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The Ghosts of Bindings Past: Micro-Computed X-Ray Tomography for the Study of Bookbinding

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Abstract: This paper describes the results of a new application of micro-computed x-ray tomography towards nondestructive investigation of the binding structures of select premodern books. This application addresses a two-fold challenge in the study of historic binding and their construction. Few premodern books survive in their original bindings, and historically the rebinding process has been poorly documented and the remains usually discarded. Where original bindings do remain *in situ* much of their structure is, by design, hidden. Particulars of construction may be surmised, but without destructive disbinding little can be proven. μCT enables an exploratory, multi-linear approach to codicological investigations that makes bindings accessible in the form of tractable volumetric data.

Books survive in greater numbers from the past than almost any other human-made artefact. Containing precious evidence of languages, scripts, art, and stories of past peoples, historical manuscripts are also vibrant archives of human encounters with the nonhuman. They are confections of animal skins, plant textiles, and mineral pigments as well as words; they have been marked by insects as well as inks; they witness epidemiological and climate change as well as religious and political upheavals. This article seeks to expand the scope of study for premodern books by describing our application of micro-computed x-ray tomography—micro-CT or μCT imaging—to examine concealed evidence from inside books. We describe, in particular, our use of μCT to investigate the materials used in bookbinding, and traces of the sort of early structures that are frequently concealed by a book's current form.

In recent decades the study of historical bookbinding—the internal substances and forms of books that transform piles of leaves or bifolia into durable, codicological structures—has undergone significant and exciting advances. Historical bindings of premodern Western books have been described much more fully, in particular in J.A. Szirmai's *Archaeology of Medieval Bookbinding*, published 1999. In just over 300 pages Szirmai provides a conspectus of over a millennium of book binding techniques, from the fourth to the sixteenth century CE, with a focus on medieval European styles.[1] Szirmai's efforts have been complemented by more intensive studies of books from particular locations, periods, and collections, such as Christopher Clarkson's work on the bindings of books in The Walters Art Museum; Nicholas Hadgraft's doctoral thesis on fifteenth-century English bindings; and the series *Reliures médiévales des bibliothèques de France*, directed by L'Institut de recherche et d'histoire des textes.[2] Outside of Western Europe there have been many more significant contributions, including work by Jinah Kim (Buddhist book production), Mina Song (early Korean books), Georgios Boudalis (the codex in late antiquity, including in Coptic Egypt), and Karin Scheper (bindings on books from the premodern Islamic world).[3]

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[1] J. A. Szirmai, *The Archaeology of Medieval Bookbinding* (Aldershot: Ashgate, 1999; reprinted 2017).
[2] Lilian M. C. Randall, ed., et al., *Medieval and Renaissance Manuscripts in the Walters Art Gallery, I: France, 875-1420* (Baltimore, MD: Johns Hopkins University Press, 1989); Nicholas Hadgraft, "English Fifteenth Century Book Structures" (PhD diss., University College London, 1998); the French series is published by Brepols with CNRS, Paris, under the general editorship of L. Diercken.
[3] See for example Jinah Kim, *Receptacle of the Sacred: Illustrated Manuscripts and the Buddhist Book Cult* (Berkeley: University of California Press, 2013); Mina Song, "The History and Characteristics of Traditional Korean Books and Bookbinding," *Journal of the Institute of Conservation* 32, no. 1 (2009), 53-78; Georgios Boudalis, *The Codex and Crafts in Late Antiquity* (Chicago: University of Chicago Press, 2018); Karin Scheper, *The Technique of Islamic Bookbinding: Methods, Materials and Regional Varieties: Second Revised Edition* (Leiden: Brill, 2018).

Experts have also come together lately to work towards systematizing the description of medieval binding practices.[4] The extensive vocabulary and descriptive principles laid out by the Ligatus "Language of Bindings" project, led by Nicholas Pickwoad with Aurelie Martin, Alberto Campagnolo, Boudalis, and Athanasios Velios, are intended to provide a standardized conceptual framework by which to link the various vocabularies of academic bibliography.[5] Another tool for manuscript description, Dot Porter's data model, VisColl, can be used to model the way pages are gathered for binding into books.[6] VisColl 2.0 is now under development at the University of Pennsylvania's Schoenburg Institute; and the Old Books, New Science Lab at the University of Toronto developed this data model into a web application, VisCodex, which produces interactive visualizations of codicological models.[7] Together these systems expediate the collection and display of collation data, which was previously drawn up manually, and facilitate their manipulation to solve intellectual problems.

New tools for understanding medieval bookbindings promise important results for scholars of the premodern period. Approaches focused on codicological structure offer one way to move book history beyond the logocentrism that sometimes constrains it, revealing books not just as vehicles for texts and art but as repositories of evidence of techniques, technologies, materials, and human approaches to textual production. Investigated thoroughly, such evidence has transformative historical potential. Bookbindings are rich archives of overlooked knowledge—about book makers' economic, environmental, and ecological contexts; about the evolution and the transmission of craft techniques over time and across regions; and about the treatment, use, and significance of books for human societies around the globe.

However, the study of bookbindings runs up against some practical limits. Most medieval manuscripts no longer retain their original bindings. Szirmai estimates that no more than 1 to 5% of medieval manuscripts survive in an original or early binding.[8] Under heavy use, a "permanent" medieval binding with wood boards made in the European-style might last for roughly a generation.[9] Many books were therefore rebound multiple times during the medieval and early modern periods. Still more bindings have been repaired or replaced during conservation since entering institutional collections. In such cases, support for ongoing use of the book has been considered—almost always fairly—as more important than the *in situ* preservation of the binding. But, until recently, when bindings were replaced in this manner the historic structures that were removed were also discarded. A case in point is that of the Ellesmere manuscript of the *Canterbury Tales*, which was in an early binding, probably its first, right up until the twentieth century. In 1911, it was rebound by Riviere and sons. When conserving the book recently, Anthony G. Cains and Maria Fredericks recorded what evidence they found of the book's early structure: in short, the answer was, very little.[10]

Historians of medieval books are also limited by what they are able to observe. Aside from some singularly paired back structures, most European styles of bookbinding obscure the binding's mechanical workings. Leather covers, which wrap around the front, back, and spine of

[4] Guy Lanouë, ed., with Geneviève Grand, *La reliure médiévale. Pour une description normalisée*, Actes du colloque international (Paris, 22-24 mai 2003) organisé par l'Institut de recherche et d'histoire des textes (CNRS) (Turnhout: Brepols, 2008).
[5] Nicholas Pickwoad et al., "Language of Bindings", Ligatus, accessed March 18, 2021, https://www.ligatus.org.uk/lob/
[6] Dot Porter et al., "VisColl," Kislak Center for Special Collections, University of Pennsylvania, accessed March 18, 2021, https://viscoll.org/.
[7] Rachel di Cresce, Monica Ung, Dickson Law, and Jana Rajakumar, "VisCodex," University of Toronto Libraries, University of Toronto, accessed March 18, 2021, https://viscodex.library.utoronto.ca.
[8] Szirmai, *Archaeology of Medieval Bookbinding*, ix.
[9] Kathryn M. Rudy, *Piety in Pieces: How Medieval Readers Customized their Manuscripts* (Cambridge: Open Book Publishers, 2016), 121-3.
[10] Anthony G. Cains and Maria Fredericks, "The Bindings of the Ellesmere Chaucer," *Huntington Library Quarterly* 58 (1995), 127-57.

the book, conceal the stitching and supports that attach groups of pages together. Only in damaged books, like, for example, a twelfth-century copy of Bede's *Seven Catholic Epistles*, Oxford, Jesus College, MS 70, on which the spine is coming away exposing the lining, supports, and sewing pattern, are the inner workings of bindings structures directly observable (FIG 1). Damage like this is not uncommon: most original medieval bindings have endured considerable wear and tear. But where books remain intact their concealed structures further restrict an already limited corpus of evidence. Investigations that extend beyond damaged items—as many do—must rely on spatial reasoning and extrapolation, and the conclusions of this work, however carefully it is undertaken, are often speculative.

Our primary interest, in this article, is in the potential of µCT to meet the challenges we have just described. µCT, we argue, offers scholars a non-destructive way to bypass the limits of their own vision, and recover new evidence about books' material composition and structure, even in the case of books that have been repaired or rebound.

Problems in Bookbinding: An Example and a New Approach

A recent study of a second *Canterbury Tales* manuscript, the Hengwrt manuscript—Aberystwyth, National Library of Wales, MS Peniarth 392 D—made by two of our authors establishes some of the stakes of our research. Jessica Lockhart and Alexandra Gillespie's investigations of Hengwrt revealed some of the challenges and the opportunities that medieval bindings present scholars of the medieval past; we describe their findings here briefly, because they laid the ground for our approach to µCT.[11]

The Hengwrt manuscript is important for literary scholars of the late medieval English literature, as it preserves what is likely the oldest surviving copy of the *Tales*, Geoffrey Chaucer's most-celebrated work. Some of the work of copying this manuscript may have been carried out within Chaucer's lifetime (d. 1400), if not under his supervision.[12] Consequently, the selection, layout, and order of the contents of this book are thought to provide useful evidence of the organization and curation that made this series of tales and tale-tellers into a cohesive, codicological whole—whether these were authorial or not.

Using evidence from the text, inks, and decorative features and the gross physical appearance of leaves, previous students of Hengwrt have reached some agreement about the collation of the book. According to this consensus, the manuscript was first copied in five discrete booklets, which were added to and rearranged early in the book's history, perhaps before it was bound at all, and certainly before it was sewn into the binding in which it survived from the late fifteenth to the early twentieth century. Internal references show, for instance, that what is now Booklet III at some point came after what is now Booklet IV.[13] Some of the booklets are broken into even smaller units, which contain short sequences of one or two *Tales*: two gatherings of leaves in Booklet I, which contain most of the Miller's Prologue and Tale, for example, are preceded by a single folded leaf (a bifolium), made from a slightly lower grade of parchment, containing two pages of the Miller's sequence.[14] Gillespie has argued that this interruption of the book's collation marks an overlooked moment of revision of Chaucer's text.

