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Nadine Schibille

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Islamic Glass in the Making
Chronological and Geographical Dimensions

Nadine Schibille

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Islamic Glass in the Making
Chronological and Geographical Dimensions

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Islamic Glass in the Making

Chronological and
Geographical Dimensions

Nadine SCHIBILLE

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Preface: GlassRoutes and the systems of change

The aim of this volume is to assemble and to dissect the available analytical evidence of the development of early Islamic glassmaking in order to identify and define compositional discriminants of regional and temporal glass productions. The meta-analysis of published (and many unpublished) data of Islamic glass assemblages reveals the broad temporal and geographical patterns in economic and technological activities, highlighting periods of transformation and differences between regional practices and markets. This study advocates a broad geographical and chronological scope in order to trace developments in the production, trade and consumption of glass at the turn of the second millennium CE, and to bring to light the motivations for and reasons underlying these changes. In a way, this book provides an analytical assessment of historical, economic and technological developments, using the compositional data of Islamic glass assemblages as main primary evidence.

The results of “GlassRoutes: Mapping the First Millennium Glass Economy”, a project funded under the European Research Council Framework Programme for Research and Innovation Horizon 2020 (Consolidator Grant Number 647315), provide the basis for much of this book. The analytical data of several of the glass assemblages have already been published with open access in scientific journals, where the analytical datasets can be consulted in full. Here I present an inclusive and integrated account of early Islamic glassmaking, highlighting commonalities and differences across time and space. Many of the ideas will certainly be developed further as new data become available and new geographical regions are explored. This volume thus offers a flexible framework for the interpretation of analytical data from consumer sites of early Islamic plant ash glass from the major glassmaking regions, including Egypt, Syria-Palestine, Mesopotamia, Central Asia and the Iberian Peninsula, dating approximately to the seventh to twelfth centuries CE. New analytical data can be integrated into this scaffold to modify and, it is hoped, expand the model in the future.

Acknowledgements

This book contains a critical reappraisal of analytical data of archaeological glass finds from numerous contexts. As such, it owes a great debt to various museums and institutions, excavations and many scholars and colleagues who shared not only their data and materials for analysis, but also their expertise and professional insights. I am immensely grateful to the following museums and institutions, in no particular order, for giving me access to some outstanding glass assemblages that form the backbone of this book: the British Museum and the Victoria and Albert Museum in London, the Musée du Louvre and the Bibliothèque nationale de France in Paris, the Bibliothèque nationale et universitaire de Strasbourg, the Museum für Islamische Kunst in Berlin, the Conjunto Arqueológico de Madīnat al-Zahrā', the Mezquita-Catedral de Córdoba, Gerencia de Urbanismo del Ayuntamiento de Córdoba, Consejería de Cultura de la Comunidad de Madrid and the Museo Arqueológico Regional de la Comunidad de Madrid, the Museo Arqueológico de Alicante, and the Parco Archeologico di Selinunte e Cave di Cusa, Sicily. The Freer Gallery of Art and Arthur M. Sackler Gallery Archives of the Smithsonian's museums of Asian art kindly allowed me to reproduce one of Ernst Herzfeld's original sketches. Many colleagues and friends have generously shared their research and data, and given me access to their collections. My thanks to Isabelle Biron, Maryse Blet-Lemarquand, Étienne Blondeau, Léa Brunswic, Claudio Capelli, Patrick Degryse, Chris Entwistle, Danièle Foy, Ian Freestone, Marc Gener-Moret, Sophie Gilotte, Bernard Gratuze, Julian Henderson, Caroline Jackson, Liz James, Jens Kröger, James Lankton, Bea Leal, Patrice Lehuede, Moujan Matin, Andrew Meek, Stephen Merkel, Éric Ollivier, James Peake, Venetia Porter, Markus Ritter, Mariam Rosser-Owen, Guillaume Sarah, Andrew Shortland, St John Simpson, Torben Sode, Mike Tite, Bendeguz Tobias, Rosalind Wade Haddon and Mark Wypyski. My research on several interesting Spanish glass assemblages was made possible thanks to the interest and generosity of many individuals. I am deeply grateful to María Teresa Casal García for the Šaqunda glass project, Alberto J. Montejo Córdoba and Ana M^a Zamorano Arenas who welcomed me to Madīnat al-Zahrā', Lauro Olmo for the opportunity to study the glass from Recópolis, Trinitat Pradell and Elena Salinas for their expertise on glazes and for providing access to the glass from Pechina, Sonia Gutiérrez Lloret and Victoria Amoros Ruiz for the collaboration on the vitreous finds from Tolmo de Minateda, and María Dolores Sánchez de Prado for her help and expertise in glass from the Iberian Peninsula.

My special thanks go to the doctoral students and young postdocs I have had the privilege of collaborating with over the years for their unfaltering energy and enthusiasm, including Francesca Colangeli for her work on Sicilian glass assemblages, Charlotte Nash who triggered my interest in Islamic bracelets, Cécile Noirot for opening up the world of materials science and the synchrotron, Veronica Occari who got me thinking about Venice and its role in the Crusades again, and especially Teresa Palomar who invited me to participate in the fascinating project on the mosaics of the Umayyad Mosque in Córdoba. If it were not for Teresa, the data on the mosaics from Córdoba would never have seen the light of day.

I am extremely grateful to the European Research Council for giving me the opportunity to pursue this exciting research project. Without an ERC consolidator grant (grant agreement no. 647315) there would be no book and none of the articles that I have published over the last six years about the archaeo-vitreous record of the Mediterranean. In fact, without its support I probably would no longer be in research. My sincere thanks go to the CNRS for hosting my project, and especially to all my colleagues at IRAMAT-CEB, past and present, for their patience and sustained support. Particular thanks are due to Henrique Da Mota, Sophie Boucetta and Fai Tcha for their technical support, and Bernard Gratuze, who was 'instrumental' in the analyses of so many glass assemblages and from whose expertise I benefit immensely to this day. I should also like to thank the *GlassRoutes* team, Laura Ward Adlington, Jorge de Juan Ares, Cristina Boschetti and Inès Pactat, for their help in obtaining and contextualising numerous archaeological glass assemblages from around the Mediterranean.

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'But we don't want to *teach* 'em,' replied the Badger.

'We want to *learn* 'em – learn 'em, learn 'em!

And what's more, we're going to *do* it, too!

