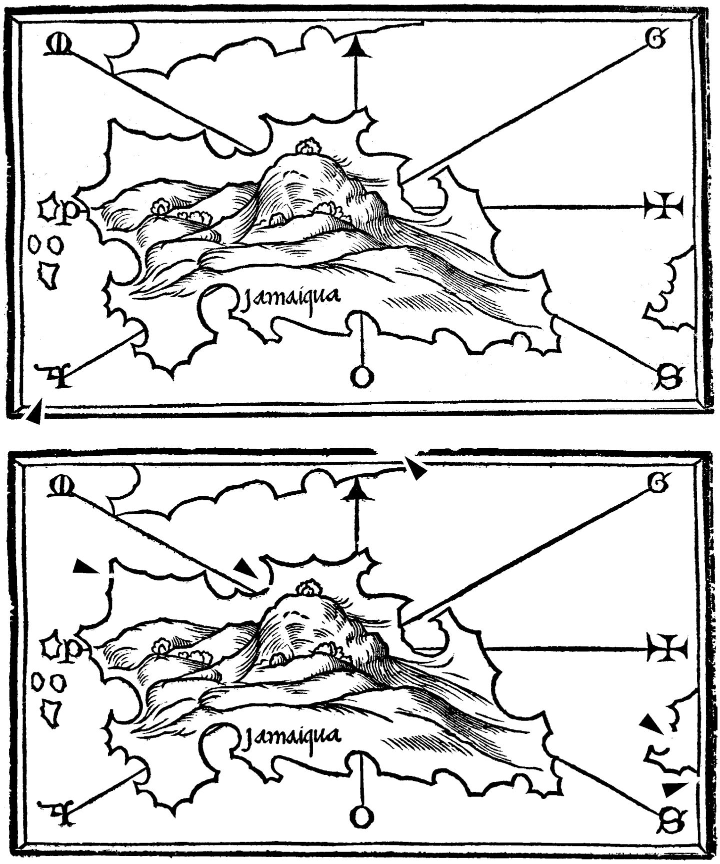

Figure 1. Renaissance woodblock print. (*a*) Map of Jamaica. One of 112 prints from the first edition (1528) of Bordone's *Isolario* (146×86 mm). Black arrow head points to woodblock deterioration (broken letter 'A') that occurred prior to the first printing. (*b*) The same print from the undated edition, showing additional line breaks (black arrow heads). Both images were auto-thresholded. Originals are from the author's collection and the Library of Congress.

For both woodblock and copperplate prints, image analyses were performed to determine the pattern and rate of image change over time. These analyses provided evidence for a constant rate of change in prints and permitted the dating of the undated *Isolario*. Measurements of individual printed lines in high-resolution images also revealed a likely mechanism for the time-dependent change in copperplate prints.

2. Material and methods

(*a*) *Woodblock print analyses*

For each of the 23 copies of Bordone's *Isolario* examined, the 112 different prints (2576 total prints) were inspected for line breaks (figure 1), discernable as an abrupt gap of any width (usually 1–10 mm) in a line (see electronic supplementary material). Owing to the low average number of line breaks per print (1.0 in the first edition, increasing to 4.6 in the last edition), the total number of line breaks in each book was calculated and used in all analyses. Correlation analysis was done with cumulative numbers of line breaks in successive editions (line breaks versus publication date) and with the data treated independently (number of line breaks between editions versus time intervals between editions). Multiple regression analysis was performed to determine the best predictor of line breaks, using publication date and two different estimates of the number of books printed. One estimate reflected relative levels from global library holdings (see electronic supplementary material) and the other assumed equal numbers for each edition. The undated *Isolario* was not used in calculating rates or determining regression lines for figures. Data points for the undated *Isolario* were plotted in figures based on the mean estimated date. The standard errors reported are those of the regression line.

For the analysis of the printer's mark and watermarks, digital images were taken by the author at rare book libraries with a 6.3 megapixel single-lens reflex (SLR) camera, using ambient light, or were obtained as digital images from libraries (see electronic supplementary material). Image analysis of the printer's mark was performed with automated thresholding (Rasband 2005) on images of the same dimension (1000×1200 pixels). Because woodblock print lines sometimes vary in width, apparently resulting from differential inking of the block, images were skeletonized (Rasband 2005) before use. Skeletonization is where pixels are repeatedly removed from an object in a binary (e.g. thresholded) image until they are reduced to a single pixel in width. Line breaks in the illustration were counted with aid of an edge-finding tool (Rasband 2005) and five other measurements were made with ImageJ: grey level (0, black; 255, white), fractal dimension, mean particle count (largest particle class), particle size and particle perimeter length (mean length of outside boundary of particles). To help reduce overall variance, each variable was converted to an index (positive slope) scaled from 0 to 1 and averaged to create a single deterioration index.

(*b*) *Copperplate print analyses*

Digital images of the Porcacchi prints and some of the Magini prints were taken by the author at rare book libraries with a digital SLR camera using ambient light. Most of the Magini prints were obtained as digital images from libraries (see electronic supplementary material). All images were auto-thresholded (Rasband 2005) prior to analysis and grey level (0–255) was measured. To limit bias from differential illumination, several large regions—instead of the entire image—were sampled and averaged for each print (see electronic supplementary material). The regions were identical across editions and were selected to avoid areas of damage on some prints, and include dense engraving. Correlation analysis was performed with grey values in successive editions (cumulative) and with data treated independently.

