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Introduction

Stained glass windows were increasingly important to medieval culture, in particular with the development of the Gothic style in the 12th century, the aim of which was to allow larger windows and bring in more light to create an earthly imitation of heaven within its walls (Bony, 1983; Nussbaum, 2000; Philippe, 1998; Scott, 2003; von Simpson, 1962; Wilson, 1990). Besides fulfilling the practical purpose of admitting light into the interior space, stained glass windows are weighted with further meaning when connected to the association of light with the God of Christianity (Duby, 1981; Marks, 1993). The windows served an iconographic function, as they often illustrated religious scenes with sacred messages for the benefit of, and to inspire reflection in, the clergy and congregation. Beyond this, stained glass windows were a sign of conspicuous spending and wealth, and played a part in elevating the status and social power of the cathedral and its clergy; there formed an informal competition between bishops – whose cathedral had the longest nave, or the highest vault – or the most magnificent stained glass (Scott, 2003). Frequently, windows were donated to the church and to God by patrons in order to curry favour for themselves in this life or the next (Marks, 1993). As an art form, medieval stained glass is one of the "least appreciated" (Marks, 1993, xxiv), perhaps due in part to the difficulty in observing it closely as well as the visual disruption of dirt, deterioration and centuries of conservation interventions. Today, medieval stained glass windows continue to serve their practical, iconographic and artistic functions, and are furthermore regarded as valued objects of cultural heritage − the pride of local communities and an attraction for visiting tourists.

Beyond all this, medieval stained glass windows are a relatively untapped source of information about medieval craft production, a topic of indisputable importance, in particular in regards to the industry supporting the building of cathedrals. The medieval period is characterised by several periods during which art, craft and technology thrived. A rise in agricultural production enabled part of the population to focus on various trades and crafts, leading to greater specialisation; the institution of the guild developed as a mechanism for tradesmen and craftsmen to protect their interests in the transforming economy. A capital-based economy formed, through growing numbers of markets, increased commerce, the emergence of a merchant class, greater use of money, and increased wealth. The development of the medieval institutions of kingship and feudalism, and their role in and relationship to the Church, led to increased conspicuous and strategic spending. These highlight the medieval era as a significant period in the economic history of the Western world, and the industry of cathedral building is intimately related to the technological, political and social changes occurring at the time (Burnett, 2013; Epstein, 2009; Haskins, 1927; Ovitt, 2013; Scott, 2003; White, 1978, 1972).

Stained glass windows inhabit the interesting intersection of art and craft, but have traditionally been studied with an art historical approach. A materials science approach has the potential to shed further light on the life history of a stained glass window, which represents a complex *chaîne opératoire*: from glass-making technology, to the acquisition of the glass, to the practices of the workshop that painted and constructed the window, as well as its life post-production of function and admiration, re-use and re-purposing, and deterioration and conservation. Monumental windows that are well dated and relatively undisturbed by historic conservation are a particularly interesting and rare opportunity to study a large volume of glass produced by one or more glasshouses, and to examine the output of a glass-painting workshop for an extended period of time. Studied through the lens of technological choice and within the historical framework of the medieval period, these topics relate to technological expertise, trade and exchange patterns, workshop organisation, and guild influence on craft operations.

1.1 The Great East Window of York Minster

The Great East Window (GEW) of York Minster (Figure 1.1), created by John Thornton of Coventry and his workshop between 1405 and 1408, is the largest expanse of medieval stained glass in England and is generally considered to be a masterpiece of artistry and iconography (Brown, 2018, 2014b; French, 2003; Marks, 1993). This magnificent window has recently been the focus of an important, comprehensive restoration project, "York Minster Revealed", an opportunity which has sparked careful study of the window by various means, including the present materials science approach. Through a comprehensive, multi-analytical study of the GEW, this investigation aims to explore aspects of medieval technology and production in the crafts of glass-making and glass-painting.

1.1.1 Glass-making technology and acquisition

This research engages with the closely related topics of glass acquisition and glass-making technology. This entails a detailed review of the available information on medieval glass-making technology, drawing on both medieval treatises as well as previous work investigating medieval glass through chemical analysis. The glass in the GEW is thought to originate from both English and European glasshouses (Freestone *et al.*, 2010) and one of