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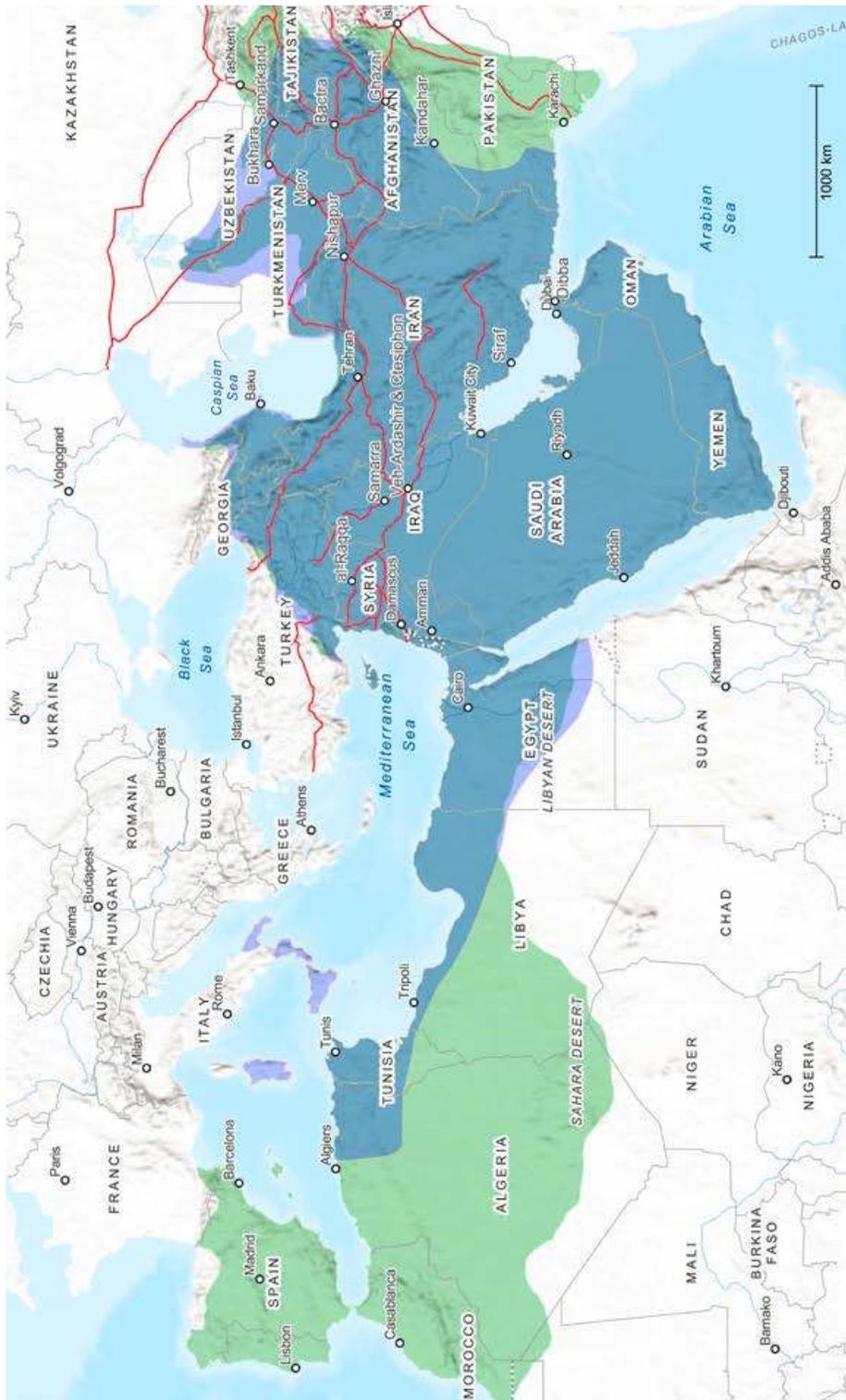


Fig. 1: Map of the extent of the Umayyad (ca. 750 CE, blue/green) and Abbasid (9th century, blue/purple) caliphates, including the approximate location of the main Silk Routes across Eurasia (red traces). Created using worldmap from ArcGIS hosted by Esri, USGS (<https://worldmap.maps.arcgis.com/apps/mapviewer/index.html>). Layers used by pkbol_worldmap and evliya_worldmap.

Introduction

By the tenth century CE, the ancient glassmaking industry and its markets had been utterly transformed. The production of natron-type glass in the traditional eastern Mediterranean glassmaking centres in the Levant and Egypt had ceased entirely. New recipes based on the use of plant and wood ash emerged in both the Islamic world and in Carolingian Europe, respectively. Primary production centres multiplied and the scale of production continued to shrink. Glass was nonetheless still ubiquitous and very much part of everyday life at least as far as wealthy abodes and palatial contexts were concerned (Carboni and Whitehouse 2001). Glass was also used for prestigious large-scale architectural decorations, most famously perhaps in the form of mosaic tiles and intricate glass inlays at ninth-century Samarra in Iraq (Lamm 1928; Schibille *et al.* 2018a), where glass was instrumental in a new architectural aesthetic. Archaeological excavations of Islamic sites from al-Andalus and the Maghreb in the west to Central Asia in the east have yielded considerable quantities of glass finds that provide a glimpse of the range and sophistication of glassmaking during the first centuries of Islamic rule (e.g. Barfod *et al.* 2018; Foy 2020; Freestone 2020; Henderson *et al.* 2004; Henderson *et al.* 2020; Kröger 1995; Phelps 2017; Ritter 2019; Scalon and Pinder-Wilson 2001; Schibille *et al.* 2018a; Shindo 2000). The Arab conquest in the seventh century did not at first demonstrably upset the organisation and scale of glass production in the traditional glassmaking centres in Egypt and the Levant (e.g. Phelps *et al.* 2016; Schibille *et al.* 2019). It had nonetheless a notable impact on glass consumption patterns at the other end of the Mediterranean. In al-Andalus glass had once more become a relatively rare commodity by the eighth century compared to the Roman and late antique periods (De Juan Ares *et al.* 2019a; Schibille *et al.* 2020a). Hence, geopolitical developments clearly fuelled some of the fundamental transformations in the production and exchange of vitreous materials, ultimately resulting in the development of more or less independent local glassmaking traditions.

The primary aim of this book is to explore the development of early Islamic glassmaking recipes and to establish compositional markers that delineate regional and temporal production groups of plant ash glass. The observations by Sayre and Smith (1961) that ancient glass can be sorted into several well-defined compositional groups linked to specific geographical origins has given rise to one of the most enduring methodological approaches in archaeological glass studies, that of affiliating archaeological glass finds with a primary production location based on their compositional fingerprint. Roman and late antique natron-type glass from the Mediterranean region has since been differentiated into ten major compositional

groups, each being the likely output of a discrete primary production centre that was active during a restricted time frame (Freestone 2020). The classification of natron glass is based on the assumption that its major compositional characteristics are a reflection of the silica source, and that elements commonly associated with the silica source such as aluminium, titanium, zirconium and hafnium are therefore diagnostic of the different geographical production zones. However, while many of the first millennium CE natron glass groups can successfully be distinguished from one another by means of their silica-related elements, the use of plant ash as the main fluxing agent introduces an additional layer of complexity because of the highly variable nature of the plant ash component (Barkoudah and Henderson 2006). As a consequence, the interpretation of plant ash glass requires a new set of criteria to separate and define regional production groups. Here I compare the compositional profiles of glass assemblages from across the Islamic world to identify the distinguishing features that are characteristic of specific geographical origins. The first step in this endeavour was to detect continuities and changes, and to explore whether some characteristics of natron glass productions are carried over into plant ash glass recipes, thereby allowing the categorisation of geographically distinct source areas. By looking at the distribution patterns of glass, the aim was to infer the multidimensional relationships that existed within the early Islamic world and to advance hypotheses about what might have caused the fundamental transformations of the medieval Islamic glass industry.