(*c*) *Copperplate line analyses*

Four Porcacchi prints were available for detailed examination of line change in the laboratory. Two came from the 1576 edition and were maps of Hispaniola and Jamaica. The other two came from the 1604 edition and were also of Hispaniola and Jamaica. The objective was to take measurements of engraved lines in these two pairs of maps to examine changes that occurred between

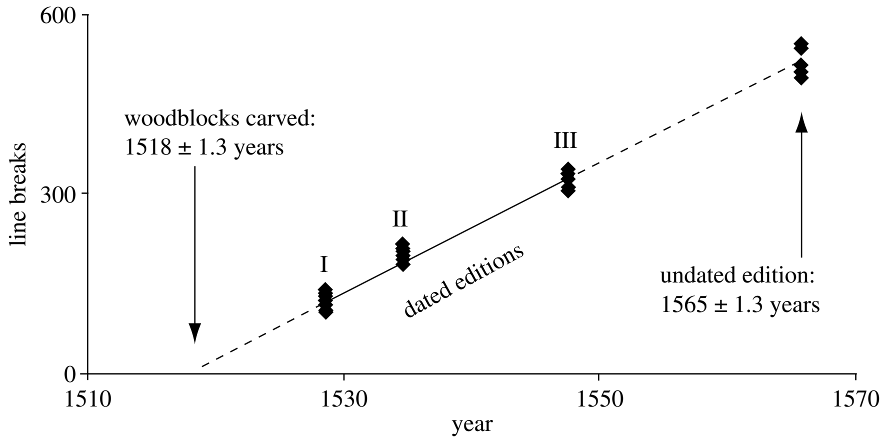

Figure 2. Time-dependent change in woodblock prints. Plot of total line breaks in each of 23 *Isolario*'s ($r = 0.99$). The regression line was calculated based on the three dated editions (1528, 1534 and 1547), and extended forward to predict a time for the printing of the undated edition and backward, prior to the first printing, to predict the time when the woodblocks were carved (x-intercept). The data points for the undated edition, not used in the regression, were centred at their corresponding position on the trendline.

the editions separated by 28 years. For this, high-resolution (4800 dpi) digital images were made with a flatbed scanner (Hewlett-Packard). The images were auto-thresholded to provide sharp line edge boundaries for measurements. Line width measurements were taken with an image measurement tool (Rasband 2005). The 4800 measurements that were made included 600 of engraved lines and 600 of etched lines from each of the four prints. For each pair of prints (different editions), the same location along the line was measured.

Further experimental details are listed in electronic supplementary material, which is published on the *Proceedings A* web site.

3. Results and discussion

(*a*) *Woodblock print analyses*

Among the three dated editions, the correlation of the number of line breaks and time of publication was high, regardless of whether the data were treated independently, as breaks occurring between editions ($r = 0.98$) or cumulatively ($r = 0.99$; figure 2). Besides the constant rate of change, relatively little variation in the number of line breaks was observed among different books of the same edition, which would suggest that deterioration arose primarily between printing events rather than during the printing process. Moreover, multiple regression analysis showed significant support ($p < 0.001$) for a relationship with time but not with number of prints, as estimated indirectly from global library holdings or assuming the same number of books was printed in each edition.

The clumping of data provided another clue. If all deterioration occurred during the printing process rather than between editions, a continuous distribution of line breaks would be expected rather than a clumped distribution (figure 2). Such a continuous distribution was rejected with a chi-square test ($p < 0.05$). This test of clumping also assumes, in this case where gap data from multiple prints in a book were combined, that there is a relationship among prints within each book in terms of impression order during the print run. This assumption is supported by knowledge of how early books were assembled; printed pages were stacked after drying in the order they were printed (Gaskell 1972).

Extrapolation of the regression line permitted the dating of the undated edition to 1565.2 ± 1.3 years (figure 2), making it clearly the last (fourth) edition. These data also permitted dating the time when the woodblocks were carved, prior to the first printing in 1528. Normally, it would be assumed that woodblocks were carved immediately prior to their first use. However, some historians have argued that Bordone's blocks were carved as much as a decade earlier based on documents from that time period, including a privilege (copyright) issued to the printer by the Venetian Senate in 1521 (Lelewel 1850–52; Skelton 1966). Others have concluded that the blocks were carved shortly before printing in 1528, mainly because the book contains a map of an Aztec city derived from a 1524 illustration by the Spanish explorer Cortés (Harrisse 1892).

Extrapolation backward in time using the print clock, to the x-intercept (the date at which estimated line breaks $=0$), resulted in a mean time estimate of 1518.1 ± 1.3 years (figure 2) for the carving of the *Isolario* woodblocks, a decade prior to their first use. This early date agrees with Lelewel (1850–52) but not with Harrisse (1892). It also agrees with cartographic knowledge portrayed in Bordone's maps of the New World, dating to the first 15 years of the sixteenth century (Skelton 1966). But how could that be if Bordone's Aztec city map postdates 1524? The line breaks provide an answer: the Aztec map has an unusually low number (one line break in six copies examined $=0.17$ breaks per print) compared with the overall average for the first edition (1.01 ± 0.10 breaks per print), consistent with being carved later in time (1524–1528) and added to an otherwise complete set of blocks.

An independent dating of the undated *Isolario* was possible with the use of the printer's mark. Compared with Bordone's maps, analysis of the printer's mark was more challenging owing to its small size (50×58 mm) and complexity (figure 3). For this, several types of automated digital analyses were made to quantify change in the image. The printer of the undated *Isolario*, Francesco de Leno, may have printed books as early as 1542, but he was most active between 1559 and 1570, during which he printed at least 37 books. Of those, nine have the same printer's mark as appears on the undated *Isolario*. It was clear that the printer's mark woodblock deteriorated during that decade because numerous line breaks are present in the later prints that were not present earlier (figure 3*a*,*b*).

Digital images of the printer's mark from seven of those nine books (15 prints total) were compared with images of the mark from five undated *Isolario*'s. Digital skeletonization of the images, resulting in lines of equal width, helped control for differences in inking of the prints and permitted better quantification of the deterioration (figure 3*c*–*f*). Deterioration of the printer's mark was quantified with six types of measurements, and time estimates for the undated Isolario were: grey value (1565.3, $r=0.80$),