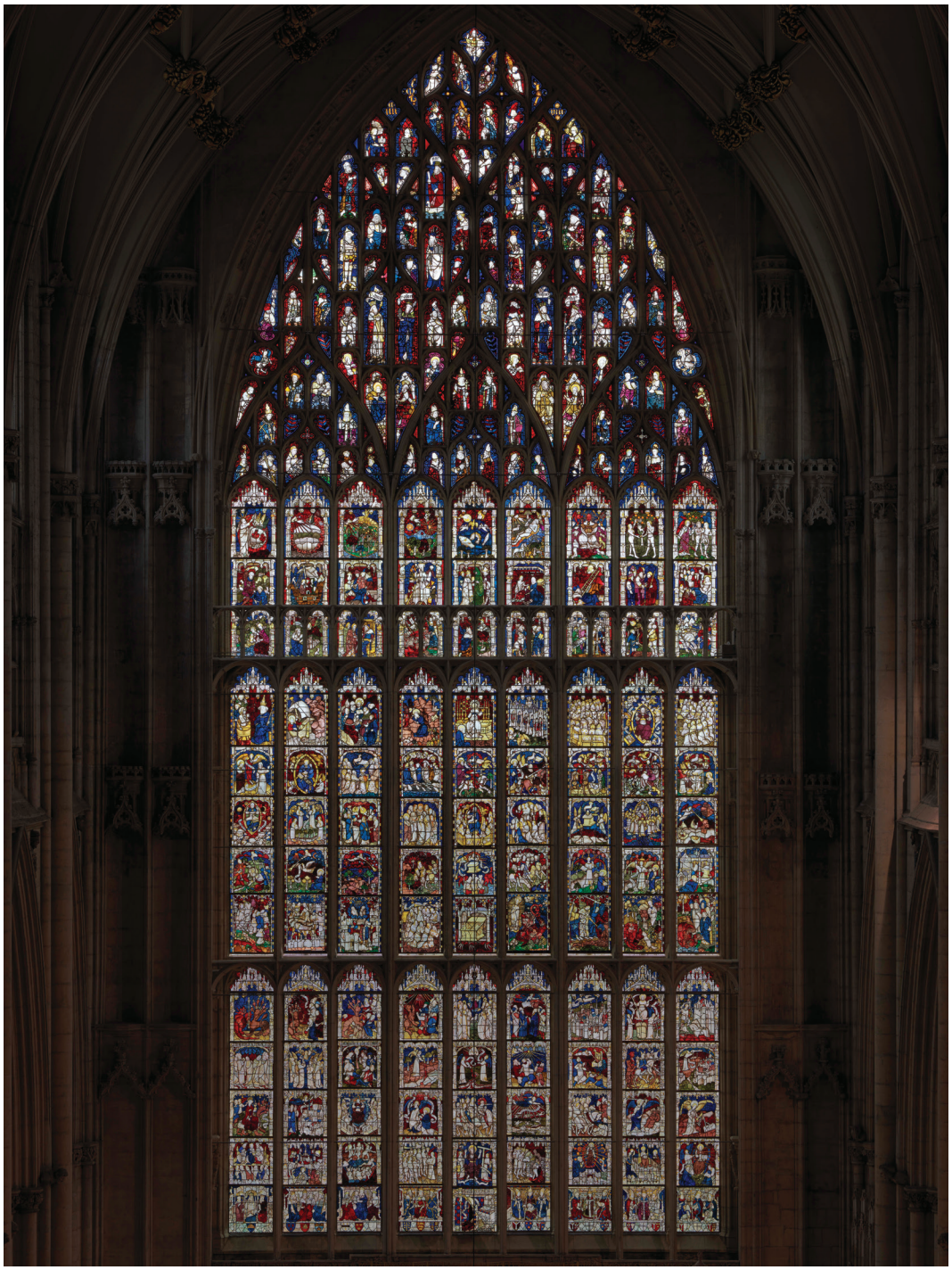

Figure 1.1. The Great East Window of York Minster, in 2018 after conservation © Taken by The York Glaziers Trust, reproduced by kind permission of the Chapter of York.

the aims of the present study is to provenance the glass to a region or glasshouse. Possible sources for the GEW glass are suggested, referring to historical documentation where available. The GEW glass are compared with glass from an English kiln site, and furthermore a synthesis of legacy data allows the examination of regional patterns in glass composition for comparison to the GEW glass.

Different recipes are identified using major and trace element compositions. The factors that affect the generation of colour in glass are also reviewed. Colour is closely related to the composition of the glass as well as furnace conditions, and so the different glass recipes are examined in detail to determine which, if any, were made with the same raw materials and therefore presumably from the same place. The identification of the alteration of a base recipe also informs us about the technological skills of the glass-makers who supplied the window.

The results are also interpreted outside the narrow scope of York in 1405, which will be possible by identifying and examining non-original medieval glass pieces in

the window (removed from other windows and inserted during historical conservation interventions), which yields details about York glass acquisition at different times. In this way, York Minster's longer-term relationships to its suppliers can be examined. By comparing the results to previously published work, this book will also comment on the acquisition of window glass in England at the end of the 14th and beginning of the 15th century.