The past two decades have witnessed a massive expansion in the analytical study of early Islamic glass assemblages from archaeological contexts stretching from the Iberian Peninsula to the eastern Mediterranean, Mesopotamia and along the Silk Roads to Afghanistan (Brems *et al.* 2018; De Juan Ares and Schibille 2017a; De Juan Ares and Schibille 2018; Duckworth *et al.* 2015; Duckworth 2017; Fiorentino *et al.* 2018; Fiorentino *et al.* 2019b; Foy 2017; Henderson *et al.* 2004; Henderson *et al.* 2016; Phelps 2018; Schibille *et al.* 2018a; Schibille *et al.* 2019; Swan *et al.* 2017). The spatial and chronological coverage of early Islamic glass compositions is still far from complete. For instance, analytical data from north African assemblages are all but absent, data securely attributed to Egyptian productions are limited, and the early Abbasid phases (750 – 950 CE) remain largely unexplored, especially in the western Mediterranean. Despite these limitations, the available data increasingly permit the identification of general chronological and geographical patterns of the circulation of vitreous materials, and allow us to build up a coherent picture of the archaeo-vitreous record of the Islamic world.

To grasp fully the transformational processes in the history of Islamic glassmaking and working requires a broad chronological scope, one that accounts for changes prior to the Arab conquest and the impact of geo-historical events on different scales (Fenwick 2018; Frantz-Murphy 2006; Gutiérrez Lloret 2015; Loseby 2005; Necipoglu 2012). Broadly speaking, this volume looks at glass compositions across a long time span, from the Roman period through to the twelfth century CE, in an attempt to tease out commonalities in glass productions in specific geographical areas and at different points in time, even though the main focus of this study is glass production during the early Islamic period. Since we mostly rely on circumstantial evidence, this broad chronological approach helps to reinforce the evidence about the likely origins of individual glass groups based on common compositional traits. The underlying premise is that in order to understand what changed with the Arab expansion we need to identify the developments and practices prior to the Arab conquest. This is particularly pertinent as natron glass production continued well into the Islamic period, and the transition towards a soda-rich plant ash recipe occurred only at the turn of the ninth century in Syria-Palestine, and considerably later in Egypt and the western Islamic world.

The interconnectivity of early Islamic glassmaking traditions across a vast geographical area from the Straits of Gibraltar to the Iranian plateau necessitates likewise a large-scale comparative approach. The main objective is to develop an interpretative protocol for the initial classification of Islamic plant ash glass into distinct compositional groups associated with different regional production centres. A similar strategy was recently adopted in a comprehensive review of the archaeological and typological evidence of early Islamic glass assemblages (Foy 2017). Such a multidimensional perspective moreover resonates with current trends in Islamic art historical and archaeological research that increasingly emphasises diversity within unity (Anderson 2014; Anderson and Pruitt 2017; Fenwick 2018; Gutiérrez Lloret 2015; Necipoglu 2012). In short, investigating the transitions from natron to plant ash glassmaking means drawing attention to the multitude of cultural and technological connections across the Islamic world, and to the market forces and geopolitical trends that may have driven the transformations in the organisation of the glass industry and trade.

This work presents a synthesis of published and unpublished analytical data of early Islamic glass from the *Dar al-Islam* (territory of Islam) from its beginnings in the second half of the seventh century to the eleventh and twelfth centuries CE. This involves in many cases the critical re-evaluation and re-interpretation of published data in light of newly identified production groups and the increasing availability of analytical data. Depending on the analytical method employed and the archaeological context, the quality and quantity of published data vary greatly.

The discussion of the different glass categories can therefore not be equally detailed. In addition, not all geographical regions are covered in the scientific literature to the same extent and with the same level of detail, and allowances need to be made for gaps in the available evidence. For example, our current understanding of the glass industry in Egypt during the early Islamic period relies almost entirely on the analytical data of glass weights that we have recently generated. Although I am convinced that these data give very good insights into the types of compositional glass groups that we can expect in Egypt, it remains a matter of debate whether these specialised objects are truly representative of the glass industry as a whole. The immense advantage of the glass weights is that they can be dated very precisely. Hardly any other (glass) object comes even close in terms of dating accuracy. In the case of Egypt, I thus take the data of glass weights as a chronological and compositional benchmark, against which I compare other assemblages from consumer sites as well as broader historical developments. While this is far from perfect, the purpose of the present study was to advance new ideas and theories about the technological transformations and the transfer of skills and recipes that ultimately led to a distinct Islamic glassmaking industry based on the currently available compositional data. In a nutshell, this study makes assumptions based on data that are necessarily fragmentary in nature. To what extent the conclusions drawn and the resulting hypotheses will stand the test of time remains to be seen. The aim was to formulate such hypotheses in the first place which can then be tested in the future using targeted research strategies.

Furthermore, it is important to stress that I will concentrate the discussion on the analytical data. This work does not contain a consideration of typologies or secondary working techniques other than brief descriptions of the use of glass in architectural decorations, particularly monumental mosaic decorations, and some general observations about colours and opacifiers. Instead, the aim is to identify patterns in the compositional characteristics of Islamic base glass types across time and space in order to reveal the exchange and trade of glass and the transmission of technologies and recipes. Because glass has been utilitarian and ubiquitous since Roman times, it is argued that glass and more specifically its chemical composition can serve as an indicator of historical change and a source material in its own right.

The competing dynamics responsible for the transformations in the production of and trade in glass will be examined in relation to five regional polities: Egypt, Greater Syria, Mesopotamia, Central Asia and the Iberian Peninsula, along with some preliminary considerations about Sicily and the Maghreb (Fig. 1). Initially, I will focus on those areas which had a long history of primary glass production and from where there is direct evidence that glass was produced during the

Roman, Byzantine and early Islamic periods. These are Egypt, the Levantine coast and Mesopotamia. The first chapter investigates early Islamic glasses from Egypt and the possible impact of the fragmentation of the Abbasid caliphate in the late ninth century on the local glass industry. The second chapter assesses the changes in the composition of glass assemblages in Greater Syria (Bilâd al-Shâm) with an emphasis on the dynamics of interregional exchange, particularly between the Levantine coast, Egypt and Mesopotamia. This is followed by a discussion of Mesopotamian and Central Asian glassmaking traditions from the Sasanian through to the Abbasid period in relation to the evolution of plant ash-based recipes. The final chapter deals with changes in the chemical make-up of glass assemblages in the Iberian Peninsula, which provide good circumstantial evidence of the introduction of primary plant ash glassmaking to the western Mediterranean sometime between the ninth and tenth centuries CE. Prior to the establishment of local plant ash glassmaking, our data also demonstrate the invention of a novel glassmaking technology in al-Andalus, using metallurgical waste for the production of lead and soda ash lead glasses in the region around Córdoba (Schibille *et al.* 2020a).