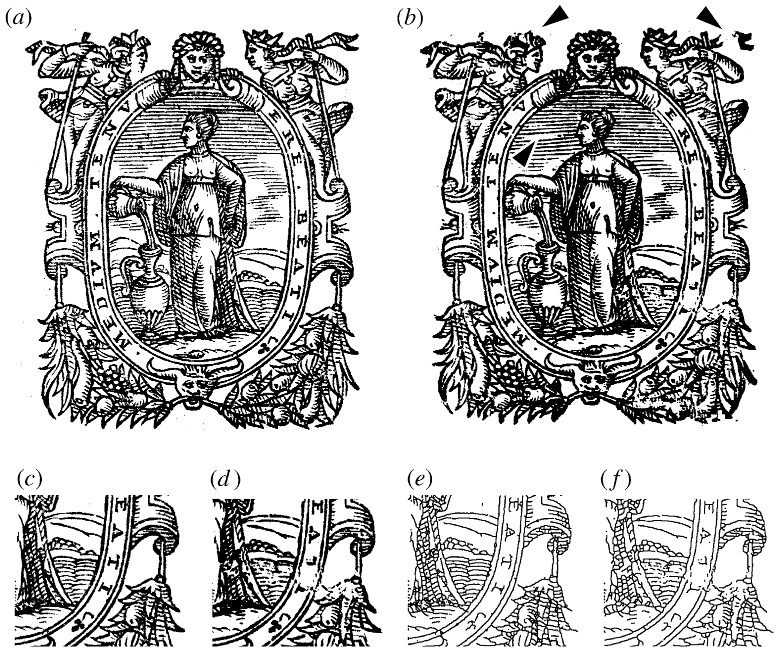

Figure 3. Printer's mark (trademark), a small woodblock print (50×58 mm) used by the printer of the undated *Isolario.* (*a*) Example from the title page of a book by Fiasche printed in 1563. (*b*) Example from the title page of a book by Sfortunati, printed in 1568, showing deterioration; the darker imprint is from application of more ink at the time of printing. Black arrow heads indicate several major breaks among many smaller gaps throughout the image. Close-ups of the lower right region of the print from (*c*) 1563 and (*d*) 1568 showing line breaks in the later print. The same two images from (*e*) 1563 and (*f*) 1568 after application of digital skeletonization, used to compensate for the differential inking of the prints. All images were auto-thresholded. Originals are from Emory University and the Burndy Library (used with permission).

fractal dimension (1564.3, $r=-0.72$), line breaks (1566.9, $r=0.82$), large particle count (1565.2, $r=-0.74$), large particle size (1565.6, $r=-0.79$) and particle perimeter (1564.9, $r=-0.75$). A deterioration index comprising all six measurements (figure 4, $r=0.93$) resulted in an estimate of 1565.4 ± 1.0 years, which was not significantly different from the date estimated independently using the prints contained within the *Isolario* (see above). The slightly lower correlation coefficients obtained with the printer's mark are probably attributable to the shorter interval examined (10 years) and limited sample of prints from a single woodblock. Also, in this case, the source of the deterioration (time versus printing press) could not be tested.

For comparison, a more conventional analysis of physical evidence was performed to determine the date of publication. Fonts and watermarks were photographed in the undated Isolario and in other books by the same printer. The fonts used in the *Isolario* (a folio) were larger and not obviously shared with any of the other books (quartos and octavos) by that printer. Although 51 different watermarks were documented (see electronic supplementary material), none of the 11 found in the *Isolario* were shared with those in other books or were present in relevant watermark atlases (Briquet 1907; Mošin 1973; Woodward 1996*a*).

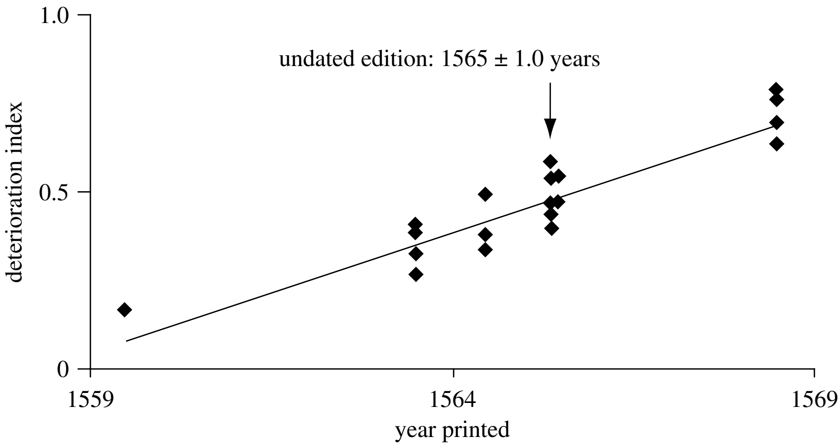

Figure 4. Deterioration of the printer's mark over a 10-year period in the 1560s (r=0.93), showing the estimated date for the undated *Isolario*. Each data point corresponds to a single print and is the average (deterioration index) of six measurements. The regression line was calculated based on the five dated books; the data for the undated *Isolario* were centred on the corresponding position of the trendline.

Even concerning the 40 books examined other than the *Isolario*, watermarks were remarkably unique: only three (6%) were present in more than one book, with two involving pairs of books published in the same year and the third involving a pair of books published 2 years apart. But this uniqueness also meant that they were unusable for dating the undated *Isolario*.

(*b*) *Copperplate print analyses*

The primary form of deterioration in copperplates is fading (paling) of the image over successive editions. For the analyses of Porcacchi's *L'isole più famose del mondo* (Porcacchi 1572), three prints were selected for detailed analysis: Cuba (figure 5*a*), Hispaniola (figure 5*b*) and the title page illustration (figure 5*c*). As an additional test, Magini's *Geographiae* (Magini 1596) was selected, because the spacing of printed editions in time was considerably uneven: 2 years between the first (1596) and second (1598) editions compared with 23 years between the second and third (1621) editions. This unevenness provided an assessment of the print clock hypothesis: if the deterioration is time dependent, there should be little difference between the first two editions, whereas if print dependent, then the second edition should have intermediate levels of deterioration between the first and third editions. The last print in Magini's *Geographiae*, a nautical map of the world (figure 5*d*), was selected owing to its dense engraving.

Digital photos of the Porcacchi prints were taken from 20 original books representing all six editions. Both individually and combined, the correlations between grey level and time in the two maps were high (figure 6*a*). Multiple regression analysis showed significant support ($p<0.001$) for a relationship with time but not with the number of prints, as estimated indirectly from global library holdings or assuming a constant number of books printed for each edition.

