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Discovery of the New World's Oldest Extant Metal-Type–Printed Book in Korea through Image Acquisition, Comparison, and Analysis

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Image acquisition, comparison, and analysis technology was applied to address questions regarding medieval Korean printing technology that have existed for fifty years. Two nearly identical books of *The Song of Enlightenment* (南明泉和尙頌證道歌), with Korean treasure status, were investigated based on material properties of metal, wood, and ink. It led the discovery of the new world's oldest extant metal-type-printed book in the thirteenth century in Korea. One version was identified as metal-type-printed in early September of 1239, as stated in the inscription. It predates *Jikji* (直指), the oldest extant metal-type-printed book officially recognized by UNESCO, by 138 years and the Gutenberg 42-line Bible by 216 years. This was a stunning discovery of the history of innovations in printing technology in the thirteenth century from the East. The other version was identified as woodblock-printed in the Joseon dynasty of Korea between the fifteenth and sixteenth centuries. Omni-directional shrinkage of printed pages was observed from the duplicated woodblock printed version. Ink tones and printing patterns of medieval Korean printing techniques were also significantly different and provide important clues for printing technique identification. The characteristics of the two books were compared with the *Jikji* and Bible to find similarities and differences between medieval prints from the East and the West.

La technologie d'acquisition, de comparaison et d'analyse d'images a été appliquée pour répondre à des questions sur la technologie d'impression coréenne médiévale qui existent depuis cinquante ans. Deux livres presque identiques de *Le Chant de l'immédiat satori* (南明泉和尙頌證道歌), ayant le statut de trésor en Corée, ont été étudiés en fonction des propriétés matérielles du métal, du bois et de l'encre. Cela a conduit à la découverte du plus ancien livre imprimé en caractères métalliques existant dans le monde, datant du XIIIe siècle en Corée. Une version a été identifiée comme imprimée en caractères métalliques au début de septembre 1239, comme indiqué dans l'inscription. Elle précède le *Jikji* (直指), le plus ancien livre imprimé en caractères métalliques officiellement reconnu par l'UNESCO, de 138 ans, et la Bible de Gutenberg en 42 lignes de 216 ans. Cette découverte a bouleversé l'histoire des innovations en technologie d'impression au XIIIe siècle en provenance de l'Est. L'autre version a été identifiée comme imprimée en xylographie durant la dynastie Joseon en Corée, entre les XVe et XVIe siècles. Un retrait omnidirectionnel des pages imprimées a été observé dans la version imprimée en xylographie. Les tons d'encre et les motifs d'impression des techniques d'impression médiévales coréennes étaient également très différents et fournissent des indices importants pour l'identification des techniques d'impression. Les caractéristiques des deux livres ont été comparées avec le *Jikji* et la Bible pour trouver des similarités et des différences entre les impressions médiévales de l'Est et de l'Ouest.

1. Introduction

The invention of paper and printing has been an icon of creativity and innovation in the development of human society because it allowed literacy to expand more rapidly and promoted the sharing of ideas among people (Brockman 1999; Gormley 2000). The history of printing starts as early as 3000 BCE. Woodblock printing for texts on paper originated during the Tang (唐) dynasty (618–907 CE) of China in the seventh century. Later, a copper-based movable type printing technique was developed and implemented in the Goryeo (高麗) dynasty (918–1392 CE) of Korea. The invention of the printing press by Johannes Gutenberg in 1450 was listed as the greatest invention of all (Gormley 2000; Carter [1925] 1955). Without the invention of paper (Hunter 1943; Gunarantne 2001), woodblock printing techniques (Galambos 2015; Shi 1988; Harvill 2023; Coppola 2024; Yan 2023; Hang and Van 2020; Pan 1997), metal-type casting, proper ink, and metal-type printing techniques (Ok 2013; Sohn 1959; Sohn 1971; Ch'on 1978; Ch'on 1984; Newman 2016) before Gutenberg in 1450, the printing press would have never been invented. As such, consideration of the origin and dissemination process of metal-type technology is a major research topic to confirm the progressiveness of human history. Numerous studies have been conducted in the area of philology, paleography, and bibliography to reveal the true history of printing.

Wooden movable type printing was first invented in Asia. Korea is known to be the pioneering country in the history of printing. The Great Dharani Sutra (Korean: 무구정광대다라니경, 無垢淨光大陀羅尼經) is a copy of the Uṣṇīṣa Vijaya Dhāraṇī Sūtra, a scripture of Mahayana Buddhism, which is considered to be the oldest woodblock printed text in the world (Pan 1997; APHA 2024). The size of the scroll is approximately 8 cm wide and 620 cm long. The width of the printed text is 6.5–6.7 cm. This ancient work was discovered in October 1966 during repairs of the Seokgatap (釋迦塔, the three-storied pagoda) in the Bulguksa Temple (佛國寺), which is located in Gyeongju (慶州), Korea. It was printed on mulberry paper during the Silla (新羅: 57 BCE–935 CE) dynasty of Korea. It has been speculated to have been made during the reign of Empress Wu (武則天) (690–705 CE) of China's Wu Zhou (武周) dynasty and no later than 751, the year of completion of the Bulguksa Temple construction (Park 2014). Metal movable type printing was a new development introduced in Korea in the twelfth to thirteenth centuries (Ok 2013; Sohn 1959; Sohn 1971; Ch'on 1978; Ch'on 1984; Newman 2016; Park 2014). Unlike wooden movable type printing, it posed two greater development challenges of metal-type casting of fine features and proper ink, with good wetting properties, on the metal-type surface through surface tension of the ink and surface energy of the metal type.