1.1.2 The organisation of stained[1] glass window production

This research also delves into the organisation of production in the glass-painting[2] workshop that produced the GEW through the new application of archaeology-based approaches related to technological choice and the concept of the batch to a topic that has traditionally been addressed through art historical and stylistic approaches. A review of current knowledge, including information based on medieval treatises, guild ordinances and other historical documentation; the evidence of the Girona glazing table; previous research based on art historical methods; and a review of the concepts of *chaîne opèratoire,* technological choice and the concept of the batch provide the framework within which to interpret the results. The study of the GEW is centred on the identification of different sheets of glass, and the interpretation of their distribution against different models of production. This allows investigation of the organisation of skilled labour in the production of each panel, as well as tracking changes in production during the three year project. The intimate relationship between medieval craft and apprenticeship will also allow some discussion of learning in a medieval craft workshop and provide insights into a system that is known to have been highly stratified by skill.

1.2 Challenges in the study of medieval stained glass by materials science methods

The study of medieval stained glass windows by materials science methods has been inhibited by their architectural contexts; their positions embedded in the walls of our ecclesiastical monuments makes the removal of samples impossible unless the window is dismantled, an expensive and intensive undertaking. Therefore, the removal of samples is generally only feasible when a conservation programme demands the dismantling of the window as well as the removal of the lead strips, called cames, that hold the glass pieces together.

Unsurprisingly, the use of in situ techniques such as handheld portable x-ray fluorescence spectrometry (pXRF) has become very popular in the archaeology and cultural heritage sectors. Handheld pXRF can be used directly on the surface of an object; the technique is completely non-invasive and non-destructive, thus there is no removal of sample material nor any sample preparation. The popularity of the technique in archaeology and cultural heritage studies can be explained by numerous factors, including that often a curator's or conservator's desire to preserve an object's physical integrity outweighs the desire to sample invasively, or, as is often the case for stained glass, removing a sample is simply impossible.

There are major reservations amongst archaeological scientists about the use of pXRF (e.g., Shackley, 2010). There are some limitations inherent in the technique; for example, handheld pXRF cannot be used to measure light elements (for example, sodium), due to the lack of a vacuum and the absorption of the characteristic x-rays in air. The most problematic limitation, however, lies not in the technology, but in the sample material itself: for best results, the test area must be flat, level, homogeneous, and its surface clean and free of corrosion or, for example, painted details or another surface treatment. This is not always or even often the case for archaeological materials.

In many ways, window glass is an ideal candidate for pXRF analysis; it is flat and level, and glass is homogeneous. Recent work on historic windows in England, mostly post-medieval, is an example of a highly successful application of this technique (Dungworth, 2012a). Unfortunately, the characterisation of medieval glass by pXRF is problematic, due to the presence of corrosion and painted detail, which in effect creates a layer of altered composition that dramatically affects the analyses by pXRF, and due to the presence of lead cames (the strips of lead which hold the glass pieces together), which prevent the placement of the spectrometer directly on the surface of the glass.

1.2.1 Trace element methodology

A key focus of this project is to develop a robust methodology for the in situ analysis of medieval stained glass windows, both to benefit the study of the GEW and to enable future work. This work builds upon previous work which focused on the in situ analysis of post-medieval window glass made in England (Dungworth, 2012a). This English Heritage (now Historic England) study identified three heavy trace elements (rubidium, strontium and zirconium) that were both analysed well by pXRF despite corrosion and other surface conditions, and that served to identify several glass types for the purpose of broadly dating the glass, focusing primarily on post-medieval glazing.

[1] The term "stained glass" is misleading, as most colours present in stained glass windows were created by coloured pieces of glass rather than anything applied to the surface. The exception is silver stain, a cementation process that included the application of a silver compound in a carrier medium such as clay or ochre that was then fired onto the surface of the glass. The glass pieces were also often painted with a grey-, black- or brown-monochrome pigment called grisaille, which was also fired onto the glass. Both techniques are described in greater detail in Chapter 5.

[2] In the medieval period, the term glazier was used to mean a range of craftsmen working with glass, from glass-makers, to those who installed plain glass quarries, to those who made the works of art known as stained glass windows (Brown and O'Connor, 1991; Lillich, 1985). The term "glass-painter" is first used in the late fifteenth century (Brown and O'Connor 1991, p 23) and will be used in this work as its meaning is unambiguous: it refers to the craftsmen who created stained glass windows, although this required more skills than just painting the glass.