Foregrounding a Mediterranean-wide scale of analysis that takes into account well over 5,000 individual data points, this study shows how, in a remarkably brief period of time, the Islamic glassmaking industry was recast through a combination of imperial expansion and the foundation of new capital cities and caliphal residences. By examining the compositional nature of glass assemblages from well-dated archaeological contexts, it is possible to advance an integrated model of how the organisation of the trade, production and consumption of glass was transformed in the aftermath of the Arab conquest and the establishment of the Umayyad Caliphate. In the absence of quantitative information about the absolute volume of glass that was produced or traded at any given time, it is nonetheless possible to highlight changes in the relative abundance and variety of glass within the archaeological record of different periods. The scarcity of Egyptian glass types outside the eastern Mediterranean after the sixth century, for example, gives the impression of a contraction of the Egyptian glass industry. This, however, may reflect a shift in commerce rather than a reduction in the actual output of production in Egypt. When commercial activities refocused on Greater Syria and the new capital city of Damascus at the end of the seventh and the beginning of the eighth centuries, large amounts of glass from Egypt were imported to this region which had previously been virtually self-sufficient. Egypt appears to have been the main supplier for the large-scale mosaic decoration of the Great Umayyad Mosque of Damascus and many other smaller foundations, such as the palatial complex of Khirbat al-Minya. Similarly, the foundation of new caliphal residences in Greater

Syria and Mesopotamia during the early Abbasid period led to the intensification of local industrial activities in these more easterly regions. At the same time, al-Andalus was apparently cut off from fresh supplies from the east and eventually developed its own local glassmaking industry.

This study is primarily concerned with the definition of compositional discriminants between Egyptian, Levantine, Mesopotamian, Central Asian and Iberian (and Sicilian) glasses, especially with respect to plant ash glass types. In the case of Egyptian plant ash glass, the definition is based on the premise that the features that distinguish Egyptian natron-type glass may also apply to plant ash glass groups. Similarly, elevated chromium to lanthanum ratios that have been demonstrated to discriminate between Egyptian and Mesopotamian Late Bronze Age glasses (Shortland *et al.* 2007) appear to be equally applicable markers for early Islamic glass produced in Mesopotamia. This criterion seems to be applicable only to glass types of Mesopotamian origin in the strict sense and not to glasses manufactured further east on the Iranian plateau or Central Asia. This makes it possible to separate Mesopotamian from eastern Iranian and Central Asian glass productions on the basis of chromium to lanthanum ratios. Given the lack of sufficient reliable data on early Islamic glasses from the Mesopotamian and western Asian regions this has to be seen as a first attempt to define distinctive features that will have to be validated in future research.

A global strategy may not positively identify the provenance of a specific glass composition, but it can exclude sources and, together with the relative ubiquity of the glass groups, may indirectly reveal the likely origin of a particular glass type. Needless to say, the attribution of a single archaeological glass find to a specific origin or regional group remains highly problematic and the approach advocated here relates to entire assemblages and their overall compositional spread. Even though the discussion seemingly centres on the question of provenance, it goes far beyond the simple determination of origin of archaeological glass assemblages. Comparisons between regional compositional groups are intended to reveal geographical and chronological ranges and the potential causes of change. Issues of recycling will feature intermittently throughout the following chapters, because the transformation of the glass industry and the introduction of new recipes have often been preceded by increased levels of glass recycling. The scientific analysis of archaeological glass can thus elucidate aspects of human response to socio-economic transformations and contribute significantly to the study of the early Islamic period, most notably to the technological, cultural and economic processes that over the course of several centuries have come to define an Islamic glassmaking tradition.

The diversity of the geographical regions covered in this study poses terminological challenges, beginning with regional names such as Syria, Mesopotamia and al-Andalus. Greater Syria and Bilâd al-Shâm are here used interchangeably in the sense of the *Encyclopaedia of Islam* to include the political entities of Syria, Lebanon, Jordan, Israel and Palestine and extending into modern Turkey (Bosworth *et al.* 2012). Mesopotamia pertains to the catchment area of the Tigris and Euphrates river system, overlapping in the north with the north-eastern parts of the Bilâd al-Shâm. This is, in fact, reflected in the glass assemblage from al-Raqqa that features in the second chapter on Greater Syria, as well as in the third chapter on Mesopotamian glasses. Included in the chapter about Mesopotamian glassmaking traditions are also several archaeological collections from the eastern Iranian plateau and Central Asia such as Nishapur, Merv and Ghazni which, as shall be seen, do not correspond to the definition of Mesopotamian glasses as such. Al-Andalus refers to the entire Iberian Peninsula under Muslim rule. For reasons of simplicity and convenience I exclusively use the common era (BCE/CE) system of dating. Note that compositional data, unless otherwise stated, are given as weight per cent of oxides [wt%] in the case of the major and minor elements, and in parts per million [ppm] in the case of trace and rare earth elements. Regarding the bibliography, I have tried to cover the most important and recent publications without claiming completeness. In many cases the latest publications contain extensive lists of references to which I would like to refer the reader. Finally, the term **Islamic glass** is used in this volume to denote glasses produced during the Islamic period in areas under Islamic rule without denying the cultural complexities and local variations of early Islamic societies and culture. This study accordingly makes no assumption about the ethnic or religious identity of the glassmakers, workers or patrons, nor about the types of glass objects that were produced. Glassmaking during the Islamic period was a global phenomenon, but glassmaking activities were embedded into local contexts to accommodate local expectations and requirements, often exploiting local resources. It is precisely from these local differences that we can glean some of the most interesting reasons for the dynamic changes in glass production during the first millennium CE.

Islamic glassmaking in Egypt contingent on local administration

Several fundamental issues shape our interpretation of Islamic glassmaking. First, to detect and quantify change over time, Islamic glass production needs to be considered in relation to the nature of the glassmaking traditions that preceded the Islamic era. At the time when the Umayyads controlled the eastern Mediterranean, both the volume of glass production and its recipes were still firmly rooted in the ancient tradition of natron-glass making. Second, the question of the adoption of plant ash recipes across different regions in the Islamic world as well as the exchange between orient and occident presuppose a cultural and technological unity. Ultimately, however, the products and techniques are integrated into local contexts, thus giving rise to new industries with new technologies and raw materials. Hence, the vitreous landscape of the early Islamic period is defined by numerous regional developments that impact on the circulation and uses of glass. Finally, the assessment of the chronological and geographical dimensions of the transformations of Islamic glassmaking is severely constrained due to the limitations of the available evidence, particularly as regards the eighth and ninth centuries CE, in both the east and the west. The lack of analytical data is particularly acute in the case of Egyptian glass assemblages, not least because of the restrictions on the export of archaeological materials from Egypt. An obstacle to the question of an Egyptian provenance is the absence of archaeological evidence of primary production sites from the late antique and Islamic periods. Several primary production locations are known from Egypt, most of which date between the second century BCE and the end of the second century CE (Nenna 2015). Two primary glass workshops identified around Lake Mariout are not particularly well dated, but the finds from the southern shore at Marea/Philoxenité are attributed to the fifth to eighth centuries CE (Nenna *et al.* 2000), thus covering the transition from the Byzantine to the early Islamic period. The remains of a primary glass furnace recently discovered at Antinoopolis in Middle Egypt have tentatively been dated to late antiquity (Silvano 2015). Furthermore, no complete set of compositional data of major, minor and trace elements exists of glass assemblages

firmly attributed to an Egyptian provenance and securely dated to the sixth and/or seventh centuries CE. For the most part we instead rely on circumstantial evidence and the observation made by Picon and Vichy (2003) that high heavy element contaminations are characteristic of Egyptian glass productions. A recent analysis of hafnium isotopes has confirmed the Egyptian provenance of a number of Roman and late antique glass groups (Roman Sb, Foy 2.1, Egypt I). This represents semi-independent evidence for the Egyptian origin of these glasses, in addition to their elevated titanium and zirconium contents (Barfod *et al.* 2020).