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[11] For a more detailed discussion of these issues see Alexandra Gillespie, "Are *The Canterbury Tales* a Book?," *Exemplaria* 30, no. 1 (2018), 66-83, esp. 75-6.

[12] Estelle Stubbs, "'Here's one I Prepared Earlier': The Work if Scribe D on Oxford, Corpus Christi College, MS 198," *Review of English Studies* 58, no. 234 (2007), 139-40.

[13] Gillespie, "Are *The Canterbury Tales* a Book?," 75; for a detailed codicological evaluation of the evidence see Estelle V. Stubbs, "A Study of the Codicology of Four Early Manuscripts of the *Canterbury Tales*," (PhD diss., University of Sheffield, 2006), 60-92, who draws on A. I. Doyle and M. B. Parkes, "Palaeographical Introduction," in *The Canterbury Tales: A Facsimile and Transcription of the Hengwrt Manuscript, with Variations from the Ellesmere Manuscript*, ed. Paul Ruggiers (Norman: University of Oklahoma Press, 1979), xix-xlix, and John M. Manly and Edith Rickert, eds., *The Text of the Canterbury Tales: Studied on the Basis of All Known Manuscripts*, vol. 1 (Chicago: University of Chicago Press, 1940), 266-83.

[14] Stubbs, "Codicology," 60.

The book's structure, she suggests, changes the established scholarly history of Chaucer's work, and in doing so, demonstrates the need for closer consideration of the manuscript's complex codicology, including its early collation and binding.

The Hengwrt manuscript was rebound by the National Library of Wales in 1956, approximately two decades after its late fifteenth-century medieval binding was removed and stored separately from the bookblock. Oak boards from that medieval binding survive, with the tawed leather sewing supports—onto which the pages were sewn—still attached.[15] Examination of these boards shows that they had been used to support at least two bindings. Each board has a set of six sewing supports laced into one side and a set of four supports laced into the other. There are two possible explanations for this physical evidence. Either the boards were used to bind another book, before they were used on the Hengwrt; or Hengwrt was bound to these boards twice during the first century of its history. Its first binding perhaps wore out, and its rebinder simply reversed and reused the original boards.[16]

The case could be confirmed either way by examining the book's sewing. It would be particularly useful to identify unused holes—some of which are visible on fly leaves—that might align with previous sewing structures. Alternatively, the absence of such holes that might point to later additions to the sewn text block. Gillespie has posited that, at an early stage in its history, the makers of Hengwrt may have sought to forestall final decisions about its form or content, and kept it either in a heap of loose booklets, or in a tacketed binding. Tackets, wetted strips of parchment or occasionally loops of cord or thread, could be pushed through holes in a limp leather or parchment cover, to produce a bound book in which units might be easily removed, adapted, and reattached in a different place. If any of the leaves, quires, or booklets of Hengwrt were once tacketed, that method of production probably also left its mark, in the form of tacket holes left in spine folds, where they would likely be discernably larger and differently shaped and positioned from sewing holes. Only very limited investigation of the relevant evidence is possible, however, without disbinding the Hengwrt manuscript as it currently exists. The manuscript's previous sewing, and all traces of even earlier structures, are hidden by its modern binding.

The purpose of this article is not to advocate for taking apart the Hengwrt manuscript of the *Canterbury Tales*. Instead, it is to investigate a technological solution that might solve research problems very much like this one. As we show in this article, μCT presents a possible non-destructive solution to cases like that of the Hengwrt manuscript: a way to see fragmentary evidence hidden inside later covers, permanent deformations, and reused material, and thus to trace some of the details of earlier phases in the book's existence.

Our group is not the first to explore the potential of x-ray imaging for researching the internal structures of bookbindings. In 1975, Graham Pollard used single-shot plain film x-rays to image a group of books, in which boards from the earliest English period had been reused to bind the same manuscripts after the Norman conquest. Pollard's work was elaborated further by Clarkson in 1996.[17] Both scholars focused their x-ray imaging on attachment methods—that is, the mechanisms by which the binder laced into the boards the bands onto which the gatherings of pages were sewn. Results were mixed. Both studies confirmed the presence of modes of attachment that had not been identified in these books before. However, the limitations of the static images, particularly the superposition of structures that is inherent to plain film radiography, led to "inevitable difficulties" in interpretation.[18] Without the ability to view the

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[15] Images of the binding have been digitized. See National Library of Wales, "The Hengwrt Chaucer," accessed March 18, 2021, https://www.llgc.org.uk/?id=257.
[16] See Gillespie, "Are *The Canterbury Tales* a Book?," 80, n. 23.
[17] Graham Pollard, "Some Anglo-Saxon Bookbindings," *The Book Collector* 24 (1975), 130-59; Christopher Clarkson, "Further Studies in Anglo-Saxon and Norman Bookbinding: Board Attachment Methods Re-examined," in *Roger Powell, the Compleat Binder: liber amicorum*, ed. John L. Sharpe (Turnhout: Brepols, 1996), 154-214.
[18] Pollard, "Some Anglo-Saxon Bookbindings," 133.

inner and outer extent of the boards, and trace the path of the band through them, much analysis had to remain deductive.

High-resolution data from µCT alleviates some of these problems by producing a volumetric visualization of the book at ~40–100µm voxel size. In October 2013, a British Library team including Christina Duffy, Claire Breay, Paul Garside, Flavio Marzo, Kristine Rose-Beers, Shaun Thompson, and Nicholas Pickwoad transported the early eighth-century St Cuthbert Gospel, the earliest book from medieval Europe to survive intact in its original binding, from the British Library to the Natural History Museum, where it was imaged in a Metris X-Tek HMX ST 225 CT scanner with an operating voltage of 225 kV. The team conducted three scans: two of the manuscript at 85 µm and 65 µm voxel size respectively, as well as of a modern facsimile created by Thompson and Rose-Beers. Using the results, they were able to answer a number of longstanding questions about the book's unique, historic binding. They found, for example, that the book's binder created the raised decorative pattern on the leather cover by attaching it over plaster core laid on the board.[19]

Scholars of early books have made other use of µCT. In recent years, teams led by computer scientist William Brent Seales have achieved headline grabbing results using µCT to investigate carbonized rolls—a Pentateuchal scroll found at En-Gedi and a fragment of papyrus from Herculaneum—and a Coptic codex. In each case, the focus of the µCT research was on the recovery of the text, which had been lost to history inside an object too damaged and friable to open and read.[20] Projects exploring other advanced x-ray technologies have likewise been focused on the recovery of text. In 2016, a group led by Erik Kwakkel and Joris Dik reported on their use of macro x-ray fluorescence spectrometry (MA-XRF) to "see through" the the leather on a medieval book's spine and identify the text on the fragment of a medieval manuscript used as a liner.[21] And, as recently as this year a research team led by Jana Dambrogio used a dental µCT scanner to unfold and read undelivered seventeenth-century letters without breaking their wax seals.[22]

The focus of our group's work, in contrast to these projects, is on the development of µCT as a tool for the investigation of the structures of books. In this article we report what we have learned through intensive analysis of a book of less obvious historical significance—and nearer at hand for us—than either St Cuthbert's Gospel or Hengwrt: a Book of Hours from the special collections of Western University in Ontario, Canada. Our experiments with Western University's book suggest that µCT can bring to light otherwise inaccessible evidence of books' collation and bindings, in the form of tractable volumetric data. In the case of the Western

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[19] See Nicholas Pickwoad, "Binding," and Christina Duffy, Paul Garside, and Flavio Marzo, "Appendix 2: Microscopy, Radiography, and CT Scan," in *The St Cuthbert Gospel: Studies on the Insular Manuscript of the Gospel of John (BL, Additional MS 89000)*, ed. Claire Breay and Bernard Meehan (London: The British Library, 2015), 41–64, 159–162.

[20] William Brent Seales, Clifford Seth Parker, Michael Segal, Emmanuel Tov, Pnina Shor, and Yosef Porath, "From damage to discovery via virtual unwrapping: Reading the Scroll from En-Gedi," *Science Advances* 2, no. 9 (2016), e1601247; Clifford Seth Parker, Stephen Parsons, Jack Bandy, Christy Chapman, Frederik Coppens, William Brent Seales, "From invisibility to readability: Recovering the ink of Herculaneum," *PLoS ONE* 14, no. 5 (2019), e0215775; Maria Fredericks, "Inside Story: Using X-ray Microtomography to See Hidden Features of a Manuscript Codex," Thaw Conservation Center's blog, The Morgan Library & Museum, January 11, 2020, https://www.themorgan.org/blog/inside-story-using-x-ray-microtomography-see-hidden-features-manuscript-codex; Nicholas Wade, "Scanning an Ancient Biblical Text that Human's Fear to Open," *New York Times*, January 5, 2018, https://www.nytimes.com/2018/01/05/science/biblical-codes-morgan-library.html respectively. For an overview of projects see Paul L. Rosin et al., "Virtual Recovery of Content from X-Ray Micro-Tomography Scans of Damaged Historic Scrolls," *Scientific Reports* 8, art. no. 11901 (2018).

[21] Jorien R. Duivenvoorden, Anna Käyhkö, Erik Kwakkel, and Joris Dik, "Hidden library: Visualizing medieval fragments of medieval manuscripts in early-modern bookbindings with mobile macro-XRF scanner," *Heritage Science* 5 (2017), art. no. 6.

[22] Jana Dambrogio et al., "Unlocking history through automated virtual unfolding of sealed documents imaged by X-ray microtomography," *Nature Communications* 12 (2021), art. no. 1184.

manuscript, we were able to identify the sort of empty sewing holes that might help explain the Hengwrt manuscript to its students—remnants of an earlier structure, or "ghost binding." We also found that µCT added new dimensions to more linear—question and answer—research formats. As it opens views into and around the book's three-dimensional form, µCT prompts further questions that can then be followed up through re-interrogation of data from the same scan. As such, µCT offers a new, dynamic mode of codicological inquiry.