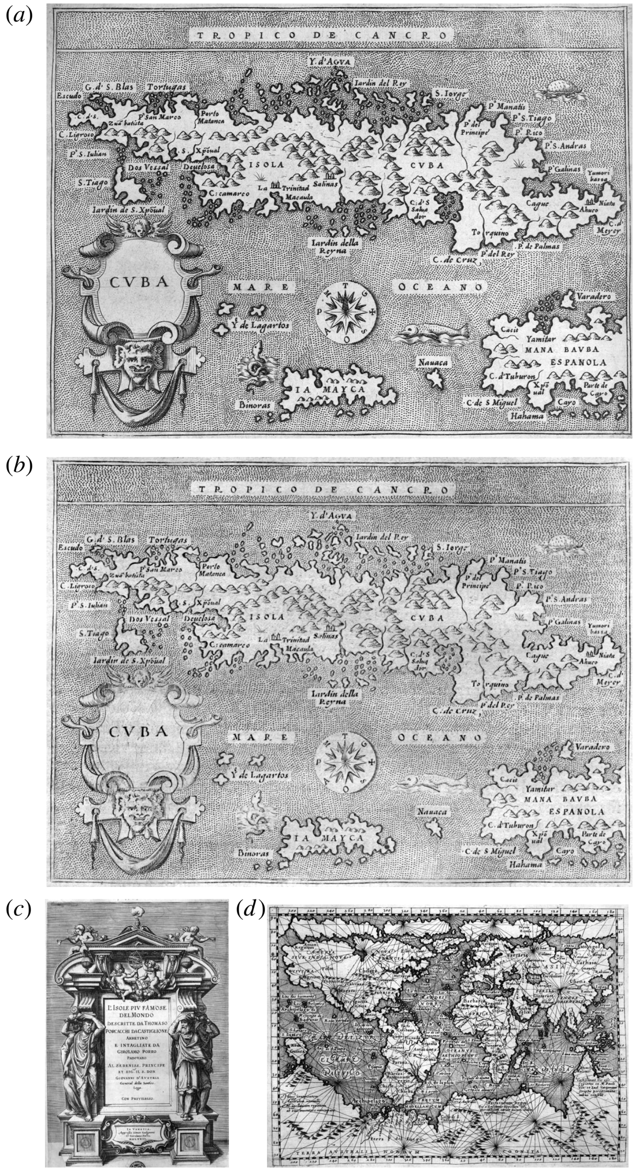

Figure 5. Renaissance copperplate prints. (*a*) Map of Cuba from first edition (1572) of Porcacchi's *L'isole più famose del mondo* (143×104 mm). (*b*) A print made by the same copperplate, from the sixth (1620) edition, showing fading caused by deterioration of the plate, not from aging of the print itself. (*c*) Title page (print) from the first edition of Porcacchi's book (247×170 mm). (*d*) World map from the first (1596) edition of Magini's *Geographiae* (170×125 mm). All images were auto-thresholded. Originals are from Lehigh University (used with permission), the author's collection and the Library of Congress.

The title page showed a similar relationship between grey level and time (figure 6*b*) until the last edition (1620), which is much darker than others and shows obvious signs of retouching (recutting) by the printer, which would have occurred immediately prior to the printing in 1620.

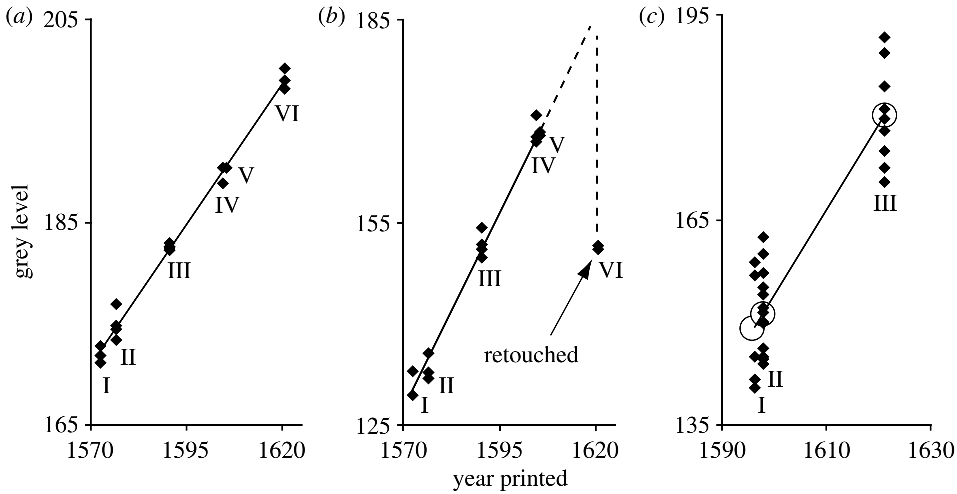

Figure 6. Time-dependent change in copperplate prints. (*a*) Fading of Porcacchi prints (Cuba and Hispaniola combined) as measured by increasing grey level through six editions: 1572, 1576, 1590, 1604, 1605 and 1620 (editions indicated by roman numerals). (*b*) Fading of Porcacchi's title page through time, with abrupt reversal in last edition caused by retouching of the plate that occurred around 1620 (dashed line). (*c*) Fading of the print (map of world) from Magini's book through three editions: 1596, 1598 and 1621 (open circles indicates the mean for each edition).

Analyses of images from 27 Magini prints, all made by the same copperplate over three editions, showed changes in mean grey level that were proportionate with time (figure 6*c*). Again, multiple regression analysis showed significant support ($p<0.001$) for a relationship with time but not with number of prints. The variance within editions, including broad overlap of 1596 and 1598 editions (figure 6*c*), was probably caused by variation in image sharpness (most likely) or differential inking of the grooves during printing. Most of these images were acquired from libraries, using different photographic conditions, whereas the Porcacchi images were taken by the author. Regardless of the source, this variation is unlikely to be from action of the printing press, because such print-dependent change would be cumulative and would not overlap between editions.

(*c*) *Copperplate lines*

Until now, the copperplate analyses in this study have involved measurement of black and white pixels (grey level) over broad areas without regard to the specific details of the print. Because engraved copperplate prints are typically made up of thousands of individual lines, it is of interest to know how the lines changed with time.

The prints were composed of both engraved and etched lines (figure 7). The etched lines average 200–300 μm in width and form the borders and outline the major features of the print, such as the cartouche, islands and some lettering. Engraved lines are typically narrower, averaging 100–200 μm in width, and illustrate finer details, such as sea dots and cartouche shading (figure 7).