To detect changes within the archaeo-vitreous record of Egypt and to extrapolate possible causes of change requires a large-scale and comparative approach. The main objective of this chapter is therefore to outline the compositional and isotopic characteristics of Egyptian glass groups from the Roman through to the early Islamic periods and to thereby identify markers of Egyptian primary glass production and its technological transformations. The inherent strength of this methodology is that it relies on large datasets of a representative cross-section of the population. In other words, the larger the available dataset the more reliable will be the conclusions drawn from it. The focus is therefore not on individual objects, but on compositional groups the size of which varies from a handful of samples among the Wadi Natrun finds to several hundred data points in the case of Roman antimony-decoloured glass. Archaeology provides here independent evidence that the glass from the Wadi Natrun and, to a lesser extent, the glass from Lake Mariout indeed represent primary production groups. Before exploring the compositional properties of the numerous Egyptian glass groups, it is thus useful to give an overview of the archaeological evidence of primary glass workshops discovered in Graeco-Roman Egypt (Nenna 2015, and references therein).

Primary glass workshops in Egypt – the archaeological evidence

A total of six primary production sites have been identified in Egypt, two around Lake Mariout west of Alexandria, at Marea-Philoxenité on the southern and Taposiris Magna on the northern shore of the lake, three in the Wadi Natrun (Zaki, Bir Hooker and Beni Salama) (Nenna *et al.* 1997; Nenna *et al.* 2000; Nenna *et al.* 2005; Nenna 2015; Thirion-Merle *et al.* 2003), and recently one at Antinoopolis in Middle Egypt, 286 km south of Cairo (Fig. 2; Silvano 2015). Some of the raw glass recovered from the primary glassmaking installations at Lake Mariout and the Wadi Natrun were analysed, and while they differ significantly in their compositional signature they also show some commonalities. Several compositional groups have been distinguished based on the analysis of more than 50 glass samples recovered from the three primary production sites in the Wadi Natrun, Beni Salama, Bir

Hooker and Zaki (Nenna *et al.* 1997; Nenna *et al.* 2000; Nenna *et al.* 2005; Picon *et al.* 2008; Thirion-Merle *et al.* 2003). The different glass groups show strong positive correlations of the silica-related elements aluminium, titanium, iron and magnesium (Fig. 3). The scatter along the linear regression line of, for example, magnesium to iron and aluminium to titanium concentrations reflects the more or less constant ratios between different heavy minerals in the silica source and, by extension, variations due to sedimentary effects in the glassmaking sands (Freestone *et al.* 2009a; Schibille *et al.* 2017; Shortland *et al.* 2007). An exception might be group Wadi Natrun c (Wnc), a colourless glass with very low contamination levels of elements associated with the silica source and decoloured using antimony (Picon *et al.* 2008). Even though none of the sands analysed from the Wadi Natrun corresponds to the chemical fingerprint of group Wnc (Degryse 2014; Nenna *et al.* 2000; Nenna *et al.* 2005; Thirion-Merle *et al.* 2003), it is still believed to have been manufactured there (Nenna 2015, p. 15). Specifically, nine out of the 11 samples belonging to group Wnc came from Beni Salama (Nenna *et al.* 2000; Nenna *et al.* 2005; Picon *et al.* 2008; Thirion-Merle *et al.* 2003). The furnaces excavated at Beni Salama appear to represent the latest phase of primary production activities in the Wadi Natrun which ceased no later than at the beginning of the third century CE (Nenna 2015, p. 18).

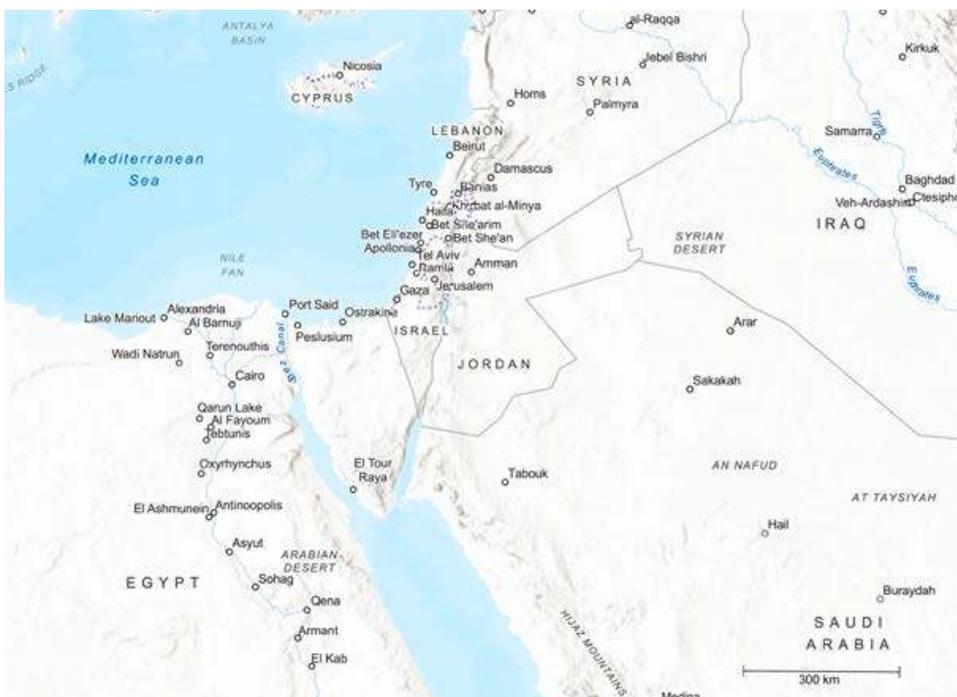


Fig. 2:

Map of major sites in Egypt and Greater Syria mentioned in the text. Created using worldmap from ArcGIS hosted by Esri, USGS (<https://worldmap.maps.arcgis.com/apps/mapviewer/index.html>).