Despite these greater technical challenges, the invention of metal-type printing took place as early as 1234 in the Goryeo dynasty of Korea. It was more than 200 years prior to the invention of the printing press in Europe (Ok 2013; Sohn 1959; Sohn 1971; Ch'on 1978; Ch'on 1984; Newman 2016; Park 2014). It is comparable to the most advanced semiconductor manufacturing technology today.

There is a lot of ambiguity regarding the history of printing, in particular, the origin of metal-type printing. It is worthwhile to investigate the old books, previously overlooked and/or ignored by historians based on their previous knowledge or very subjective personal opinions. We have applied new image analysis technology to probe medieval Korean printing technology and draw conclusions on questions and debates, which have lasted for half a century, on the printing technique of an ancient Korean book.

Digital images contain very rich information for quantitative analysis of colour, brightness, contrast, white balance, etc. The shape, area, dimensions, outline, and contour information can be extracted based on digitized pixel values. It can provide valuable data for objective reasoning to clarify ambiguous and potentially subjective justifications based on an examiner's personal experience, knowledge, and uncertain memory. Digital image forensics can provide additional insights into old document heritage.

2. Materials and method

2.1. A candidate for the oldest metal-type printed book

Officially, the oldest extant metal-type–printed book to date, recognized by UNESCO, is *Jikji* (直指), abbreviated name for *Baegun Hwasang Chorok Buljo Jisimcheyojeol* (白雲和抄錄佛祖直指心體要節), printed by the Heungdeoksa Temple (興德寺)in Cheongju (淸州), Goryeo dynasty of Korea in 1377 (Ch'on 1978; Park 2014; Päk un 1377; UNESCO 2023a; Yoo 2022a; Yoo 2022b; Yoo 2022c; Yoo 2023a). The *Jikji* book is kept at the National Library of France (Bibliothèque Nationale de France). Victor Collin de Plancy (1853–1924), the first French diplomat to Korea, had brought the book back to France at the end of the nineteenth century from Korea. He served as a French diplomat in Korea nearly a decade from 1884.

The 42-line Gutenberg Bible, printed in Mainz, Germany, in the 1450s (often said to be 1455), is the oldest metal-type–printed book from the West (Brockman 1999; Gormley 2000; Gunarantne 2001; Galambos 2015). Both *Jikji* and the Gutenberg 42-line Bible were confirmed by UNESCO, who included them in the Memory of the World Programme in 2001 (UNESCO 2023a; UNESCO 2023b; Päk un 1377; Sakhri 2022).

According to ancient Korean literature, twenty-eight (28) copies of Sangjeong Gogeum Yemun (詳定古今禮文) are estimated to have been printed between 1234 and 1241, and are possibly the first examples in recorded history of movable metal-type printing (Ok 2013; Sohn 1959; Sohn 1971; Ch'on 1978; Ch'on 1984; Newman 2016; Park 2014). Since no copies have been found, it has not been recognized as the oldest book printed with metal movable type. For years, many Korean historians have been searching for metal-type–printed books that predate 1377, the publication year of *Jikji*. Six very similar books, with the printed postscript stating metal-type print and dated September 1239, have been found since the 1920s (Ok 2013; Sohn 1959; Sohn 1971; Ch'on 1978; Ch'on 1984; Newman 2016; Park 2014).

The books have 87 printed pages. The title of the book is Nammyeong Cheon Hwasangsong Jeungdoga (南明泉和尙頌證道歌; Song of Enlightenment with Commentaries by Buddhist Monk Nammyeong Cheon). For simplicity, the book will be referred to as *The Song of Enlightenment* or SOE, afterwards. According to the authors' investigation, they are different editions, using different printing techniques in different periods, between the thirteenth and sixteenth centuries, even though all six books contain the identical postscript of Jinyanggong (晉陽公) Choi Yi (崔怡), a powerful ruler of the Goryeo dynasty of Korea (Yoo and Kim 2021; Yoo 2022a; Yoo 2022b; Yoo 2022c; Yoo 2023a; Yoo 2023b; Yoo 2023c).

Two out of the six books were designated as Korean Treasures in 2012 (SOE A) (CHAK 2012) and 1984 (SOE B) (CHAK 1984), respectively (**Figure 1**). They were identified as woodblock printed books in the Goryeo dynasty in the thirteenth century. Their historic value has been recognized and highly appreciated as documentary cultural heritage by Korean historians, as well as by the Cultural Heritage Administration of Korea.

However, it is highly suspected that both books of interest have been misidentified in terms of printing techniques and printing period for the SOE A, as well as the printing period for the SOE B. Currently, both were recognized as woodblock-printed books from the thirteenth century of Goryeo dynasty of Korea (Yoo and Kim 2021; CHAK 2012; CHAK 1984). Contrary to the Cultural Heritage Administration of Korea and Korean historians' statements, the SOE B was identified to be the woodblock-printed book from the fifteenth to sixteenth centuries of the Joseon (朝鮮) dynasty (1392–1894) of Korea based on the authors' previous study Korea (Yoo and Kim 2021; Yoo 2022a; Yoo 2022b; Yoo 2022c; Yoo 2023a; Yoo 2023b; Yoo 2023c).