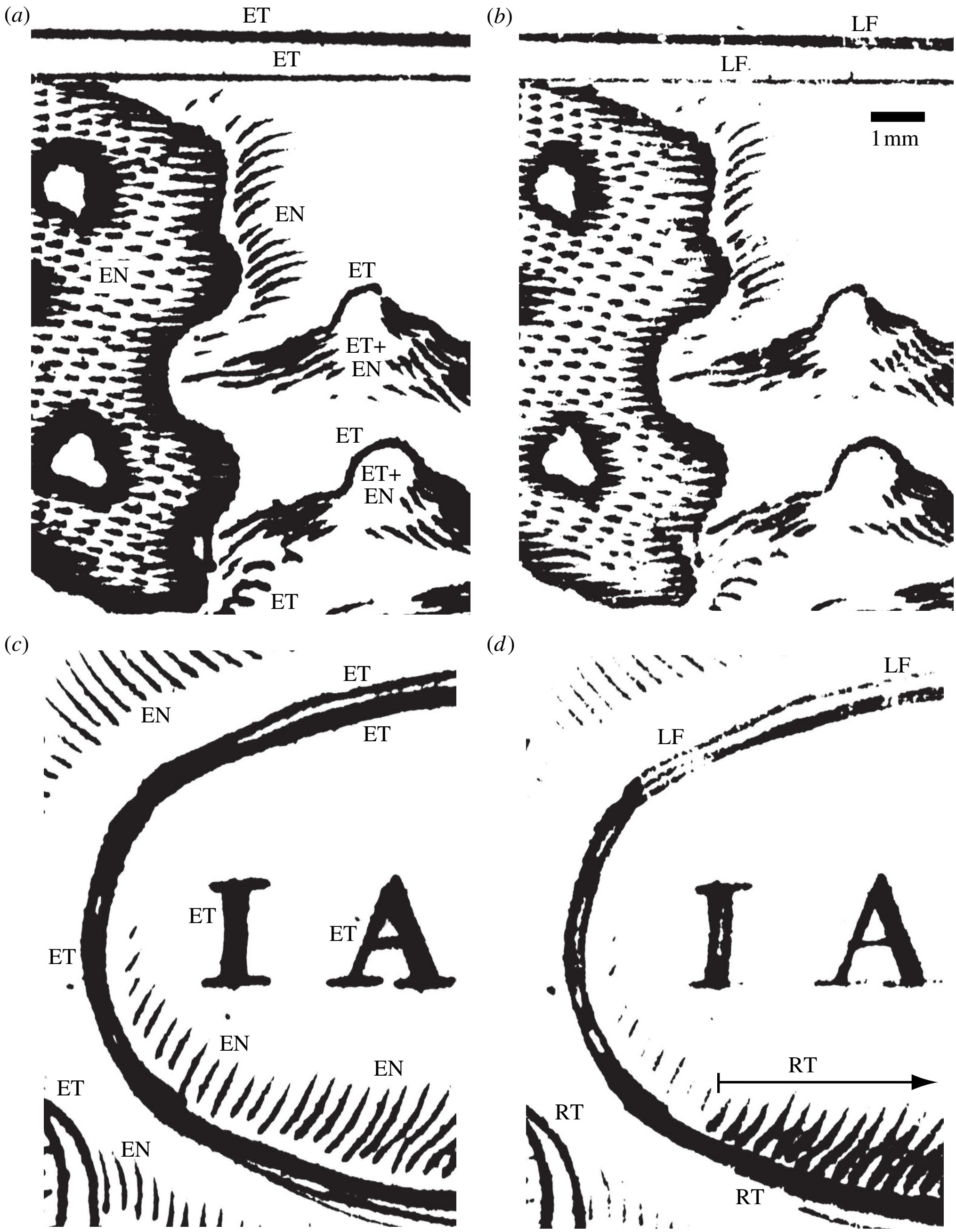

Figure 7. High-resolution (4800 dpi) images of two small (8.5 mm wide) portions of a copperplate print (Porcacchi's Jamaica), from the 1576 edition (left) and 1604 edition (right), illustrating engraved lines (EN), etched lines (ET), line fading (LF), retouching (RT) and line thinning (all lines except those retouched). Some lines probably combine etching and engraving (ET+EN). (a, b) Part of the upper right border of print showing sea, islands, coastline and hills below two upper border lines. (c, d) Part of the cartouche on the upper left region of the print. All images were auto-thresholded. Scale bar in (b) applies to all four images. Originals are from the author's collection.

Both etched and engraved lines are visibly thinner in the later (1604) edition, compared with those in the earlier (1576) edition (figure 7). In the later edition, the narrowest engraved lines are absent and other engraved lines are shorter at the narrow end. Some lines in the later edition appear faded and contain gaps, referred to here as 'line fading'. This was observed more frequently with etched lines than with engraved lines. Also, small areas of retouching were found on the Jamaica print, identified by coarser lines of greater width in the later edition, easily distinguishable from surrounding lines (figure 7).

The line measurements provided a quantitative estimate of the degree of line thinning (figure 8). First, they showed that both etched lines and engraved lines exhibit line thinning. However, etched lines (figure 8*a*,*b*) were less variable and changed at a slower rate than engraved lines (figure 8*c*,*d*). The rate of line thinning of etched lines was 1.48 ± 1.05 (Jamaica) and $1.50 \pm 1.01\ \mu\mathrm{m\ yr}^{-1}$ (Hispaniola), whereas the rate for engraved lines was $2.09 \pm 1.02\ \mu\mathrm{m\ yr}^{-1}$ (Jamaica) and $2.12 \pm 1.12\ \mu\mathrm{m\ yr}^{-1}$ (Hispaniola). Furthermore, the narrow etched lines changed at the same rate as the wide etched lines (slope=0.96, Jamaica; 1.00, Hispaniola), whereas narrow engraved lines changed more slowly than wide engraved lines (slope=0.65, Jamaica; 0.60, Hispaniola).