A Book and its Binding, Examined through µCT

Western's Book of Hours—an abbreviated form of the Divine Office intended for personal use—was copied in the late fifteenth century in the surrounds of Lille (FIG 2).[23] The book contains an unusually full litany, including some saints whose veneration was limited to Flanders: Saint Bavo (Ghent), Saint Gaugericus (Cambrai), and Saint Ghislain (Tournai). The liturgical calendar typically found at the front of this type of book is missing, but this too is likely to have followed the Tournai Use. Masculine endings in several Latin prayers suggest that a male user was originally anticipated for the book. Ownership inscriptions place the book in the library of the Capuchin friary in Lille, and it is possible that it was always intended for the use of a religious house in the area. Alternatively, it may have passed to the Capuchins from a private patron. A pencil note on the paper flyleaf at the back of the manuscript reads, "Aurait appartenu au chanoine Grandel (would belong to Canon Grandel)." It is this association that gives the manuscript its modern moniker, Canon Grandel's Prayer Book.

It is quite possible that the date, 1734, which is written in ink on the same flyleaf and in several other locations, is contemporary with the manuscript's current binding. The binding is covered in dark brown tanned leather, rough and cracked in places and patched where it was most worn as part of the restoration work undertaken on its arrival at Western. Under raking light, it is possible to see faint impressions on this leather cover left by metal clasps. There are no other traces of these clasps however, and no evidence they were ever attached to the book's existing boards. The impressions suggest instead that the leather cover is earlier than the current binding. We believe that the cover was removed from the book's previous binding and recycled for use on this one. That might explain another idiosyncratic feature of the book: when Western University acquired the manuscript in 2011, the spine title was the wrong way up, apparently because the recycled leather had been attached upside down.

The boards on the Prayer Book are lightweight. At several points, where the leather is worn through it is apparent that they are made from an early precursor to cardboard, rather than wood. However, the exposed areas were stained and waxed to match the color of the leather cover, obscuring a more detailed assessment of the material. Three raised sewing supports are visible from external observation. In all visible aspects, then, the binding conforms to Nicholas Pickwoad's description of inexpensive commercial bookbindings from the eighteenth century.[24] Abigail Bainbridge produced a similar binding by following the instructions given by Diderot in his 1751-72, *Encyclopédie, ou dictionnaire raisonné des sciences, des arts et des métiers*. Other examples provided in this article are comparable, though the covers on these books are new rather than recycled.[25]

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[23] Figures can be found in the appendix. For further detail on the particulars of this manuscript see King Alfred's Notebook LLC, *Enchiridion 6: Manuscripts for Teaching, Cont'd* (Cayce: King Alfred's Notebook, 2011), Lot 2, pp. 4-6. An opensource digital copy of the manuscript, currently excluding images of the binding, is available: "Canon Grandel," Internet Archive, November 30, 2013, https://archive.org/details/CanonGrandel/.

[24] Nicholas Pickwoad, "Onward and Downward: How Binders Coped with the Printing Press before 1800," in *A Millenium of the Book: Production, Design, & Illustration in Manuscript and Print, 900-1900*, ed. Robin Myers and Michael Harris (Delaware: Oak Knoll, 1994), 61-106.

[25] Abigail Bainbridge, "Bookbinding According to Diderot: An Exploration of Eighteenth-Century French Binding," *Journal of Paper Conservation* 16, no. 2 (2015), 67-73.

Several considerations prompted our choice of this manuscript as a candidate for our pilot study. Because it is not a manuscript of particular note for historians, we were permitted to work with it in a more intensive way than—for example—the British Library team could with St Cuthbert's Gospel. Because of its relatively small size, it fit easily into the μCT scanner which allowed us to obtain fairly high-resolution scans (the largest object that could be comfortably scanned in the machine we used is an object about 18cm wide and/or tall). The binding on the Western Book of Hours is of a type familiar to students of European binding, so we were relatively confident about what we might expect to see. That meant we felt able to assess the capabilities of the technique to produce clear and accurate data, even as we tested some hypotheses about what might be going on beneath this book's covers and used μCT's potential to reveal new information about its history. Finally, and most significantly for our purposes here, the eighteenth-century binding of this Book of Hours apparently replaced one or more lost, earlier structures. We hoped it would serve to answer one of our key questions: is μCT an effective, non- or minimally-destructive method for investigating a book's earlier bindings?

Method

Canon Grandel's Prayer Book was imaged using a Nikon XT H 225 ST μCt scanner housed at the Museum of Ontario Archaeology in London, Ontario. The book was mounted in a white foam carrier with the longest side held vertically, as it might be on a modern bookshelf. Two scans were taken, one of the entire book at a resolution of 80μm voxel size, and the other of just the textblock at a resolution of 40μm voxel size, with smaller voxel size indicating higher resolution images. A molybdenum target was used to maximize the contrast. Technical specifications were the same for the two scans: 110 kVp, 97 μA, 1 second exposure, 1mm Al filter and 3141 projections for a 53-minute scan. The capture software was X-Tec Inspect-X v 4.4 and the projections were reconstructed using X-Tec CT Pro v 4.4. The volumes were exported to 16bit gray scale TIF slices for viewing in Image-J, or they were viewed in native VGI/VOL format in Dragonfly v 2020.1.[26]

In preparation for scanning medieval boxwood prayer beads intended for display at the Art Gallery of Ontario's "Small Wonders" exhibition in 2016, Madalena Kozachuk et al. demonstrated that the x-ray energies encountered during typical laboratory analysis, including μCT imaging, did not damage wooden artifacts. Their results confirm that the analysis undertaken here is a safe, non-destructive approach to the study of organic heritage materials.[27] Further work is in process at Western University to examine the effects of other x-ray and laser based analytical techniques on parchment.

Results and Discussion

CT and μCT scans capture data from an object by taking a series of projection images (essentially digital x-rays) which are then algorithmically reconstructed into a volumetric digital model. The model can then be viewed in 3-dimensions or sliced and resliced in any plane. Medical CT scans are generally sliced in 3 orthogonal planes: the axial plane (cutting the body into upper and lower portions); the coronal plane (cutting the body into front and back portions); and the sagittal plane (cutting the body into right and left portions). Since a book does not share its anatomy with the human body, we needed to redefine the planes. For this set of experiments, we still refer

[26] For a detailed discussion of μCT, scanning parameters and more see Gerald J. Conlogue, Andrew J. Nelson, and Alan G. Lurie, "Computed Tomography (CT), Multi-Detector Computed Tomography (MDCT), Micro CT, And Cone Beam Computed Tomography (CBCT)," in *Advances in Paleoimaging: Applications for Paleoanthropology, Bioarcheology, and Cultural Artifacts*, ed. Ronald G. Beckett and Gerald J. Conlogue (Westborough: CRC Press, 2020), 111-78.

[27] Madalena Kozachuk et al., "Possible Radiation-Induced Damage to the Molecular Structure of Wooden Artifacts due to Micro-Computed Tomography, Handheld X-Ray Fluorescence, and X-Ray Photoelectron Spectroscopic Techniques," *Journal of Conservation and Museum Studies* 14, no. 1 (2016), 1-6.

to the axial plane, which bisects the book horizontally through the spine, cutting it into top and bottom portions. We refer to the plane running parallel to the spine as the spinal plane, and the plane that is parallel to the pages and covers as the paginal plane (FIG 3).

i. Materials

Sewing supports: μCT confirmed what visual examination had already indicated. The book is sewn on three supports cognate with the ridges across the outside of the spine. Volumetric images showed us sewing supports made of single lengths of cord, raised up from, rather than recessed into, the bookblock. Pickwoad associates the use of single sewing supports with the economizing of binding structures after the first quarter of the sixteenth century. They are not commonly found before that point.[28] Our imaging from the middle and ends of the cord clarifies its composition: it is roughly 2mm in diameter and comprises a two-ply strand that has been doubled up and twisted together (FIG 4).

Boards: Scanning also confirmed that the manuscript's protective boards are made from a precursor to modern cardboard (FIG 5). The lamination visible in axial segments is indicative of the layering of materials used in the production of pasteboard (paste-laminate board.) Internal fissures across the board in both axial and spinal planes show points at which the adhesion between layers is beginning to degrade, resulting in separation and air pockets. Such fissures support our identification of the material: breaks are clean, occur in a single plane (between two flat surfaces), and do not produce the "crumbling" effect typical of uneven or pulped materials. At the edges, where the board is vulnerable, wear has caused further separation, creating a frayed or fanned out appearance. In European bookbinding pasteboard was largely replaced by pulp board, the production of which was less labor intensive as paper was pulped and dried in a single operation rather than layered by hand, by the late eighteenth century.[29] So, the use of pasteboard in this binding supports the dating evidence laid out above.

From the fifteenth century onward pasteboard was most commonly made out of paper, which was by then widespread and relatively cheap. When we compared the thickness of the layers within the binding and that of the manuscript's parchment pages, we found the material in the pasteboard to be considerably thinner. Additionally, where parchment tends to stiffen and curl with age, paper is softer and more pliable. The ripples visible along the edges of fissures, then, are more typical of paper. Until the late eighteenth century paper was made from rags, collected from the surrounding community, soaked, pulped, and dried into sheets.[30] This genesis might neatly explain several threads seen between or within the layers in paginal slices through the board, although these could equally have entered the material during processing.

The fabrication of pasteboard was one way to recycle waste paper, from lists and documents to unwanted books. Indeed, several important premodern texts are preserved only as fragments used to make pasteboard or otherwise stiffen later bindings.[31] Given this context, it would not be surprising to find written pages among the layers of material that make up the board: in fact, we might expect it. It is notable, then, that such evidence is not immediately apparent. It is possible that the ink on this material is carbon-based, and therefore does not contain the metal compounds picked up by x-rays. However, point-like inclusions dispersed evenly throughout the boards indicate that another substance is present alongside the paper. A more likely explanation, then, is that the lack of legible writing comes as a side effect of the production process. Eighteenth-century board manufacturing processes are detailed by Joseph Jérôme Lefrançais de Lelande in his *Art du cartonnier* (1762), one of a series of *cahiers* published by

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[28] Pickwoad, "Onward and Downward," 76.