The seven characters of 募工重彫鑄字本 (meaning: recruited craftsmen to re-publish books using metal type), described in the postscript, are highlighted by red rectangles in **Figure 1**. Missing strokes and age rings and originated splits found from printed

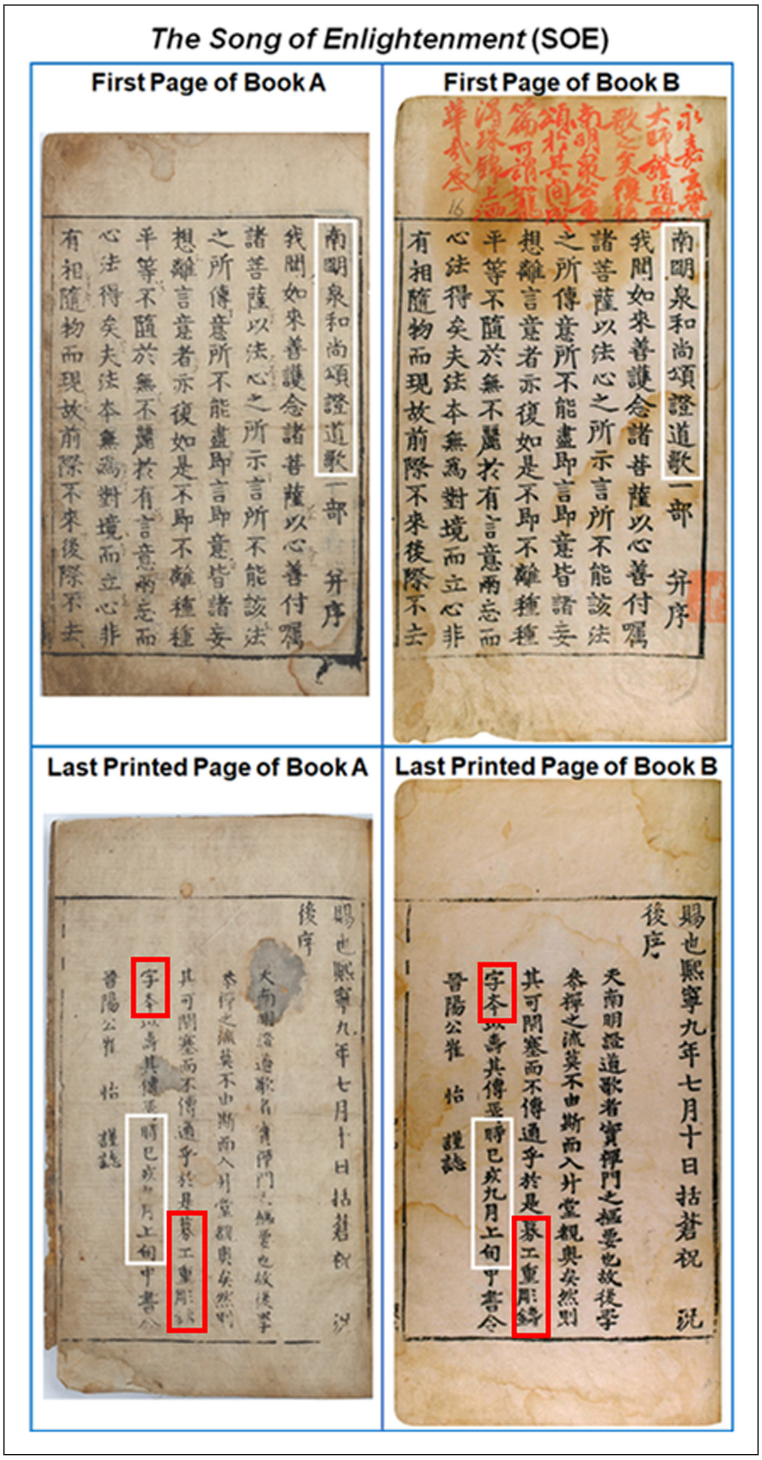

Figure 1: The first and last pages of two books of *The Song of Enlightenment* (SOE). The white rectangles highlight the title (南明泉和尙頌證道歌) of the books and printing dates (時己亥九月上旬: early September 1239) in the postscript. The red rectangles highlight the printing technique (募工重彫鑄字本, meaning: craftsmen were recruited to re-publish books using metal type), as described in the postscript.

characters in the SOE B were very clear evidence of woodblock printing. They also modified the interpretation of one character (彫, carve), which is only applicable to wood, and not for metal. At that time, it was interpreted as evidence for re-publishing the original metal-type–printed book by carving the woodblock. The SOE A was discovered after the publication technique was adopted by many Korean historians, about fifty years ago. The poor quality of printing and the poor appearance of its paper led Korean historians to believe it was a woodblock print at a much later time than the SOE B. They claimed that the SOE A was printed using identical but heavily damaged woodblocks several tens or hundreds of years later. This has been intermittently debated among historians in Korea for the last fifty years. These historical debates were not known outside Korea until the authors' reports (Yoo and Kim 2021; Yoo 2022a; Yoo 2022b; Yoo 2022c; Yoo 2023a; Yoo 2023b; Yoo 2023c). It is time to conclude this debate, with the help of scientific evidence, as implied by the literal meaning of "printing technique" stated in the seven characters of 募工重彫鑄字本, in the postscript.

It is very important to correctly identify the printing techniques and printing periods of the SOE A and SOE B from the viewpoint of understanding and correctly recording the history of this, one of the most important technological innovations of mankind. It will also help to pass the very valuable cultural heritage to future generations by bringing awareness worldwide, perhaps listing them in the Memory of the World Programme of UNESCO.