(*d*) *Copperplate grooves and rates of change*

Together with knowledge of how copperplates were prepared and used in printing, from early reference manuals, these line measurements now reveal how copperplates changed in successive editions. It is widely held that deterioration of copperplates is the result of the printing process itself and, in particular, the great pressure of the rolling printing press (Hind 1923; Verner 1975; Griffiths 1996). Such a mechanism predicts that copperplates are compressed over their lifespan, and that lines become wider. However, the observation here that lines become thinner indicates that compression is not involved. As an additional test of the compression hypothesis, precise measurements (0.01–0.05 mm precision) of overall print dimensions (between outer borders) were made to check for expansion in later editions that might indicate compression of the plates that produced them. Measurement differences between early and later editions of prints were negligible (less than 1%) and did not show expansion (see electronic supplementary material).

Engraved grooves in a copperplate are triangular shaped. Therefore, the thinning of lines with time indicates that the surface of the plate was eroded, exposing the lower and narrower portions of the grooves. The explanation for surface erosion can be found in printing manuals, including the earliest (Bosse 1645; Faithorne 1662; Verner 1975; Saff & Sacilotto 1978). Plates were routinely polished prior to each print run to remove any nicks, stains, or corrosion that accumulated during storage. This abrasion was done in a stepwise fashion (coarser to finer) by using a grinding stone, pumice stone, hone stone, hardened charcoal, steel burnisher, and finally the plate was rubbed with stale bread crumbs or powdered chalk for a smooth finish. Otherwise, the defects would retain ink and be printed.

An alternative explanation is that plate wear was caused by wiping during the inking process (Gascoigne 2004). After ink was poured and distributed in the grooves, the plate was wiped vigorously with rags to remove excess ink. However,

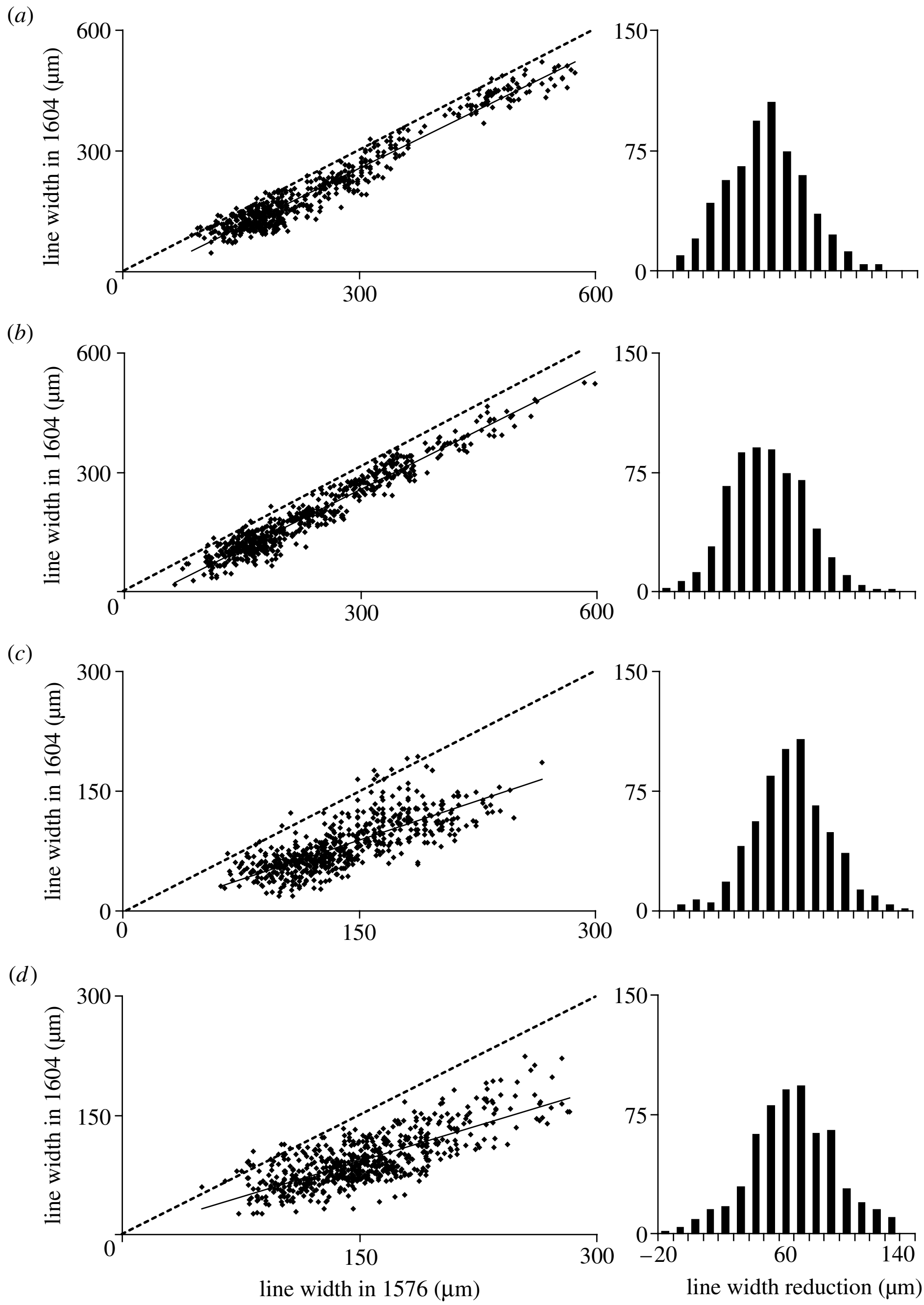

Figure 8. Thinning in etched and engraved copperplate lines in Porcacchi prints between 1576 and 1604. In each case, a scatter plot of the line width data is shown on the left followed by a histogram of the amount of line width lost (1576 line width minus 1604 line width) on the right. (*a*) Thinning of etched lines in the Jamaica print (slope = 1.00). (*b*) Thinning of etched lines in the Hispaniola print (slope = 0.96). (*c*) Thinning of engraved lines in the Jamaica print (slope = 0.60). (*d*) Thinning of engraved lines in the Hispaniola print (slope = 0.65). Solid lines are the trendlines of the data; dashed lines indicate position of data if there was no change (slope = 1).

copper is a metal that cannot be eroded easily by rubbing with cloth, and therefore this mechanism would not explain the significant amount of copperplate erosion predicted by line thinning.