[29] Bernard Middleton, *The History of English Craft Bookbinding Technique* (London: British Library, 1996), 64-6.

[30] Dard Hunter, *Papermaking: The History and Technique of an Ancient Craft* (New York: Dover Publications, 1947; reprinted 1978), 309.

[31] For this practice see especially N. R. Ker, *Fragments of Medieval Manuscripts used as Pastedowns in Oxford Bindings, with a survey of Oxford binding c. 1515-1620* (Oxford: Oxford Bibliographical Society, 1954).

the Académie royale des sciences to document French industrial processes. Unlike in previous centuries, when layers of waste paper were stuck together using flour-based adhesive (or simply "packed" into bindings to stiffen them), eighteenth-century rag paper was re-pulped to produce new sheets for use in boards. Pulping proceeded in several stages, which may have varied depending on the scale of the operation. First, the paper was heaped up, soaked, and left to ferment for around a week. Once the material was soft enough in could then be broken up into small pieces by hand with a wooden shovel or iron scraper. If the new paper that made up the board was manufactured at this point, we would expect to find small fragments of written material embedded throughout, resulting inclusions clustered in specific areas of the scan. But (at least by the 1760s) many French board-makers employed horse driven mills to grind the material into a finer pulp. In this case any remaining ink on reused waste would be deposited evenly throughout the resulting board, as we see in our scan. Molds were used to form the boards, which were then couched onto felts to dry. The order of drying, pressing, and pasting material together varied depending on the desired quality of the final product. To make *cartons rédoublés* (couched laminates or multi-couched boards) wet layers of pulp were couched directly on top of each other and either pressed, or dried under their own weight, into light and durable boards. No adhesive was used in this construction method, which explains why we cannot see the same characteristic layers of paste within the boards that we find attaching the leather to their outsides.[32]

Nevertheless, we know that writing sometimes *did* survive inside pasteboard, and that when iron gall ink is present writing can be identified using μCT. So, the fact that we can identify between the layers of paper used to produce the pasteboard in ours scans suggests that in the future the same techniques used to virtually unwrap the carbonized En-Gedi scroll, or unfold sealed premodern letters, may facilitate the recovery of lost fragments of medieval texts within bindings without damaging their structures.

In several key places fissures also run vertically through multiple layers within the pasteboard. In the frontal plane some of these breaks are shown to be the holes of bookworms (FIG 6). However, none of the cracks found are easily detectable from external examination. In a Kashmiri manuscript from the Fisher Rare Books and Manuscript Library at the University of Toronto, which some of the authors scanned in collaboration with Grasselli's Geomechanics Group, the cracking is more acute.[33] In the case of the Kashmiri book, there are several points where the binding has lost some stability (though none that require urgent conservation). However, the scale and severity of the damage could not be easily assessed without removing the fabric covers, and that would represent an undesirable intervention before even the development of a treatment plan for the book. We suggest that another use of μCT imaging might be as a non-destructive alternative to a more destructive diagnostic assessments of a book's condition.

ii. Techniques

Sewing: In most Western European books, pages are produced in conjoined pairs (sometimes as part of larger leaves), which are piled into groups, folded down the middle, and then sewn through the center channel to produce small gatherings. In the axial plane the threads that attach the pages of the book together are visible where they run up the center of the gatherings (FIG 7). Digital measurements show such threads have a diameter of roughly a third of a millimeter. Given their visibility, in the long-term it would be possible to trace the path of a single thread through the volume in order to reconstruct sewing patterns. For the present, orthogonal views provide a rough impression.

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[32] Jane Eagan, "Board Making in Lelande's *Art du cartonnier*," in *Looking at Paper: Evidence & Interpretation, Symposium Proceedings, Toronto, 1999*, ed. John Slavin, et al. (Ottawa: Canadian Conservation Institute, 2001), 95-8. See also, David Pearson, *English Bookbinding Styles 1450-1800: A Handbook* (New Castle: Oak Knoll, 2005), 23; Julia Miller, *Books Will Speak Plain: A Handbook for Identifying and Describing Historic Bindings* (Ann Arbor: Legacy Press, 2014), 110.

[33] Toronto, Thomas Fisher Rare Books and Manuscript Library, MS 01106; a report on this scan is forthcoming.

When a book is made up of more than one gathering, as most bound books are, one method of connecting the gatherings together is to sew them one after another onto the fixed sewing supports identified above. In the frontal plane the paths of the threads may be traced as they wrap around the sewing supports (FIG 8). Here the threads run up the center of gatherings, exit to the outside and pass over the top of the supports and back in, either through the same hole or sometimes through a second hole up to 4mm beneath the first (two variations of all along sewing.) The view of the spine in the sagittal plane seems to suggest that the gatherings are sewn with straight evenly-spaced (as opposed to packed) stitches. Given that the analysis of sewing patterns was possible in fewer than a third of the Gothic bindings surveyed by J. A. Szirmai, leaving him with a sample "too small to allow any definitive conclusion," the ability to examine sewing patterns through μCT could dramatically enhance the field.[34]

Endbands: Endbands are the sewing structures that reinforce and protect the top and bottom of a book's spine. Traditionally each gathering is sewn around the endband core in the same way that they are attached to the sewing supports (described above), with the threads then passed back and anchored further down the book's spine. A secondary layer of sewing could be added to attach the endband to the outer cover, often using decorative colored silk. However, a reduction in the structural and decorative function of the endband is typical of the economizations made in bookbinding from the mid-sixteenth century onward.[35] Given our previous observations about the inexpensive materials used in this binding, therefore, it is not surprising that we found that the book has no visible endbands. Instead, the spinal plane reveals that the sewing is anchored only by a typical row of linked change over stitches—in which each stitch loops around the thread of the previous gathering and then enters the following one—at either end of the spine (see FIG 9).

Binding attachment: In books like this one the sewing supports also provide the primary way of attaching the binding to the book. The ends of cord or leather supports are laced into holes in the boards of the binding to secure them around the bookblock. Different configurations of holes were used to lace in the sewing supports in different times and places. The manner of lacing in, then, is important evidence for dating and localizing a binding. However, in European bindings the lacing in is usually partially or wholly obscured by the addition of covers, pastedowns, and flyleaves (as is the case here).

When discussing the lacing in of endbands, Pickwoad records two styles used in abbreviated bindings like this one. The cord might be pushed through holes from the outside to the inside of the board and then back; or the cord might be frayed out and stuck to the outside of the board with adhesive.[36] In this case, the book has no endbands. But moving slice-by-slice through the page plane allows us to trace the path of the other sewing supports (FIG 10). Here, supports start by wrapping around the outside of the pasteboard beneath the leather cover. They are then pushed through a hole roughly 5mm from the spine edge. The cords run along the inside of the board, beneath the pastedowns, for approximately 13mm, before exiting through a hole roughly in line with their point of entry. After this the binder has taken the cords off at an angle (between approximately 55 and 75 degrees) where they re-enter the boards roughly 8mm later. The end of the cord is knotted as close to the board as possible and then frayed out on the inside of the board beneath the pastedown. This three-hole lacing in method is typical of French bookbindings produced in the mid to late eighteenth-century.[37] We determined, from the regular deformation of the material around the edge of holes from the outside towards the inside of the board, regardless of the direction of lacing, that all of the holes were prepared prior to lacing in.

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34 Szirmai, *Archaeology of Medieval Bookbinding*, 187.
35 Pickwoad, "Onward and Downward," 80-1.
36 Pickwoad, "Onward and Downward," 83.
37 See examples by Bainbridge, "Bookbinding According to Diderot," 69; Jeffrey S. Peachey, "Late 18th Century French Binding Structures," Guild of Bookworkers 2010 Standards of Excellence Seminar, posted October 11, 2018, https://vimeo.com/ondemand/10gbw1.

Not all of the evidence visible from our scan was immediately meaningful to us; or, to put this another way, the application of μCT does not relieve the book historian of the burden of interpretation, nor of its challenges and risks (from confirmation bias to plain error). What μCT offers, consistently, is more evidence of a book's history. Among the data produced by our μCT scans of Western's book of hours, approximately two thirds of the way down the axial stack, was a bright point of dense material. The material produced an x-ray artifact in the fold at the center of a gathering. It remains in shot for 251 slices, before disappearing again. When we located the same position in paginal plane the dense area turned out to be a thin curved object, possibly a narrow piece of metal. (FIG 11) At the first team examination of the scan we speculated on what this metallic object might be. Our best guess, from its narrow dimensions and the metal's curving shape, is a thin bristle from a wire brush, or a metallic thread. The object is not visible in external examinations of the book, which implies either that it is caught deep in the gutter, between two leaves, or that it is lodged outside the bookblock, between the outer leaves of two different quires, held in by the sewing and then the cover over the spine. Due to the curvature of the pages and the object, our μCT images did not allow us to decide between these two possibilities.

iii. Ghost Bindings

μCT imaging allowed us to vastly expand our observations about the existing binding on Western's prayer book. It also gave us some insight into the book's previous bindings. Evenly spaced along the spine between the current sewing supports are four parallel rows of holes. The holes pierce the central fold of each gathering, marking the now unused sewing stations from a previous binding. We have taken to describing these impressions of lost structures, visible to us only from the x-ray images, as "ghost" binding(s).

By flattening the spine along the sewing path, we could observe a full set of holes in a single frame (FIG 12). Doing so revealed that each sewing point is made up of a set of three sewing holes, with holes for a linked kettle stitch at either end of the spine. This pattern can only be explained if the sewing attached the gatherings to double supports using a three-point stitch. That is a common enough method of sewing in fifteenth and sixteenth century books, but it was more labor intensive than other available methods. Sewing on four double supports also means marginally more investment (of time, and perhaps cost) than was afforded the current binding, which has just three single supports. The prayer book's original binding, then, was more elaborate, if only in the details of its construction, than the binding that replaced it.