2.2. Image acquisition, comparisons, and quantitative analysis

A non-destructive, computer-aided, forensic digital image-analysis technique has been proposed and applied to identify the printing techniques and printing periods of both books, SOE A and SOE B. High-resolution digital images of the books were either downloaded from public sites or photographed using a CMOS image sensor-based, full-frame digital camera by the authors. Empirical, qualitative, and subjective characterization methods used by historians or experts in the field often cause more disagreements and hardly ever converge. The fifty years' long debates over printing techniques are challenged by advanced forensic digital image analysis techniques. Customized image analysis functions were added to image analysis software (PicMan from WaferMasters, Inc., Dublin, CA, USA). The PicMan technology was developed and used for automatic and quantitative analysis of many types of digital images, regardless of application field (Yoo and Yoo 2021; Kim et al. 2019; Yoo et al. 2021; Kim, Eom, and Yoo 2022; Yoo et al. 2022; Eom and Lee 2023; Yoo et al. 2023a; Yoo et al. 2023b; Yoo et al. 2023c). To avoid ambiguity and subjectivity, quantitative analysis results are discussed. To be clear, the same results can be reproduced by using combinations of other commercial or open-source image analysis software.

The aspect ratios (height-to-width ratios of printed rectangular borders) of each printed pages of both books, SOE A and SOE B, were measured to gain insight into printing techniques, sequence, and materials used for printing. Ink tone of the two SOE books were quantitatively analyzed and compared with the ink tone characteristics of the *Jikji* (1377) and Gutenberg 42-line Bible (~1455), which were verified to be metal-type–printed books in the East and West (Korea and Germany).

3. Results and discussions

3.1. Printed rectangular border dimensions

Figure 2 shows how the aspect ratios (border dimension ratio) of the SOE A and SOE B were measured, and a graphical summary of border dimension ratios of all forty-four (44) leaves. As seen in the upper part of **Figure 2**, the height of the printed border for the SOE B is slightly shorter than that for the SOE A.

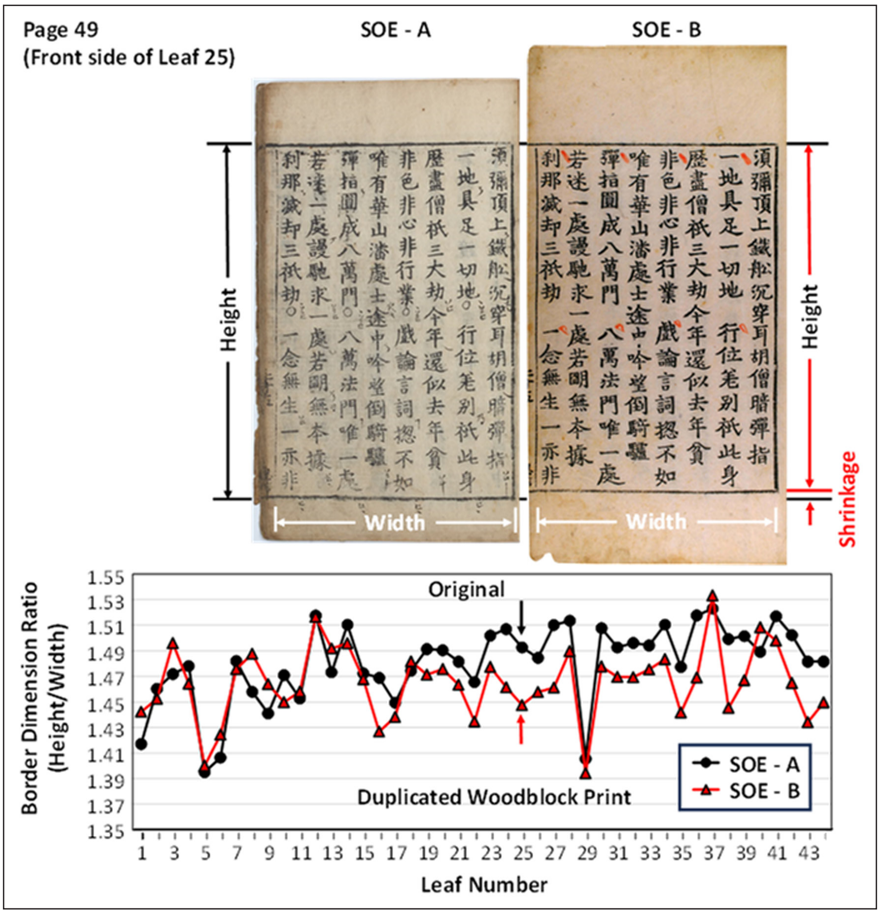

Figure 2: The images of Page 49 (front side of 25th leaf) of SOE A and SOE B (top) and graphical representation of boarder dimension ratio (aspect ratio: border height/border width) of SOE A and SOE B (bottom).

In eighty percent of the forty-four leaves (87 pages and one blank page), the SOE A showed taller border line height, while the border line widths of individual pages are almost identical between the two SOE books. Only border heights showed noticeable shrinkage in the majority (~80%) of the printed pages of the SOE B from the SOE A. It is highly suspected that one of the SOE versions was the original version and the other version is a replica printed using re-carved (or duplicated) woodblocks with various moisture content.

Based on previous studies on printed rectangular boarder dimensions of original metal-type–printed books and their re-carved woodblock-printed books from the Joseon (朝鮮) dynasty (1392–1894) of Korea, all woodblock-printed books showed 3–7% shrinkage in the vertical direction (i.e., radial direction of wood) compared to the original metal-type–printed books. We have compared more than a dozen varieties of books from the fifteenth to eighteenth centuries. It was a very consistent trend. Four specific examples of printed rectangular border shrinkage in the vertical direction of woodblock-printed books due to woodblock shrinkage were given in the previous report (Yoo 2022d; Yoo 2023b; Yoo 2024a; Yoo 2024b).