This investigation explores the resolution of these elements beyond the identification of glass types to test if they can be used to differentiate different recipes, regional provenance, and even batches of glass. This component of the book first surveys the technical and practical considerations of handheld pXRF, the deterioration processes that affect medieval glass and its surface composition, and other sources of surface heterogeneity (such as painted details). Tests are carried out to test the performance of pXRF on medieval stained glass with the purpose of identifying which elements are affected by surface conditions, and results of the analysis of the GEW glass by pXRF are compared to other more robust analytical techniques in order to identify their usefulness in addressing questions related to technology and production.

1.2.2 Interference of lead cames

The other major obstacle to the analysis of medieval stained glass by pXRF is the protrusion of lead cames that hold the glass pieces together. These cames can protrude several millimetres and the glass pieces themselves are often smaller than the face of the spectrometer; these two factors combine to prevent the placement of the spectrometer against the surface of the glass, resulting in a distance that can reach four to five millimetres. This study seeks to mitigate this problem through an evaluation of what elements are affected by the increased distance between sample and spectrometer, and how, and furthermore to test whether this effect is predictable and can be corrected through empirical calibration if the distance is held constant. Ultimately, an inexpensive, adaptive and portable solution for this problem is offered, which retains a high degree of precision in the results.

1.3 Overview

The next chapter (Chapter 2) will introduce the Great East Window (GEW) of York Minster, the window that forms the focus of, and provides the materials for, this research. The chapter identifies the documentation available related to its construction, gives a brief background to York in 1400, and provides details related to its recent conservation and previous research.

The rest of the book is structured along three strains: glass-making technology, the organisation of glass-painting, and methodological development.

Chapter 3, 'Glass-making in the medieval period', provides a review of the available information related to medieval glass-making, including documentary sources, archaeological evidence, and previous work based on materials analysis. This chapter also reports a synthesis of a large amount of legacy data on medieval glass in Europe with the purpose of defining regional characteristics in composition as a tool for provenance determination of medieval glass.

Chapter 4, 'Medieval glass-painting', continues in a similar way but on the topic of making stained glass windows, with a review of medieval treatises, other historical documentation including guild ordinances and financial records, and finally describes how this research implements a new approach to the topic of organisation of artistic production of stained glass windows through the application of archaeology-based concepts and frameworks.

Chapter 5, 'Problems and possibilities in using handheld pXRF to study medieval stained glass windows', begins with an overview of handheld pXRF technology and cover key parameters of which the typical user should be aware when planning an analytical programme. It then builds on the previous two chapters by identifying the key obstacles to analysis of medieval stained glass: poor surface conditions and the protrusion of lead cames.

Details of sampling, analytical methods, and statistical data treatment are given in Chapter 6, 'Methods'. A multi-analytical approach has been designed based on handheld pXRF as well as electron microprobe for the characterisation of major elements, laser ablation inductively coupled plasma mass spectrometry for the characterisation of trace elements, and thermal ionisation mass spectrometry for the measurement of isotopic ratios.

The results sections begin with methodological development in Chapter 7, 'Performance of handheld pXRF in the analysis of medieval stained glass'. Through a series of tests, elements that are well measured by pXRF despite surface conditions are identified as quantifiable elements in this study; all other elements reported are considered informational or qualitative. The identification of certain heavy trace elements as well analysed by pXRF is examined through the lens of the varying depths of pXRF analysis of different elements. The relationship between these trace elements and glass-making technology as well as provenance are be discussed. This chapter also reports the effect that distance between spectrometer and sample has on the analysis of different elements and investigate whether the results can be corrected through empirical calibrations if the distance is held constant. The development of an attachment for the spectrometer that will allow the analysis of in situ window glass despite lead cames is introduced, and its successful use in the study of another case study, not reported in this book, is briefly described.

The results of the analyses on the GEW glass are reported in Chapter 8, 'Chemical characterisation of the GEW glass'. Different glass types are identified, and then the chapter focuses on reporting the medieval glass in the window, with the original and non-original glass reported separately.

In Chapter 9, 'Original white glass batches and their distribution in the window', the results of the batch identification are reported and images showing their distribution in each panel assessed.

Chapter 10, 'Recipes and procurement of the GEW glass', discusses provenance and trade relationships specifically for York Minster in 1400 and for England in the 14th-15th centuries, and examines glass-making technology, in particular in the generation of different colours, through the results of the coloured glasses in the GEW.

Chapter 11, 'Glass-painting and the organisation of production in John Thornton's workshop', examines the distribution of batches both in each panel and across the window to support previous hypotheses regarding the direction of work; to suggest which panels may have been created using the same glazing table; and finally, to compare with models of production based on well-known manufacturing techniques from the automobile manufacturing industry (Fordism and Toyotism). The identification of some of the painted work of John Thornton himself is also suggested.

Finally, the concluding chapter, Chapter 12, gives a summary of the key findings of this project and points towards areas for future research.