When viewed in the paginal plane, the direction of the book's earlier sewing is sometimes identifiable. Some of the holes appear to show deformation of up to 1mm as if punctured by a sharp object. Such deformation was likely caused by the binding needle, either as the gatherings were sewn on to the supports, or perhaps before sewing if the gatherings were pierced preemptively to make the process easier. To adjudicate between these scenarios, we would need to undertake a more detailed investigation of all of the empty sewing holes, in order to identify patterns. A regular pattern of inward and outward deformation might allow us to reconstruct not only the style of the pre-existing supports, but the replicate the process of attaching pages to them. We did not embark on a study of that sort here, but we note it as a potential further use of μCT imaging, because sewing styles tell bookbinding experts so much about a book's date and locale. μCT allowed us to flesh out more of this particular book's bibliobiography. In doing so, it suggested to us a host of new ways to expand the corpus of evidence available for book history more broadly.

As we have already suggested, new evidence will of course present new interpretive challenges. Most premodern books have had many bindings, both temporary and (semi)permanent over the course of their history. Canon Grandel's Prayer Book is a case in point. We argue here that the impressions of clasps left on its leather cover mean that the cover was reused. But we were not able to determine whether that cover, or its now-missing clasps, came from the book's earliest binding or another, intermediate structure, between the original binding and the present one. Binders often reused pieces of previous bindings to expediate repairs and upgrades: covers, boards, and sewing supports might all be saved and repurposed during rebinding efforts.[38] Parchment is a durable material and if stitch holes were in good repair then a book could easily be resewn through the same holes (not only incrementally reducing the labor involved, but also avoiding further weakening of the fold). When we reconstruct early bindings from the traces revealed by µCT, we must be aware of the multi-layered, multi-temporal nature of binding history. The evidence revealed by an x-ray scan might represent a current binding, a previous one, or separate elements of several bindings. The materials we identify may have been reused in many consecutive structures. While the sewing holes we found in this book match recognizable sewing patterns from the period in which the book was copied, that is not a given. µCT images of other books might reveal multiple "ghost bindings," that will need to be interpreted carefully. Yet the layered traces themselves promise a compelling new way for scholars to recall, detect, and describe the diachronic life of a single book.

Conclusion

Our group's µCT investigation of Canon Grandel's Prayer Book transformed knowledge of this previously rather obscure manuscript. X-ray images allowed us to look at the book in much more detail than we could with the naked eye. By supplementing our external examination of the book, we drew new conclusions about the materials, structures, and techniques that constituted its binding when it was first made, as over its long history. Our experiment amply demonstrated the potential of this application of µCT. We chose this book, in an eighteenth-century rather than premodern binding, because we were confident that we would understand its structure and to recognize its features, even through an unfamiliar medium. µCT confirmed, extended, and nuanced our knowledge. µCT allowed us to describe the structure and date of the pasteboards, the French style of the lacing in, and the various sewings of the bookblock, all of which are obscured by the book's modern binding. Evidence we uncovered of various interventions in this manuscript's history—one or perhaps two rebindings, the excision of several illustrations, a piece of wire—helped to fill in this modest prayer book's bibliobiography further. µCT imaging allowed us to access visible evidence of this manuscript's "ghost" bindings. It revealed a more elaborate structure, predating the current, commercial binding on the book. It expanded the corpus of early bookbindings available for scholarly investigation. µCT emerged, in the course of this work as a new method for scholars to recall, detect, and describe the diachronic life of a single, premodern book. µCT did not relieve us, and cannot relieve any other book historian, of the need for interpretation of bibliographic evidence. What µCT offers, consistently, is more of that evidence, and with it a deeper and richer account of a book's history.

Based on our success imaging this manuscript, we would propose several other applications for µCT. As suggested above, we think it is worth investigating whether µCT could uncover text on the leaves layered into "packed" or early pasteboard bindings. In the past, the only method of recovering such material involves disbanding the book and soaking the boards to separate the leaves within.[39] Such an application would be in line with, and indeed would build on, the use of µCT and other x-ray technology by scholars such as Brent Seales and Kwakkel to recover text concealed within books.

Now that we are confident in parsing the structures of a well-documented binding type we can also apply our knowledge to structures with more complex codicological histories, especially those of more fragile and more historically significant books than Western's book of hours. The Hengwrt manuscript of the *Canterbury Tales* continues to entice us. So too do books

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[38] Szirmai, *Archaeology of Medieval Bookbinding*, 181-2.

[39] This was the technique used, for example, by Schullian, "Here the Frailest Leaves," 201-17, to retrieve fragments from bindings in the collections of the Armed Forces Medical Library in Washington, DC. The fragments are now known as the Bathtub Collection.

that, because they do not fit the Western, Eurocentric bias of much book history, tend not to the be subject to much codicological investigation. We mention the μCT that some members of our group have done in collaboration with colleagues at the University of Toronto of a Kashmiri paper manuscript with a textile covered binding in the collection of the Thomas Fisher Rare Book Library. We are now working with collaborators from Williams College and Harvard University to image a birchbark book, also from this region. Our sense is that μCT experiments could draw attention to neglected, regionally specific binding techniques, offering new evidence of the international contexts for premodern cultural inventiveness and exchange.

Finally, we think that μCT could be a valuable tool in guiding collections care in libraries and museums, and adding to records of the history of that care. Here we are guided by Christopher Clarkson's principles of "minimum intervention in [the] treatment of books", for, "[f]or minimum intervention to be practised correctly a damaged item must be very carefully analysed, understood, and assessed before any action is taken."[40] Scanning of books at the outset of conservation projects would allow conservators both to assess the condition of objects and prepare a treatment plan before taking more invasive steps. Scanning them again at the end would offer a valuable record of what has been done.

μCT already is in use to find out what is written on the pages inside the bindings of fragile and unopenable objects in particular. But all old books, like other heritage artifacts, are to some extent unopened. They conceal aspects of their past within the materials and structure of their manufacture. μCT we argue, offers new insight into old books' physical structures and material components, as well as their textual secrets.

[40] Christopher Clarkson, "Minimum Intervention in Treatment of Books," Pre-prints, 9th IADA-Congress, Copenhagen, August 16-21, 1999.

Appendix I: Figures and Captions

Figure 1: Oxford, Jesus College, MS 70, with damage to spine exposing the lining, supports, and sewing patterns. (Permissions needed).

Figure 2: The binding of London ON, Western University Library, MS Canon Grandel's Prayer Book. Photo courtesy of Archives and Special Collections, Western University, London, ON.

Figure 3: A condensed diagram to illustrate the standard components of a binding structure with microCT orthogonal planes, produced by Imran Muhammad Asghar and Shibo Liu (University of Toronto Libraries, 2021) with planes and labels by J. D. Sargan.

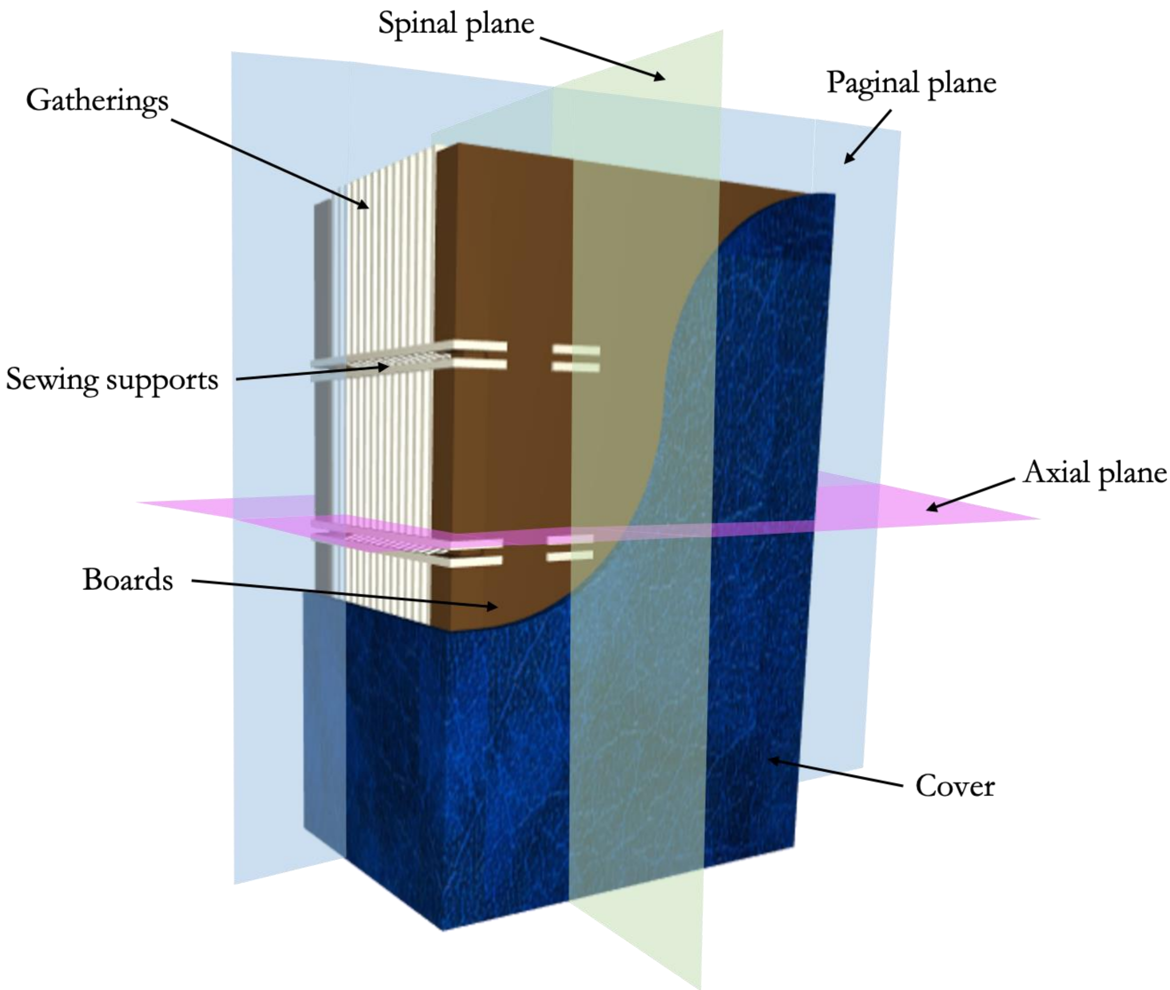


Figure 4. Close up in paginal plane of cords running through the boards (enhanced using a look up table), showing the direction of the twist—s-twist in the upper, z-twist in the lower.