Figure 3 shows an image of a typical printing woodblock from medieval Korea (Goryeo dynasty). The woodblock image is one of Tripiṭaka Koreana to the Korean Buddhist Canon or Palman Daejanggyeong (八萬大藏經) woodblocks at Haeinsa (海印寺) temple in Hapcheon (陜川) county in Korea (UNESCO 2023c). It is the oldest intact version of Buddhist canon in Hanja (漢字) script in the world. It contains 1,496 titles and is divided into 6,568 books. A total of 52,330,152 Hanja characters were carved on 81,258 sides of woodblocks. It was designated a National Treasure of South Korea in 1962 and is inscribed in the UNESCO Memory of the World Register in 2007. Each woodblock (corresponding to a printed page) measures 24 cm in height and 70 cm in length (Haeinsa Temple 2023). The thickness of the woodblocks ranges from 2.6 to 4 cm, and each weighs about 3–4 kg.

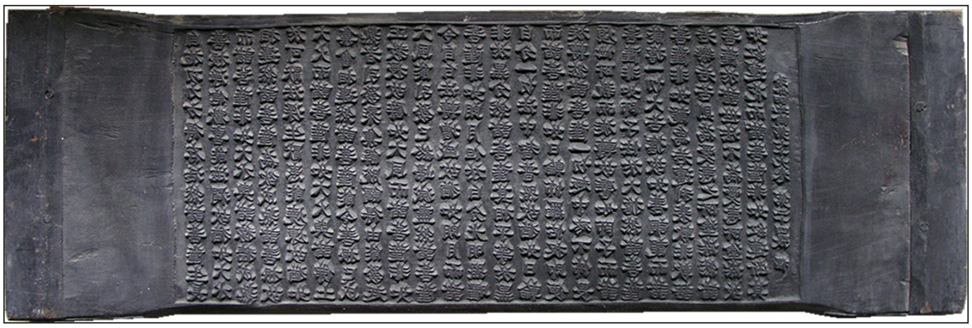

Figure 3: Shape of typical printing woodblock from medieval Korea (one of Tripiṭaka Koreana or Palman Daejanggyeong [八萬大藏經] woodblocks at Haeinsa [海印寺] temple in Hapcheon county in Korea) (Haeinsa Temple 2023).

A radial-longitudinal–cut or slightly off-centred, tangential-longitudinal–cut woodblock was typically used for printing woodblocks. It is well known that the wood is hygroscopic: it has the ability to absorb and release moisture. The wood shrinkage occurs perpendicular to the grain (cross-section dimension: both radial and tangential directions), not longitudinal to the grain (in tree growth direction). Wood shrinks because it loses moisture (water content) as it dries. The shrinkage at tangential cut is bigger than shrinkage at radial cut, as shown in **Figure 4** (McLain and Steimle 2019; Forest Products Laboratory 2010). Higher density (heavier) wood generally shrinks more than lower density (lighter) wood. In general, wood shrinkage is about 8% in the tangential direction, 4% in the radial direction, and 0.1% in the longitudinal (or tree growth) direction from fresh cut/green to fully dried condition.

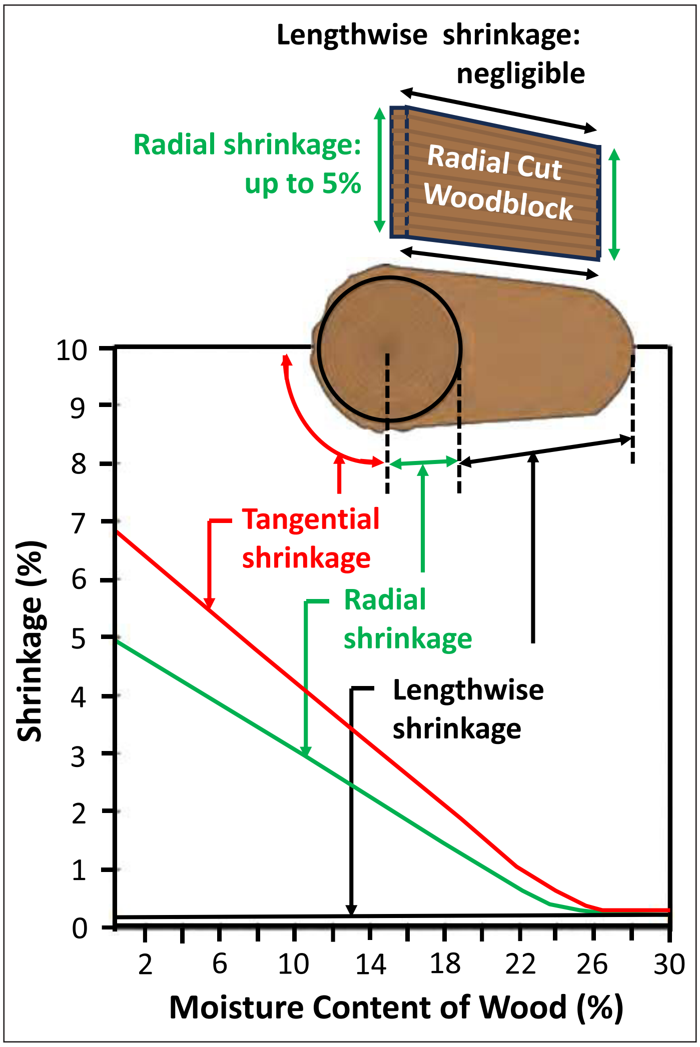

Figure 4: Directional shrinkage as a function of moisture content of wood (McLain and Steimle 2019).