For centuries, engravers have predominantly used two major types of burins: a square burin, with a 90° cutting angle, for making mostly curved lines, and a lozenge burin, with a 60° angle, for making mostly straight lines, although both burins can be used for both types of lines. Most importantly, the wider angle of the square burin makes it more useful for wide lines, whereas the narrow (steep) angle of the lozenge burin is considered best for the finest lines because it produces deeper grooves (relative to line width) that last longer (Bosse 1645; Faithorne 1662; Saff & Sacilotto 1978). An Italian printing manual from the seventeenth century (Tempesti 1994) describes square and lozenge burins and also mentions an intermediate shape (ordinary) and another (acute) with an even steeper angle than the lozenge. Therefore, it would appear that burin angles varied within the approximate range of 90°–60° and possibly included even steeper (smaller) angles. Because the specific angle determines the rate at which lines will thin, this probably explains the wide variation in the rate of engraved line thinning. Also, the preference for steep-angled (lozenge) burins for engraving narrow grooves probably explains why narrow engraved lines changed at slower rates (figure 8*c*,*d*).

In knowing the width of a printed line, it is possible to extrapolate the depth of the triangular-shaped groove in the copper that created the line. The square burin produces a groove forming an isosceles right triangle (depth $=1/2$ line width; figure 9*a*) and the lozenge burin produces a deeper groove forming an equilateral triangle (depth $=(1/2)\sqrt{3}$ line width; figure 9*b*). Thus, groove depths in the copperplates that produced the prints examined in this study, which have engraved lines 50–300 μm in width, ranged from 25 to 260 μm deep. Typical engraved lines, 100–200 μm wide, correspond to grooves that were 50–175 μm deep. This linear relationship between groove depth and line width means that, for every micrometre of copper eroded from the surface of the plate, engraved lines on the resulting prints became approximately 1–2 μm thinner. Assuming an equal mix of grooves produced by square and lozenge burins, the rate of line thinning measured in the two Porcacchi prints (2.1 μm yr^{-1}) thus corresponds to an average rate of surface erosion of the Porcacchi copperplates of approximately 1.4 μm yr^{-1}. Although this is an average, the copper was not removed continuously from the surface but rather in discreet events (plate polishing) prior to each print run.

For etched lines, it is not possible to derive these same estimates because the groove was trough shaped (figure 9*c*). Nonetheless, the reduction in line width of etched lines (figure 8*a*,*b*) with time indicates that the walls of the etched grooves must have been tapered. If there was no tapering and they were vertical, then there would be no line thinning. It is also known that etched grooves are generally shallower than engraved grooves of the same width (Woodward 1996*b*). The observation that etched lines often have pigment gaps (i.e. line fading) in later editions (e.g. figure 7*b*,*d*) is consistent with surface erosion of a copperplate reaching the bottom of the trough, abruptly ceasing its ability to hold ink. This contrasts with engraved grooves, which will continue to print thinner and thinner lines with successive editions until they reach the bottom of the triangular groove (although the thinnest engraved lines also show line fading as they reach the bottom of the triangular groove; figure 7).

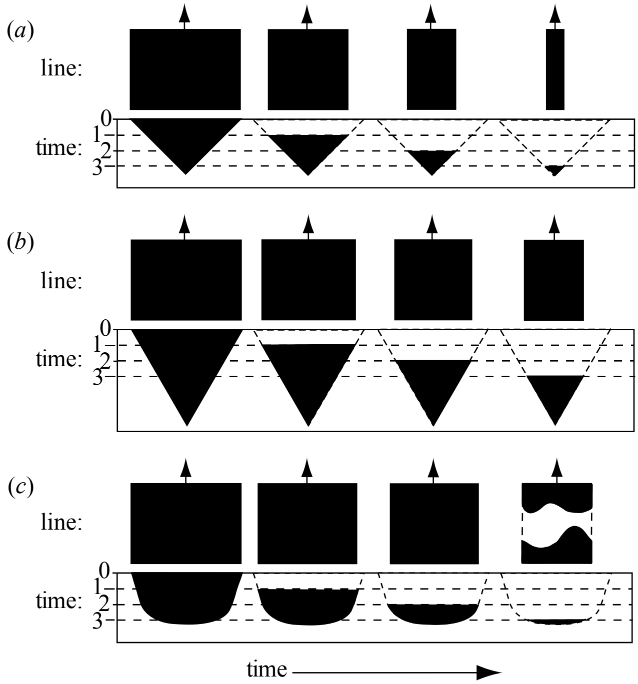

Figure 9. Model showing how surface erosion (polishing) of copperplates altered the shape of engraved and etched grooves and affected the resulting lines on paper, over time. In each panel, a single groove is shown in the copperplate at four points in time (arbitrary units 0–3). Dashed lines represent the surface of the plate at each time point, as more copper is removed and the plate becomes thinner. The cross-section of the ink-filled groove is shown in black. The resulting lines (width = horizontal) are shown above each groove. (*a*) Grooves and lines produced by a square burin, with 90° cutting angle, thin at a fast rate. (*b*) Grooves and lines produced by a lozenge burin, with 60° cutting angle, thin at a slower rate. (*c*) Grooves and lines produced by etching, thin at an even slower rate, but eventually become broken (fade) as the bottom of the trough-shaped groove is reached.

There are at least two other explanations for line fading: dried ink and uneven inking of the plate. Line fading caused by dried ink in grooves was specifically noted in early printing manuals, and procedures to remove the ink were described, such as placing the plate in boiling water (Dossie 1764). It also remains a concern with modern copperplate printing (Peterdi 1961). Based on a rate of 50–100 prints produced per day by a Renaissance printer (Woodward 1996*b*), a typical print run (edition) of 500–1000 prints would have taken at least one to three weeks. During this time, it is likely that dried ink accumulated in grooves causing at least some fading of lines (etched and engraved) in later prints from an edition. This may also explain why the darkest and most detailed prints are considered to come from early during a print run.

Owing to the way that ink was applied to grooves, uneven inking is less of a problem with copperplate prints than with woodblock prints, although over-wiping of a plate could unintentionally remove ink from grooves. However, faded lines resulting from uneven inking would be expected to occur adjacent to one another in a region of the print, not as isolated lines.