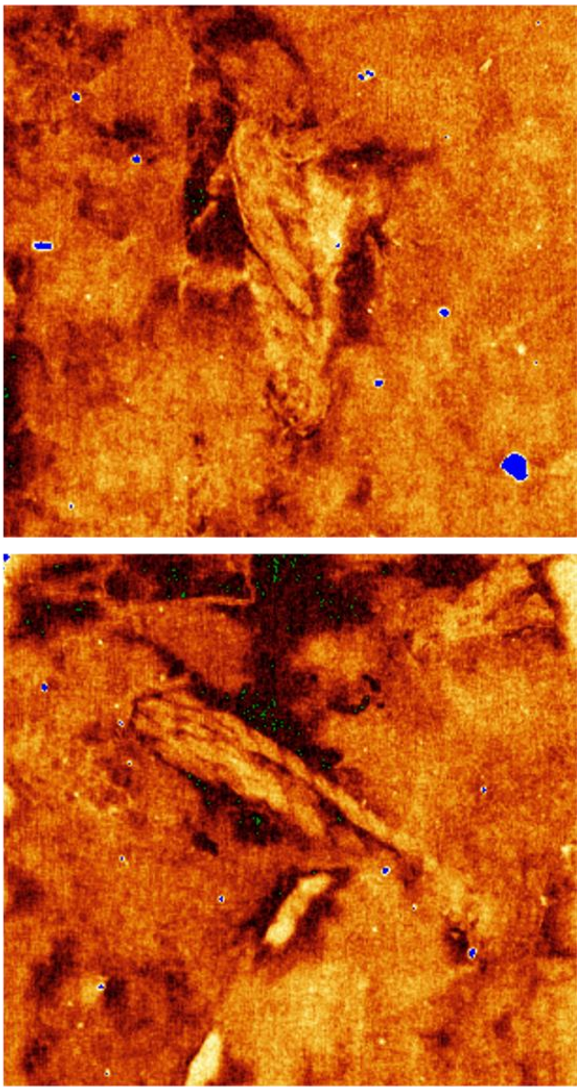


Figure 5. Axial slice of the bookblock imaged at 40µm voxel size with spine facing to the left side. The boards are represented by the denser material at top and bottom. Dark spaces in that material indicate separation between layers within the pasteboard. The white specks throughout the material are tiny metallic inclusions. Note a particularly large one in the center of the lower board.

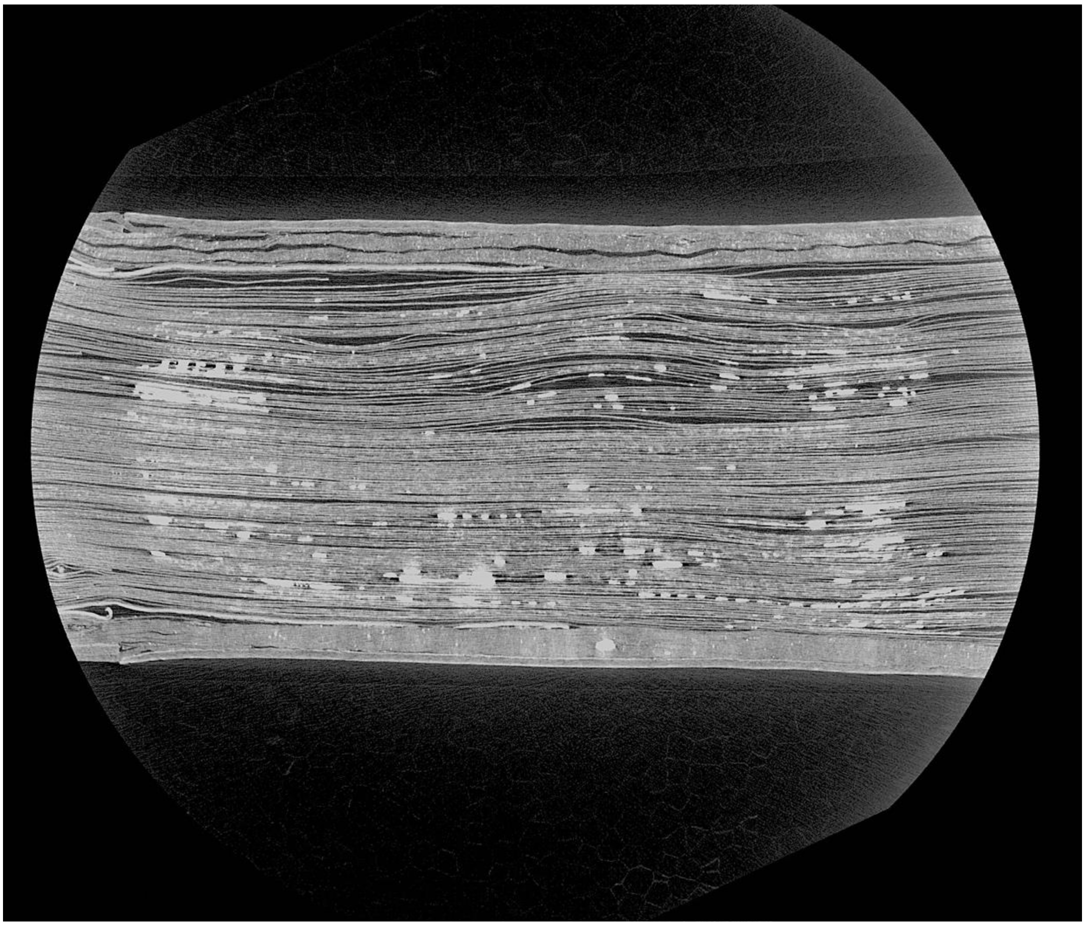


Figure 6. Paginal view of a board (b) with tunneling caused by a book worm (a). The inbuilt ImageJ lookup table “Yellow Hot” was used to emphasize the empty space in the image. Notice a narrow strip of denser material, perhaps parchment, embedded in the center of the lower third of the board, which probably testifies to the reuse of scrap material in the production of the boards. In the lower right corner the turn over from the leather covered can be seen due to the curvature of the board.

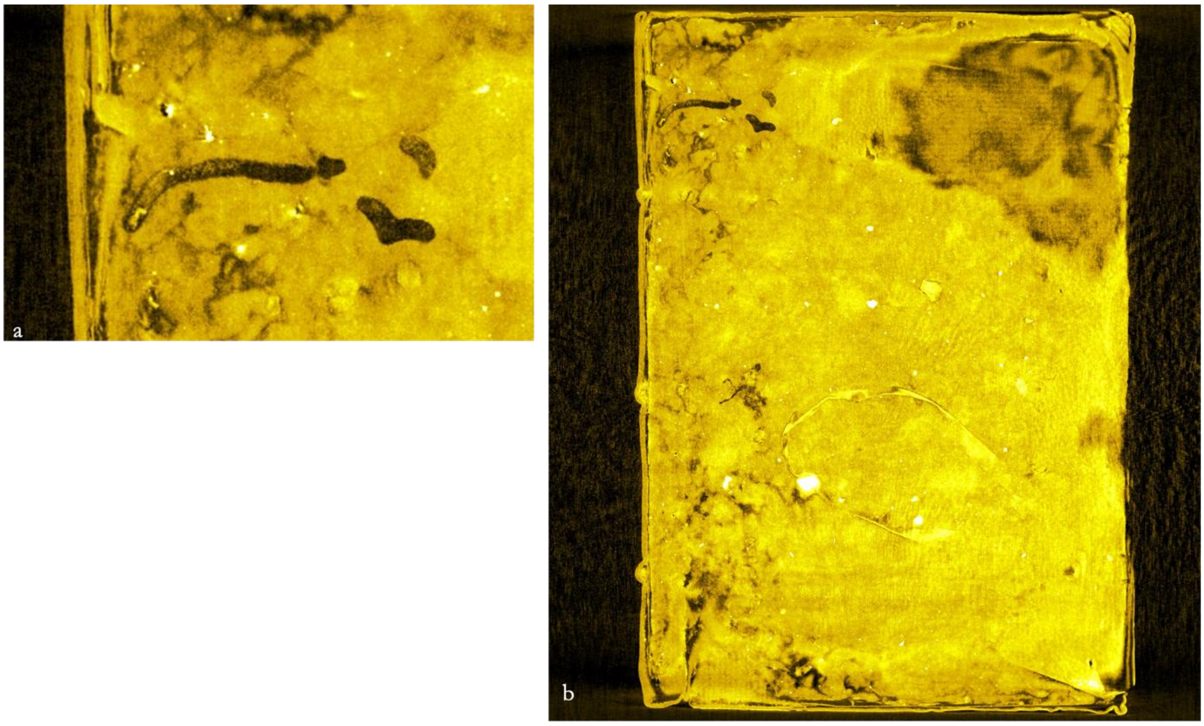


Figure 7. Axial slice through the spine showing the fold of the gatherings, spine lining, and the sewing threads (some highlighted within white circles.) Contrast in the image was enhanced using the preset ImageJ look up table “mpl magma.” Brighter orange under this lookup table indicates denser material. The focus of denser around the folds of the gatherings may suggest that an adhesive was used to adhere the spine lining (visible as several layers of material between the end of the gatherings and the leather outer cover).