Woodblocks with moderate moisture content are used for carving because it is harder to carve characters when the woodblock is completely dried. Woodblock printing is usually done once all woodblocks for printing are prepared. The moisture content of the woodblock at the time of printing is generally fully dried. The radial dimension (vertical direction of printed border) of the woodblock at the time of printing is normally a few percent smaller compared to the time of carving. The change of dimensions in longitudinal direction (i.e., lengthwise direction or tree growth direction) between the time of carving and printing is negligible. If a slightly off-centred, tangential-longitudinal–cut woodblock is used for carving, the vertical dimension of the printed border may either be shrunk or expanded, depending on the carving face, due to warpage (i.e., bow, twist, cup, and crook) after losing moisture content.

Based on the aspect ratios (border dimension ratio) of the SOE A and SOE B summarized in the graph of **Figure 2**, the SOE A is very likely the original version because it has greater aspect ratio (i.e., larger border height at the identical border width). The shrinkage of border height after losing moisture content from carved woodblocks is strongly suspected as the root cause of the omni-directional shrinkage in vertical border height. This makes perfect sense considering the directional shrinkage of woodblocks from the time of carving to the time of printing. Thus, the SOE A is the original version, and the SOE B is a replica, printed using duplicated woodblock afterwards, as indicated in the inset of the graph in **Figure 2**.

3.2. Ink tone analysis and ink-wetting characteristics

Partial images of the SOE A, SOE B, *Jikji* (1377), and Gutenberg 42-line Bible (~1455) were selected for computer-aided image comparison and analysis (**Figure 5**, top left). The objective is to gain meaningful clues on which everyone can agree. Valid evidence for the identification of printing techniques used for printing the SOE A and SOE B is needed. Heated debates have gone on for fifty years within Korea but were almost unknown to the rest of the world until recently (Yoo and Kim 2021; Yoo 2022a; Yoo 2022b; Yoo 2022c; Yoo 2023a; Yoo 2023b; Yoo 2023c). Quantification of similarities and differences in printed characters for objective characterization of their printing techniques through image comparison/analysis and scientific review of printing characteristics are the main interest of this study.

Figure 5 shows the original set of selected images and three sets of images after highlighting under different conditions. The top left portion of **Figure 5(a)** shows cropped original images from the SOE A, SOE B, *Jikji* (1377) (Päk un 1377), and Gutenberg 42-line Bible (~1455) (University of Cambridge 2023) from left to right. Darkness and uniformity of ink colour among the four books are very different. The colour difference of papers also makes contrast very different, and objective judgment on the darkness of ink colour very difficult. To overcome these difficulties, various inked area highlighting techniques were applied to clearly visualize the difference in ink characteristics. The top right images (**Figure 5[b]**) show false colour images of printed characters after elimination of background paper colour. The false colour conversion was done based on the darkness of printed ink as seen in the two horizontal bars on the right. It is obvious that SOE B showed significantly intense ink tone compared to the other three books. The ink tone for *Jikji* (1377) was the lightest of all. The bottom left images (**Figure 5[c]**) show printed characters without paper colour. The average brightness of 125 out of 0–255 brightness levels clearly separates paper colour and printed characters. Without considering paper colour, the ink tone for *Jikji* (1377) was also verified to be the lightest of all.

Figure 5: Partial images of SOE A, SOE B, *Jikji* (1377) and Gutenberg 42-line Bible (~1455) before and after image highlighting: (a) original images; (b) application of false colour to the printed characters on white background; (c) saturation at brightness threshold at 125 out of 0–255 range; (d) saturation at brightness thresholds at 65 (for SOE A, SOE B, and Gutenberg 42-line Bible [~1455]) and 85 (for *Jikji* [1377]).

To evaluate the uniformity of ink tone in the printed characters, the threshold-switching value for saturation to white colour has been lowered (the bottom right images shown in **Figure 5[d]**) from 125 to 65 for SOE A, SOE B, and the Gutenberg 42-line Bible (~1455), and 85 for *Jikji* (1377). At least three books, SOE A, *Jikji* (1377), and Gutenberg 42-line Bible (~1455) started to show spotty regions of intense ink tones, while the woodblock printed SOE B remained as unchanged characters of a solid black tone of printed characters. These differences in characteristics of ink tones in the four books under investigation could offer very important clues leading towards the identification of the printing technique used in the SOE A. If it is verified to be the metal-type printed, it would be the world's oldest extant metal-type–printed book from September 1239, predating *Jikji* (1377) by 138 years. This could be the discovery that triggers the rewriting of the history of printing.

To investigate the differences in ink tone of printed characters and colour of papers for all four books, colour information of all pixels in the highlighted regions of images has been extracted under different threshold-switching conditions. **Figure 6** shows the RGB brightness histograms of the highlighted regions from all four books: (a) original image including paper colour; (b) threshold switched image at the RGB average brightness of 125; (c) threshold switched at the RGB average of 65 for SOE A, SOE B, and Gutenberg 42-line Bible (~1455), and 85 for *Jikji* (1377).