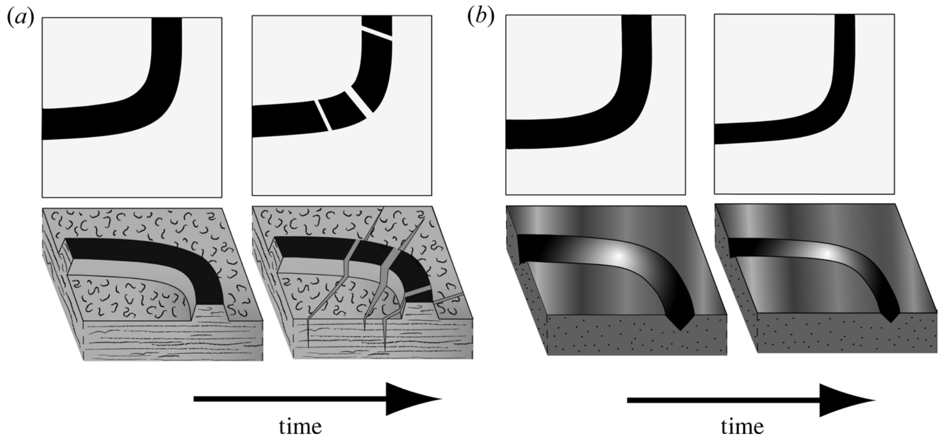

Figure 10. Summary model showing the proposed mechanism for time-dependent change in woodblock and copperplate prints (the print clock). Close-ups of part of a (*a*) carved woodblock and (*b*) engraved copperplate are shown, corresponding to a curved black line on the resulting print behind it, at two time periods. In the woodblock, where raised wood transfers ink to the paper, cracks and nicks develop randomly with time resulting in line breaks in the corresponding print. In the copperplate, where ink in grooves is transferred to paper, deterioration (e.g. corrosion) during storage is polished off the surface prior to each print run. This results in thinner grooves in the plate and thinner lines in the print. In both cases, stochastic deterioration results in a constant rate of change in the prints.

(*e*) *The print clock mechanism*

The finding of time-dependent change in early prints was unexpected owing to the general assumption that deterioration of woodblocks and copperplates occurred from use (Hind 1923; McKerrow 1927; Gaskell 1972; Griffiths 1996). Instead, a stochastic process, analogous to the random radioactive decay of geologic clocks and the random genetic mutations of molecular evolutionary clocks (Hedges & Kumar 2003), appears to be the print clock mechanism. For woodblocks, it is likely that this clock mechanism derives from the aging of the wood, forming cracks and wormholes between printing events (figure 10*a*). In the case of engraved copperplates, surface erosion produced thinner lines in later editions of prints (figure 10*b*), explaining why those later prints appear faded. But an equal amount of erosion from plate polishing before each print run would not explain time dependency. The stochastic mechanism for copperplates is likely the aging and deterioration, including corrosion, of the copper during storage.

The vulnerability of copperplates to corrosion during storage is well known (Peterdi 1961), and typical atmospheric rates of corrosion in unpolluted areas, 1–2 $\mu m\ yr^{-1}$ (Mattsson & Holm 1982), are consistent with the estimated rate of surface erosion in the two Porcacchi copperplates (1.4 $\mu m\ yr^{-1}$). Even the slower rates of corrosion that occur under protected, indoor conditions would result in loss of engraved lines over time. Modern copperplates are often protected from corrosion by application of grease or varnish (Peterdi 1961), but it is unclear how early printers protected their plates, aside from keeping them in a dry place (Bosse 1645; Faithorne 1662). Engraved plates were always considered items of value by printers and kept for years, and the relative cost of producing them, compared with other methods of producing prints, increased with time (Woodward 1996*b*). Therefore, it is possible that concern over protecting plates from deterioration increased with time as well.

Because the purpose of the polishing step was to remove surface deterioration and wear, including corrosion, longer time intervals during storage would have resulted in deeper deterioration and required proportionately more abrasion and polishing to remove it. If corrosion had nothing to do with the time-dependent change observed in copperplate prints, some other time-dependent mechanism must be proposed to explain that observation. The recent discovery that a single copperplate was used to print as many as 18 000 prints (up to 6400 without retouching; Bowen & Imhof 2005), compared with previous estimates of 1–3000 prints per plate (Hind 1923), supports the hypothesis here that most plate deterioration was probably not from the action of printing.

(*f*) *Dating early books and prints*

More research is needed to determine if the woodblock and copperplate print clocks apply generally to a diversity of prints and time periods. For example, some printing presses were located in areas with higher rates of corrosion than others, and some individual plates may have been protected from corrosion. One limitation of the print clock is that it requires calibration with dated prints produced from the same printing device, which may be unavailable. Nonetheless, even a unique book surviving as a single copy could be dated with the printer's mark alone as long as other books by that printer (e.g. written by different authors) are available.

Normally, two or more calibrations are needed, but only a single calibration might be sufficient if rates of line thinning in copperplate prints are shown to be broadly similar. One advantage of using line width in copperplate prints instead of grey level measurements is that virtually any engraved print can be used, even those with mostly retouched lines. As long as some original lines can be distinguished in the print and followed through in different editions, they can be used for dating. If the date of retouching is known, even a retouched line can be used from that point forward, until it was again retouched. For woodblock and copperplate prints, any type of illustration in a book may be used, such as title page ornamentation, enlarged letters and decorative elements (headpieces and tailpieces). Different objects will probably have different rates of change, but this is not a problem for dating.

Compared with current methods of dating, such as the use of watermarks, the print clock has the advantage of dating the print and, in some cases, the original artwork (e.g. woodblocks), rather than the paper. Nonetheless, watermarks and other physical aspects of books and prints (Needham 1994) remain indispensable tools. Unfortunately, only a small fraction of early printed works (including their watermarks) have been scanned or otherwise digitally archived, and the quality of those images varies. This and other scientific studies of art and early printed works (Bucklow 1997; Taylor *et al.* 1999; Rasmussen 2001; Lyu *et al.* 2004) illustrate the usefulness of image analysis and the need for creating global databases of images for a better understanding of our cultural history.

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