The archaeological remains of two glass furnaces at Beni Salama have been extensively studied and have revealed three and four phases of activity and the production of three different types of glass: naturally coloured blue-green glass, glass decolourised by antimony (Wnc) and manganese-decoloured glass (Nenna 2015, p. 15). The capacity of the furnaces was estimated at about 15 to 22 tons, depending on the thickness of the glass slab that was produced (Nenna 2015, p. 15). Compared to the late antique glassmaking installations known from the Levantine coast, the structures in Beni Salama were described as less standardised ‘experimental’ furnaces, and there were signs of on-site treatment of salt and natron (Nenna 2015, pp. 3, 17). Wadi Natrun was undoubtedly one of the main and presumably most productive natron sources exploited in antiquity (Shortland *et al.* 2006). Interestingly, late antique and Arab textual sources suggest that Mareotide was also known for the commercialisation of natron, as were other sites in the Delta, notably al-Barnuji in the Western Delta, as well as the region around Fayum on the shores of Lake Qarun, in Middle Egypt near Oxyrhynchos and in Upper Egypt at el-Kab (Nenna *et al.* 2000, p. 106, and references therein; Shortland *et al.* 2006). Whether any of these deposits other than those in Wadi Natrun and perhaps at al-Barnuji supplied the ancient glass industry remains unknown not least because the term ‘natron’ designates both common salt (i.e. sodium chloride) and natron (i.e. sodium carbonate), of which only the latter is suitable for glass production (Shortland *et al.* 2006).

The archaeological evidence for primary glass production in Egypt and the analytical data of some of the vitreous finds from these sites represent a small body of data that underscore the defining characteristics of Egyptian glasses during the early Roman period. The main features are elevated heavy mineral contamination and typically high soda levels, with the possible exception of the glass from Mareotide. While the absolute values of heavy elements, and especially the lime and alumina contents, can vary considerably, the ratios of, for example, iron to magnesium or aluminium, and titanium to zirconium or aluminium remain more or less constant (Fig. 3). Given the geographical proximity of the three sites within the confines of the Wadi Natrun, these similarities may not be surprising and are broadly consistent with Nile-derived heavy mineral contents of the glassmaking sands in northern Egypt (Degryse 2014; Freestone *et al.* 2009a). The glasses from Lake Mariout (Mareotide) match those from the Wadi Natrun with respect to their heavy element signature, but differ substantially in their calcium and sodium oxide levels. The Wadi Natrun glasses are characterised by very low lime (1.6% - 5.4%), intermediate alumina (1.7% - 3.5%) and very high soda (20.8% - 24.4%) contents that may be explained by the proximity of the glassmaking facilities to viable natron sources. The samples from Lake Mariout have very high lime (15.8%),

alumina (4.4%) and significantly lower soda (12.5%) concentrations (Fig. 3). This may reflect the composition of the local silica sources, inasmuch as the region of Lake Mariout is known to be exceptionally calcareous (approximately 20% CaO) (Nenna *et al.* 2000), while the divergence of the soda levels points to differences in the glassmaking recipes. However, the nature of the vitreous material from Lake Mariout is not beyond doubt and the samples may very well represent some kind of debris or remains that had been contaminated by the furnace environment and which were not destined for further processing. The analysed samples from Lake Mariout may therefore not be representative of the typical raw glass produced there. It is important to note that the secondary workshops at Marea used raw glass from Wadi Natrun and not glass from the primary workshops at Mareotide (Nenna *et al.* 2000).

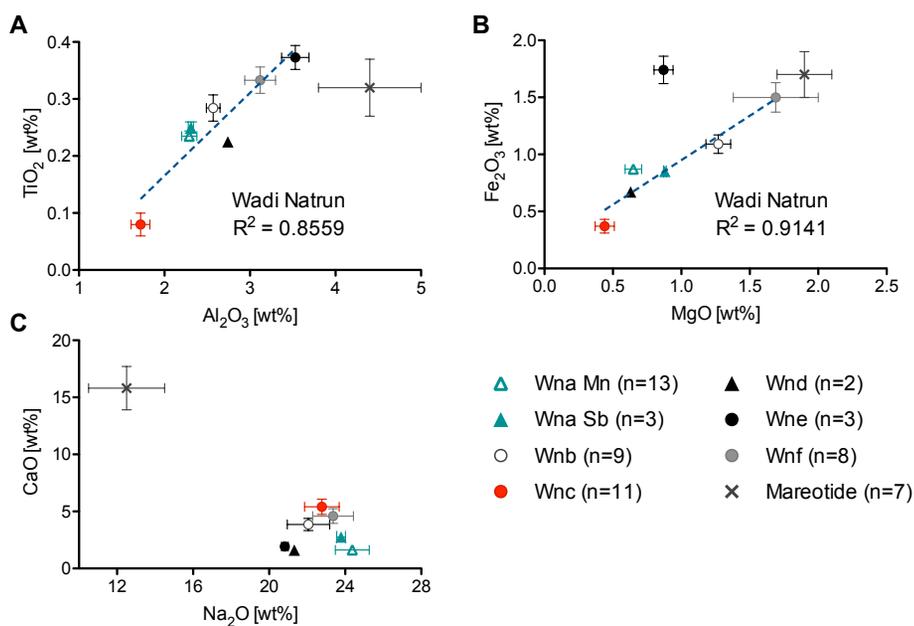


Fig. 3:

Base glass characteristics of the raw glass from the Wadi Natrun and Lake Mariout. Strong positive correlations between (a) titanium and aluminium, and (b) iron and magnesium of the different primary production groups from the Wadi Natrun suggest related geographical origins of the glassmaking sands (Wne was excluded from the linear regression in b); (c) the glass from the Wadi Natrun has a very high soda content, while the samples from Mareotide have exceptionally high lime levels. Data sources: (Nenna *et al.* 1997; Nenna *et al.* 2000; Nenna *et al.* 2005; Nenna 2015; Thirion-Merle *et al.* 2003).

From the information gathered at Wadi Natrun and Lake Mariout we can furthermore deduce that manganese or antimony were added as decolouring agents during the primary production stage, and that there is no evidence that both were added together at the point of raw glass manufacture. Hence, the concurrent

presence of manganese and antimony can be taken as an indicator of mixing and recycling (Freestone 2015). It is not at present known where the strongly coloured and/or opaque glass that seems to have been a specialty of glassmakers in Egypt was made (Nenna *et al.* 2000). This is something to bear in mind when considering Egypt's potential role in the production of glass mosaic tesserae (see for example the mosaics from the Great Umayyad Mosque in Damascus).

The extent of the markets for the glass produced in the Wadi Natrun and in Taposiris Magna during the late Hellenistic and early Roman period is unknown. In the Wadi Natrun there was no sign of secondary glass working, implying that the glass in its entirety must have been traded to secondary workshops elsewhere, presumably via the distribution centre at Terenouthis (Nenna 2015; Picon *et al.* 2008). The impression is that the raw glass produced in the Wadi Natrun and in Taposiris Magna during the late Hellenistic and early Roman period did not, however, take part in the wider Mediterranean trading system in the same way as later Roman and late antique glass groups. It may instead have supplied a local Egyptian market or may have been destined for the Indian Ocean trade (Cobb 2018; Nenna 2007; Nenna 2015). This at least can be gleaned from the composition of glass assemblages from early Roman consumer sites across the Mediterranean world that are clearly distinct from the glass groups identified among the remains at Wadi Natrun and Lake Mariout. The exception may be early Roman antimony-decoloured glass which exhibits some similarities with group Wnc from the Wadi Natrun.