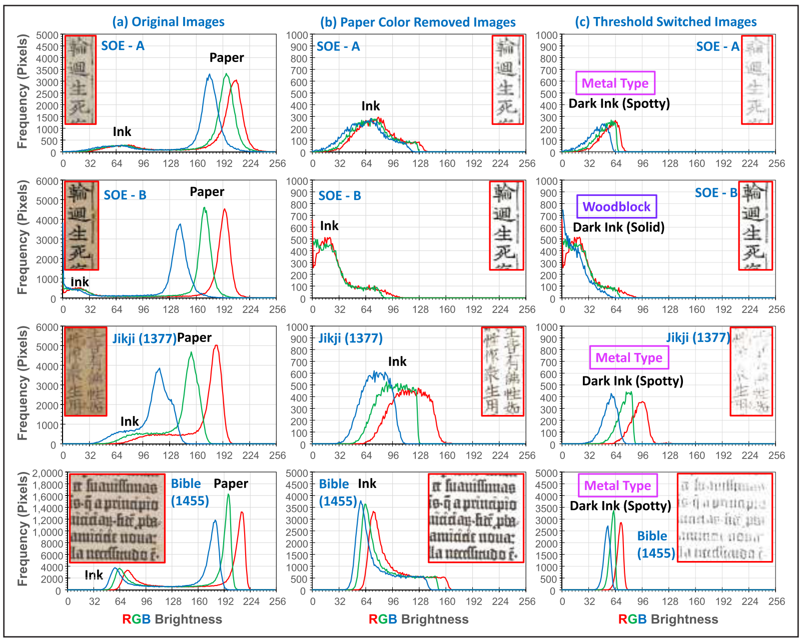

Figure 6: RGB brightness histograms of the highlighted regions from all four books: **(a)** original images; **(b)** paper colour removed images by threshold switching at an average brightness value of 125/255; **(c)** threshold switched images at average brightness values of 65/255 for SOE A, SOE B, and Gutenberg 42-line Bible (~1455), and 85/255 for Jikji (1377).

RGB histogram graphs in the left column (**Figure 6[a]**) show colour distribution of both paper and ink in all four books. As noted in the graphs, histograms of ink showed small peaks in the left side (dark side). The histograms for the *Jikji* (1377) showed strong peaks for the colour of paper and shoulders to the left for the printed ink colour. Since the ink colour was light and the paper colour is the most brownish of all four books, it was difficult to clearly distinguish the ink and paper. They were blended together. To analyze only the ink colour without the influence from the background paper colour, the RGB histograms for threshold switched at an average brightness value of 125/255 are shown in the centre column (**Figure 6[b]**). The SOE B showed a very skewed RGB histogram to the dark side, suggesting the ink tone is very intense compared to the other three books, known to be, or suspected to be, metal-type printed. The ink tone histograms of the three books were broad and skewed due to the blending of ink tone and paper colour.

To visualize the non-uniformity of ink tones, the threshold-switched images at average brightness values of 65/255 (for SOE A, SOE B, and Gutenberg 42-line Bible [~1455]) and 85/255 (for *Jikji* [1377]) and their histograms are shown (right column, **Figure 6[c]**). The SOE B only showed solid pattern of all printed characters, even at the threshold value of 65/255. The other two books (SOE A and *Jikji* [1377]) from Korea showed spotty ink patterns near the edges of printed characters. The Gutenberg 42-line Bible from Germany showed spotty ink patterns near the centre (away from the edge) of the characters. The common characteristics of metal-type prints from the East and West are the non-uniform darkness of ink tones, and they exhibit the spotty printed patterns, while the woodblock-printed book showed very intense ink tone and solid patterns of printed characters, even after threshold switching at lower threshold-switching brightness values. These characteristic phenomena can provide very important clues for printing technique identification of ancient books around the world. These characteristics are the result of combinations of materials (ink/wood and ink/metal) and techniques (hand rubbing and mechanical press) used for printing at the time of printing.

For woodblock printing, ink is easily absorbed by wood surfaces and transferred to paper when it is rubbed or pressed against the inked woodblock surface. It can be rubbed from the backside of the paper, as done in the East, or pressed, as done by Gutenberg's printing press. The carved wood surface behaves like a sponge. It absorbs ink and releases the absorbed ink to paper on contact. The absorptivity of ink to wood varies with the type, density, and surface condition of the wood, but woods are generally good ink-absorbing materials.

In contrast, metal surfaces have poor wetting properties with water or water-based ink due to the surface tension of the liquid. If water-based ink is applied to a metal-type surface, water becomes small spheres (micro droplets) on the surface or may drip to the ground. Water-based ink cannot be used for metal-type printing. Highly engineered inks, mostly oil-based inks, are formulated for metal-type printing even today. Even if metal-type casting were successful, metal-type printing is not possible without using the proper ink that can effectively wet the metal-type surface. It was well understood that the different types of ink-adhesion properties are needed for woodblock printing, and metal-type printing, even in the fourteenth century Goryeo and Joseon dynasties in Korea.

Ad Stijnman, a professional printmaker and print historian, has briefly summarized the required properties of ink for metal-type printing, as follows:

> Ink for printing from metal type on paper, for instance, has higher demands than ink for printing woodcuts on textile. It is important that the ink adheres to the metal in a smooth and as thin—while at the same time as opaque—as possible layer which offsets easily again onto the paper. (Stijnman 2000, 63)

For woodblock printing, a water-based ink stick called Songyeonmuk (松煙墨), made from pine charcoal ink, was used. For metal-type printing, an oil-based ink stick called Yuyeonmuk (油煙墨), made from plant oil charcoal ink, was used. In general, the Songyeonmuk (松煙墨) for woodblock printing has an intense (dark) tone compared to the Yuyeonmuk (油煙墨) for metal-type printing (Ok 2013; Kim, Hwang, and Eom 2022). Ancestors have gained these insights from many trials and errors. In the early development stage of metal-type printing, it would have been very difficult to figure out which properties would give the best printing results using metal type. It required a rich history of material science, physics, chemical engineering, and craftsmanship many centuries ago. Today, we understand that the surface tension of ink, surface energy of metal, and interfacial tension between ink and metal are all important for proper wetting of metal surfaces (Tian, Song, and Jiang 2013; Sensor Instruments 2013). If the metal-type printing technique was not perfectly developed when the books were printed, regardless of geographical location and time, some sort of footprint of metal-type printing could be observed from the image of printed pages, as seen in the graphs in the right column of **Figure 6**. The spotty ink marks observed from the SOE A, *Jikji* (1377), and Gutenberg 42-line Bible are direct evidence of metal-type printing. The light ink tone is also common to all three books. On the other hand, the SOE B showed a solid and intense ink pattern within the inked area, suggesting very favourable wetting of ink on the woodblock surface, as determined by other evidences in previous studies (Yoo and Kim 2021; Yoo 2022a; Yoo 2022b; Yoo 2022c; Yoo 2023a; Yoo 2023b; Yoo 2023c).