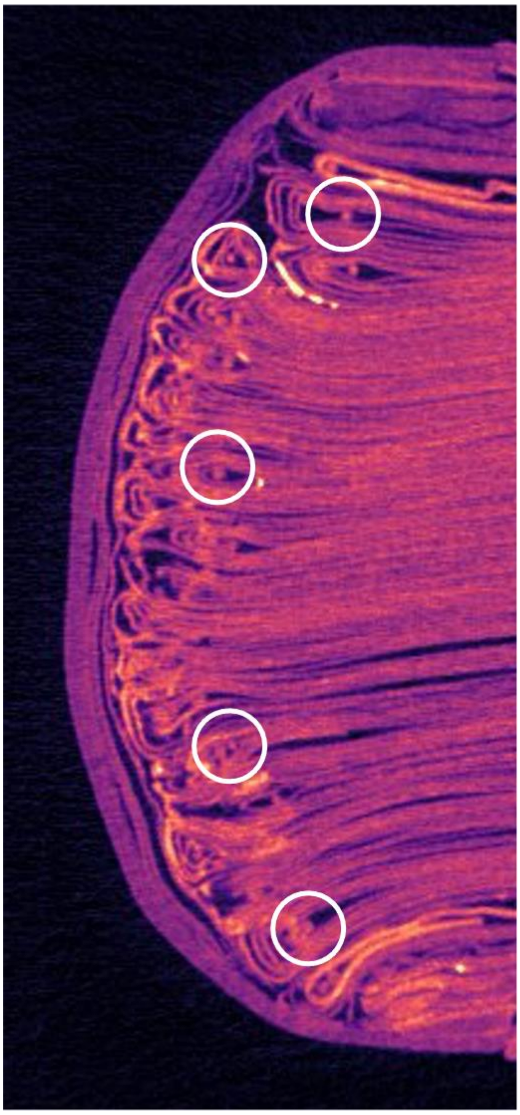


Figure 8. Path of a single thread in paginal plane through the inner fold of the gathering, showing the lower two sewing stations and the path of the thread around the supports.

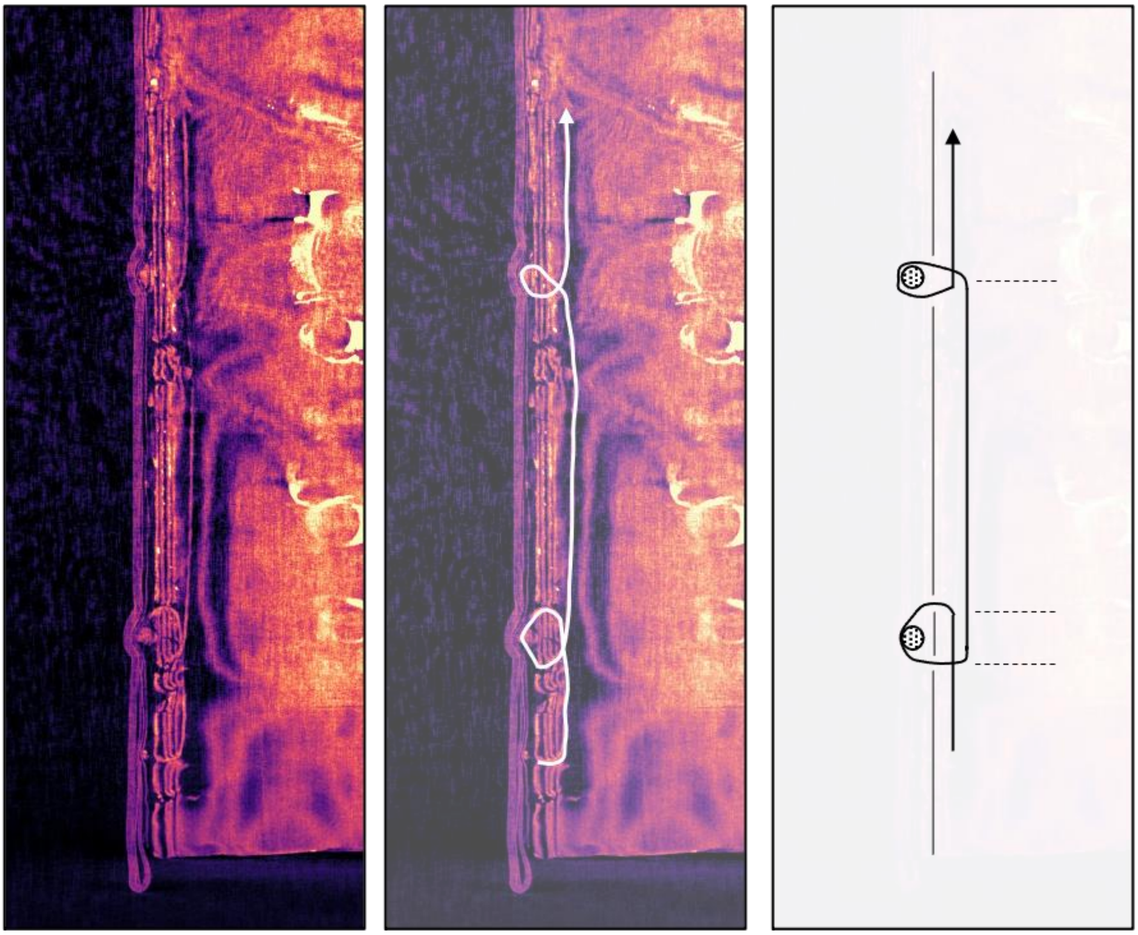
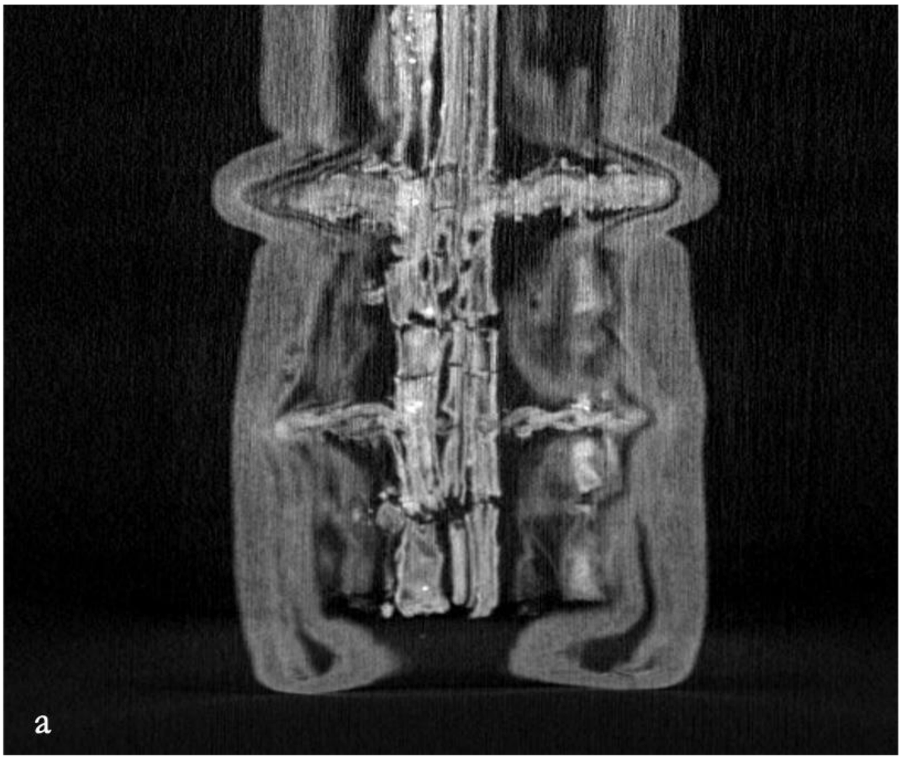


Figure 9. Spinal slice showing the linked change over stitch (kettle stitch) one third of the way up from the bottom (a). Compare to illustrative diagram from Szirmai, *Archaeology of Medieval Bookbinding*, 116, Figure 7.16 a (b). Two thirds of the way up from the bottom is the first sewing support.



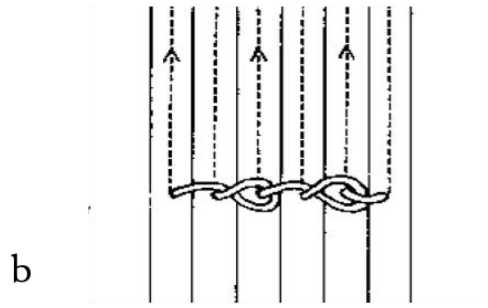


Figure 10. The lacing in of cord slips, as seen from the outside paginal face of the board (a), the inside face of the board (b), and the axial cross section (e). This data allows for the projects of the combined path (c and d).