Figure 7 shows schematic illustrations of ink-wetting properties on solid surfaces as a function of liquid (ink) surface tension and surface energy of solid (metal and wood). Two characters of 生死 (meaning life and death) from the SOE A and SOE B after threshold switching at 65/255 brightness level are shown. The light spotty print is the result of metal-type printing using a lighter tone ink stick, called Yuyeonmuk (油煙墨), in the printing of the SOE A. The surface wetting on metal-type surfaces was not very favourable at the time of printing due to non-optimum selection of materials. The intense solid print is observed from the woodblock printed SOE B.

The woodblock print had been in practice for at least 700 years prior to the first metal-type printing in the thirteenth century (APHA 2024). Ink properties and printing techniques were optimized long before the printing of the SOE B in the fifteenth to sixteenth centuries. The development of Songyeonmuk (松煙墨) is the outcome of the long-term woodblock printing technique and material optimization. The level

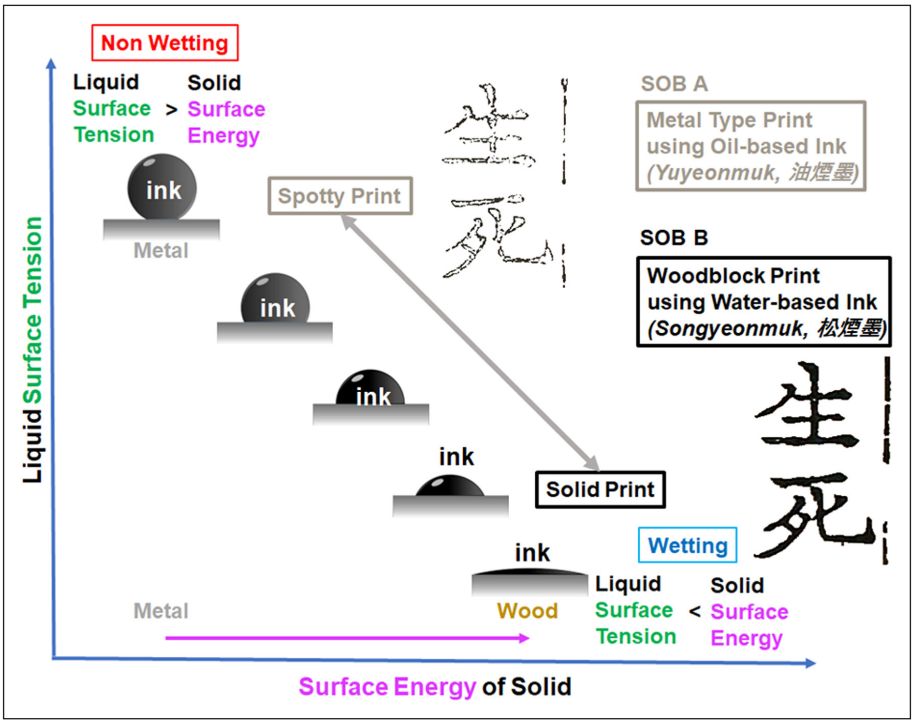

Figure 7: A schematic illustration of ink-wetting properties on solid surfaces as a function of liquid (ink) surface tension and surface energy of solid (metal and wood).

of metal-type printing technique and materials in the fourteenth-century Goryeo dynasty of Korea and fifteenth-century Germany were still at their initial stages of understanding of types of ink and materials used for printing. The importance of surface tension of liquid (ink), the surface energy of solid (metal, wood, paper, etc.), and interfacial tension between liquid and solid are now well-understood phenomena. Today, various types of ink formulas are used for testing surface tension and surface energy before printing and painting on metal surfaces.

4. Conclusions

Image acquisition, comparison, and analysis technology was applied to investigate printing techniques and materials used in medieval Korean printing technology. Forensic digital image analysis of selected images of the SOE A, SOE B, *Jikji* (1377), and Gutenberg 42-line Bible (~1455) has indicated that the SOE A was very likely to be a metal-type–printed book in September 1239. The meaning of seven characters of 募工重彫鑄字本 (meaning: recruited craftsmen to re-publish books using metal type) recorded in the postscript and the characteristics of printed characters support this conclusion. The SOE A is very likely the world's oldest extant metal-type printed book and predates the current official record of *Jikji* (1377) by 138 years and the Gutenberg 42-line Bible (~1455) by 216 years. It is currently designated a Korean Treasure. This was an important discovery of the history of innovations in printing technology in the thirteenth century from the Goryeo dynasty of Korea in the Far East.

All metal-type printed books including the SOE A, *Jikji* (1377), and Gutenberg 42-line Bible showed light ink tones and spotty printing marks due to the poor ink-wetting characteristics on a metal surface. From duplicated woodblock printed version (the SOE B), omni-directional shrinkage of printed pages in the height direction and the very intense ink tone of characters were observed. This image analysis technique can be applied for characterization of other historical documents in proving printing techniques.

The SOE A should be re-examined for Korean national treasure status and possibly nominated as a candidate for listing in the UNESCO Memory of the World Programme. The ink tone image analysis technique can be very effective and objective, as a non-destructive and non-contact biblio-forensic method for studying printing techniques of ancient books around the world.

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