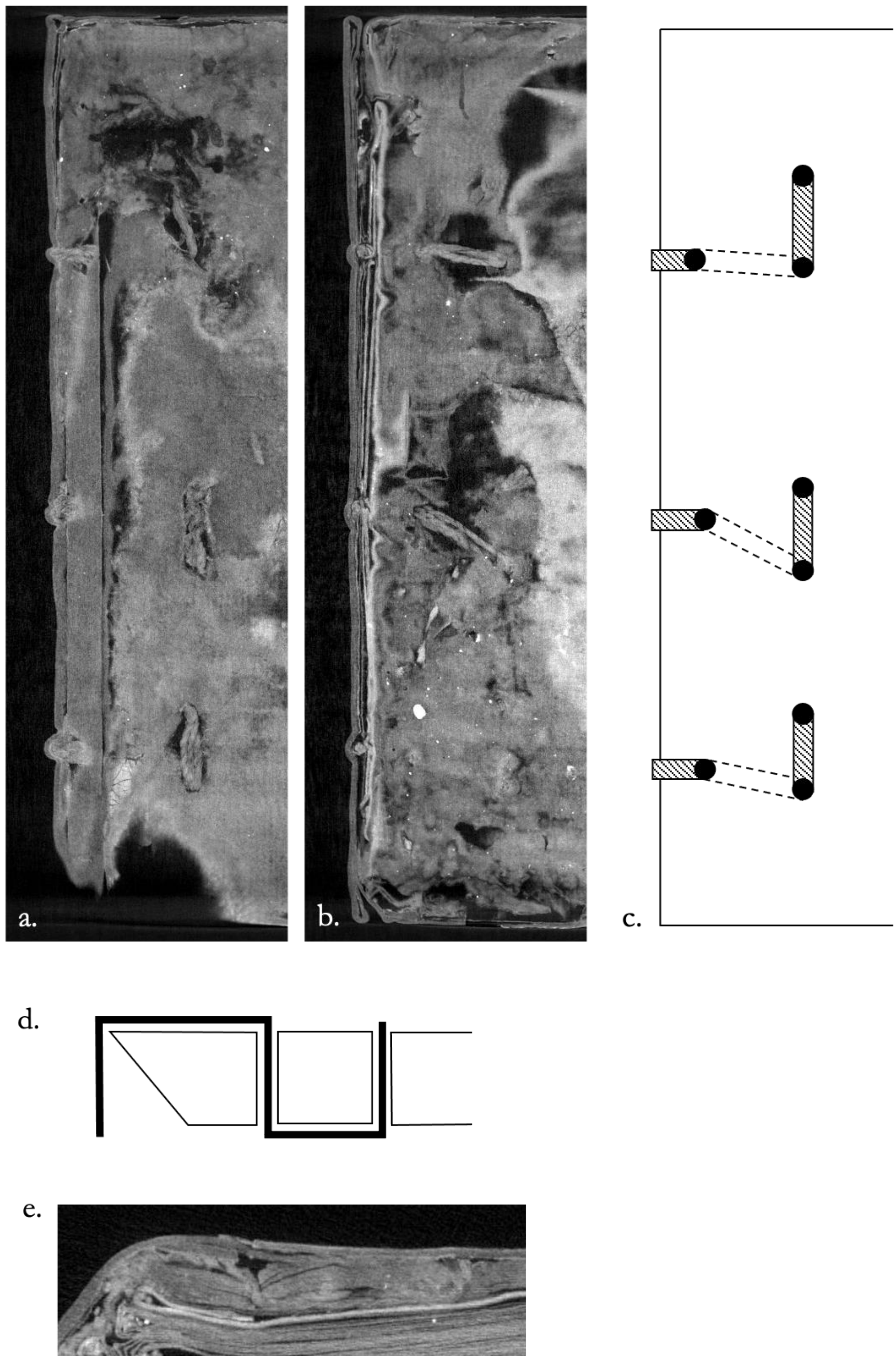


Figure 11. The curved white line on the left side of the image is the unidentified metallic wire or thread located in the gutter of the page. In the center of the image gold painted initials can be seen most clearly, the black lettering is also visible, more palely. Due to undulations in the parchment pages, several layers of letters are visible at any one time.

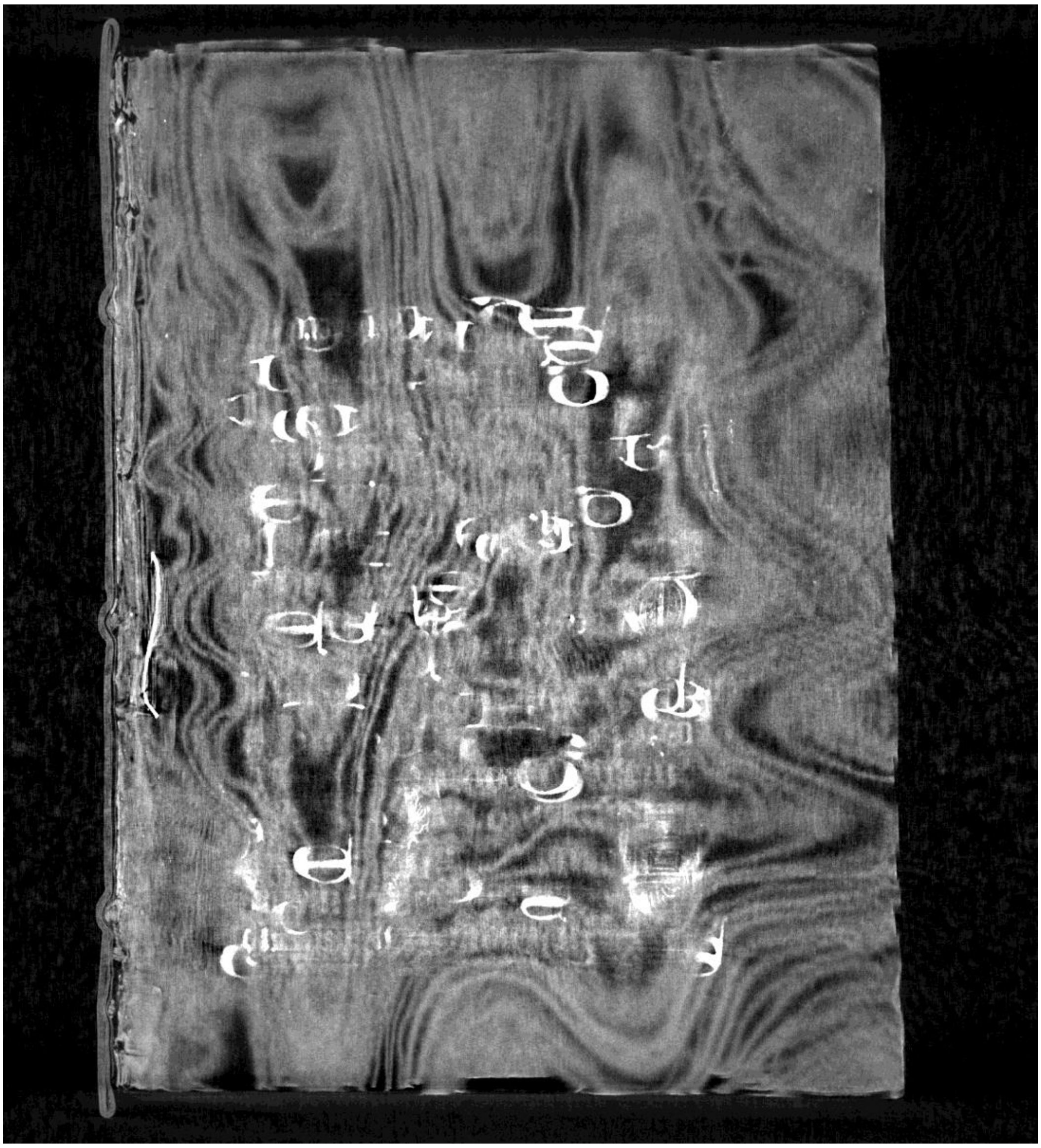
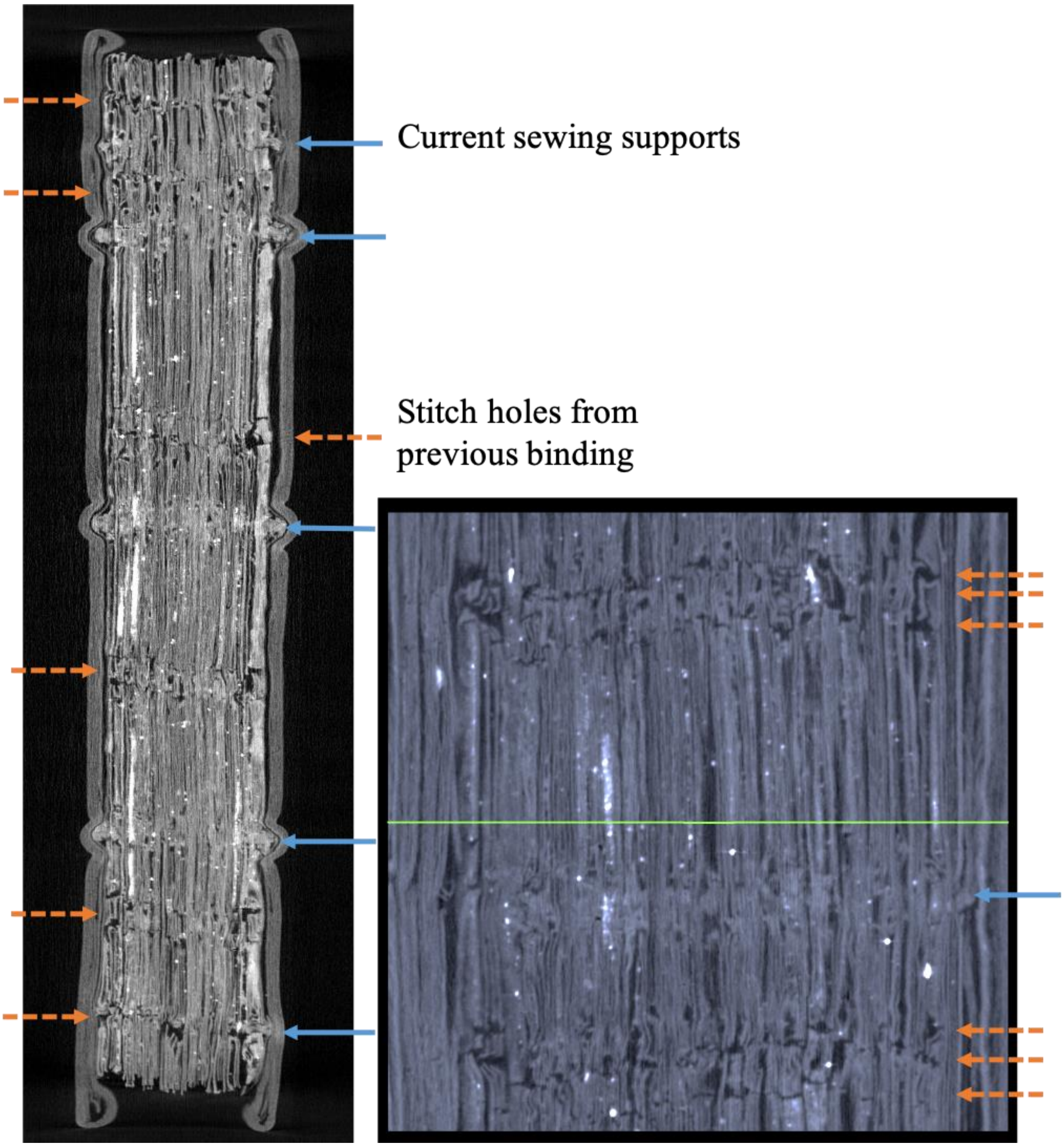


Figure 12. Spinal slices showing the current sewing and previous binding structures (a), with a close up of two of the rows of empty sewing stations, each with three holes per station (b).



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