Roman and late antique glass groups of Egyptian origin

Roman antimony-decoloured glass

Published data of a total of 1,167 Roman glasses from different parts of the Roman Empire were collated carefully to delineate the compositional characteristics of different Roman glasses in relation to the primary glass from the Wadi Natrun and Taposiris Magna. Roman glass assemblages (first to fourth centuries CE) are typically sub-divided according to the decolouring agent that was added to counteract the colouring effect of the iron naturally contained in the silica source. Two different decolourants were used by Roman glassmakers: manganese oxide (MnO) and antimony oxide (Sb₂O₃) (Jackson 2005; Sayre and Smith 1961). As mentioned above, the archaeological evidence clearly shows that either one or the other was introduced during the primary production of raw glass, but never both. Hence, the presence of both manganese and antimony is the likely result of recycling and the mixing of the two types of Roman glass: Roman antimony- (Roman Sb) and Roman manganese- (Roman Mn) decoloured glasses.

The first problem is thus to define a clean analytical dataset of Roman Sb glass. For the present study the collected data were separated into four compositional groups of naturally coloured and colourless glasses according to the presence and/or absence of MnO and Sb₂O₃. Very stringent thresholds were applied to obtain clean groups. For manganese the limit was set at Mn < 250 ppm or MnO < 0.03% (Schibille *et al.* 2017) and for antimony at Sb < 30 ppm or Sb₂O₃ < 0.004% (Degryse 2014). Below these values the two elements are considered natural impurities of the raw materials. Roman glass decoloured only with antimony (group 4 in Foy *et al.* 2003b) is thus defined as having Mn < 0.03% and elevated antimony levels (Sb₂O₃ > 0.25%) (Fig. 4a). Samples with manganese oxide levels above 0.5% and antimony oxide below the threshold (< 30 ppm) represent the Roman manganese group. A group of samples with low antimony (< 30 ppm) and manganese above 0.03% but below 0.5% were assigned to a naturally blue-green glass type (Freestone *et al.* 2015a; Jackson 2005). The Roman Mn and the blue-green glasses are closely related, as the threshold above which manganese becomes effective as a decolourant is arguable. The definition proposed by Silvestri and colleagues (Silvestri *et al.* 2005) of MnO to Fe₂O₃ ratios > 2 provides a good guideline (for Roman Mn glass see chapter 2). All glass samples that contain both manganese and antimony above the natural contamination levels are considered to be mixed, recycled glasses.

Applying these cut-off values to the published data on 1,167 Roman glasses we are left with a clean group of 680 antimony-decoloured glasses in the strict sense. The average composition shows high soda concentrations and low amounts of contaminants that reflect the glassmaking sands, such as the oxides of magnesium, aluminium, potassium, calcium, titanium and iron (Table 1). More than 90% of the samples have Al₂O₃ between 1.75% and 2.25%, and the frequency histogram follows a near Gaussian (normal) distribution (Fig. 4b). Titanium oxide values are somewhat more variable, but still within a relatively narrow range (0.05% - 0.09%). Roman Sb glass shows clear similarities with Wadi Natrun Wnc in terms of the ratios of titanium oxide, alumina and silica, while all other groups associated with the Wadi Natrun and Lake Mariout diverge significantly from it (Fig. 4c). Concentrations of lime and soda clearly separate the Roman Sb from all the Wadi Natrun glasses, in that it tends to have lower soda and higher lime contents than the earlier groups from the Wadi Natrun, including Wnc (Fig. 4d). Soda and lime are fundamental raw glass components that, in the case of Roman glass groups (Roman Sb, Roman Mn, Roman blue-green, Roman mixed), are typically distributed along a mixing line. This means that glasses with higher soda have lower lime concentrations and *vice versa*, resulting from different mixing ratios of the silica to soda constituents (Freestone 2015; Jackson 2005). Roman Sb

and Roman Mn decoloured glasses are at opposite ends of this mixing line, with Roman Sb glasses having significantly higher soda and lower lime concentrations than Roman Mn as well as naturally blue-green glasses, while the mixed glasses have intermediate concentrations of both elements (Fig. 4d). The glass from the Wadi Natrun has a distinct base glass composition with even higher soda levels, while reflecting changes in the lime content of the silica source underlying Egyptian glass productions. It can be concluded that Roman Sb clearly differs from the earlier Roman glass produced in the Wadi Natrun. A possible exception is once again the glass of group Wnc which has lime concentrations (CaO ~5.4%) comparable to those of the Roman Sb type (CaO ~5.5%).

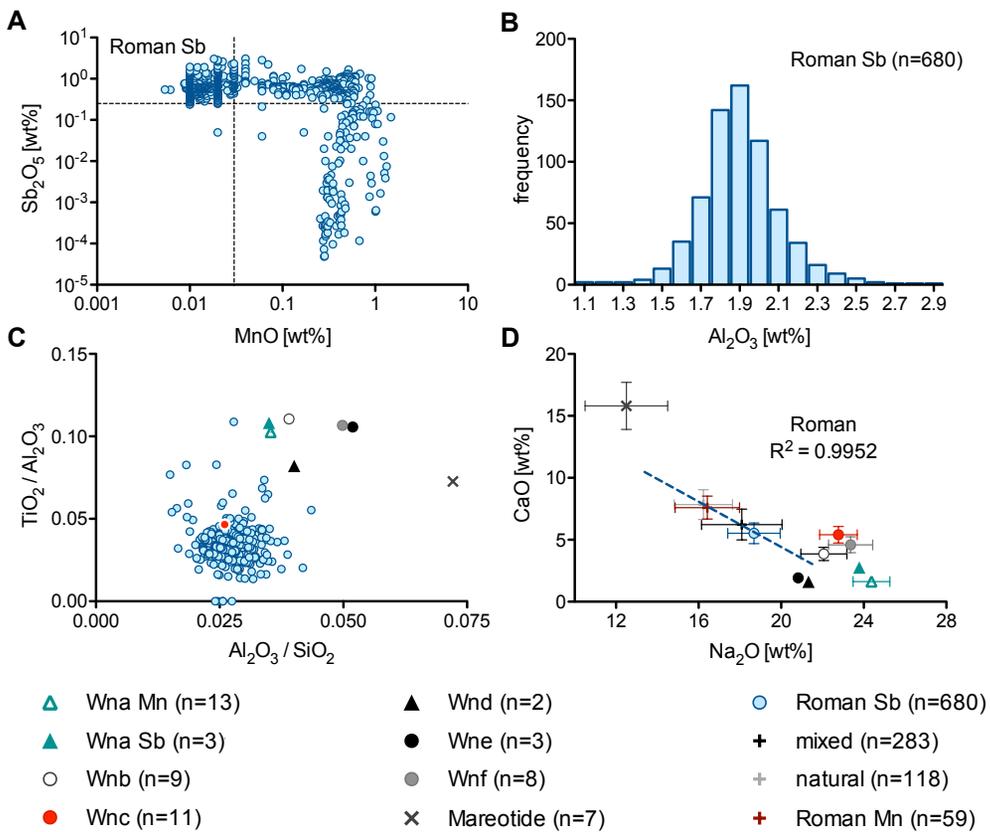


Fig. 4:

Compositional characteristics of Roman antimony-decoloured glass. (a) Thresholds of manganese oxide at 0.03% and antimony oxide at 0.25% define a clean Roman Sb ($n = 680$) group in the upper left hand corner among all the 1,167 Roman samples considered here; (b) frequency distribution of alumina contents of the Roman Sb group; (c) TiO_2 to Al_2O_3 versus Al_2O_3 to SiO_2 ratios reflect the heavy mineral in relation to the feldspar content in the glassmaking sand, highlighting the similarities between Roman Sb and Wnc glass; (d) average lime and soda contents of the different Roman groups compared to the glass from the Wadi Natrun and Mareotide, standard deviations are given as error bars. Data sources: (Baxter *et al.* 2005; Degryse 2014; Gratuze 2018; Jackson 2005; Paynter 2006; Silvestri 2008; Silvestri *et al.* 2008).

The similarities between group Wnc from the Wadi Natrun and Roman Sb glass include elements derived from the silica source (e.g. Al_2O_3 , CaO , TiO_2), the relatively high soda content as well as the fact that both glass groups have been decoloured with antimony (Paynter and Jackson 2019; Picon *et al.* 2008). These compositional similarities may hold the key to the primary production location of one of the most prolific glass groups during the first to third centuries CE, which has remained elusive to this day. Roman antimony-decoloured glass has been linked with the Alexandrian glass listed in the *Price Edict of Diocletian* (Barag 2005; Foy *et al.* 2003b; Jackson *et al.* 2018; Nenna *et al.* 2005; Paynter and Jackson 2019; Schibille *et al.* 2017; Whitehouse 2004), and compositional and isotopic evidence confirms an Egyptian provenance (Gratuze 2018; Jackson, Paynter, Nenna and Degryse 2018; Schibille *et al.* 2017). Recently, hafnium isotopic data were shown to clearly distinguish between Roman Sb glass and glass produced on the Levantine coast, thus providing firm analytical evidence for an Egyptian origin of Roman Sb glass (Barfod *et al.* 2020). Group Wnc from the Wadi Natrun may thus have been a direct predecessor of the Roman antimony-decoloured glass category, which was manufactured from a closely related silica source but using different recipes with a higher proportion of soda.

Glass group	Date	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	Cl	K_2O	CaO	TiO_2	MnO	Fe_2O_3	Sr	Zr
*Roman Sb (269 < n < 680)	1 st – 4 th	18.7	0.41	1.91	71.4	0.04	1.23	0.45	5.53	0.06	0.01	0.36	365	38.9
	stdev	1.3	0.11	0.21	1.8	0.03	0.20	0.09	0.84	0.02	0.01	0.1	86	13.3
HIMT (n=196)	4 th – 5 th	18.8	1.00	2.64	66.7	0.05	1.01	0.47	6.06	0.38	1.82	1.51	482	158
	stdev	1.2	0.16	0.34	1.8	0.02	0.09	0.11	0.63	0.13	0.36	0.37	57	83
HIMT2 (n=221)	4 th – 5 th	19.7	0.76	2.25	68.8	0.05		0.58	6.00	0.12	0.98	0.72	446	30.9
	stdev	1	0.1	0.22	1.6	0.01		0.12	0.57	0.02	0.16	0.09	51	18.5
Foy 3.2 (64 < n < 99)	4 th – 5 th	19.0	0.64	1.94	68.1	0.05	1.23	0.47	6.61	0.10	0.83	0.68	505	59.7
	stdev	1.1	0.21	0.19	1.7	0.03	0.24	0.16	0.86	0.03	0.27	0.24	97	14.1
Foy 2.1 (157 < n < 180)	5 th – 7 th	17.7	1.12	2.53	65.7	0.16	0.83	0.75	8.12	0.15	1.41	1.16	652	80.4
	stdev	1.3	0.25	0.23	1.7	0.10	0.11	0.19	0.92	0.02	0.44	0.5	88	11.9
Magby (55 < n < 65)	6 th – 7 th	16.3	1.87	2.03	65.1	0.37	0.68	1.54	9.09	0.17	1.25	1.27	752	87.6
	stdev	1.3	0.25	0.29	1.7	0.09	0.15	0.28	0.78	0.03	0.92	0.41	127	18

* $\text{Sb}_2\text{O}_5 = 0.78\%$ / stdev = 0.38

Table 1:

Averages and standard deviations of Egyptian natron-type glass groups. Metal oxides and chlorine are given in [wt%], Sr and Zr are given in [ppm]. Data sources: (Baxter *et al.* 2005; Degryse 2014; Gratuze 2018; Jackson 2005; Paynter 2006; Silvestri 2008; Silvestri *et al.* 2008) for Roman Sb; (De Juan Ares *et al.* 2019b; Foster and Jackson 2009; Freestone *et al.* 2018) for HIMT; (Foster and Jackson 2009) for HIMT 2; (Ceglia *et al.* 2019; Foy *et al.* 2003b; Schibille *et al.* 2016) for Foy 2.1; (Balvanović *et al.* 2018; Cholakova and Rehren 2018; Foy *et al.* 2003b; Gallo *et al.* 2014; Maltoni *et al.* 2015) for Foy 3.2; (De Juan Ares *et al.* 2019a; Freestone *et al.* 2008a; Schibille *et al.* 2016) for Magby.

Colourless glass resulting from the deliberate addition of antimony was exceptionally widely used between the middle of the first century CE and the beginning of the fourth (Foy *et al.* 2018). Although it was initially reserved mainly for the production of luxury glassware such as facet and high-relief cut vessels, the diversity of vessel forms and functions increased dramatically in the second and third centuries CE (Cottam 2019; Degryse 2014, p. 106; Gliozzo 2017; Nenna 2007, pp.130-131). The cargo of the second-century shipwreck *Ouest Embiez 1*, sunk off the coast of Marseilles, contained large quantities of Roman Sb glass, including raw glass, glass vessels and window glass (Fontaine and Foy 2007). The impression from a cursory review of analyses of first- to fourth-century glass finds from Britain is that antimony-decoloured glass dominated also in Roman Britain, where facet-cut beakers in particular were found to have the highest antimony levels (Baxter *et al.* 2005; Jackson 2005).

High iron, manganese and titanium (HIMT) glass

A new, somewhat unusual glass composition with elevated iron, manganese and titanium oxide concentrations appeared in the archaeological record of the fourth century CE. First isolated as a distinct glass category by Piero Mirti in the context of fourth-century Roman glass from *Augusta Praetoria* (Mirti *et al.* 1993), it was designated as HIMT by Ian Freestone (1994), group 1 by Foy and colleagues (2003b), and HIMT1 by Foster and Jackson (2009). HIMT is a very common type of glass identified throughout the Mediterranean (except the Levant) as well as in central and northern Europe (De Juan Ares *et al.* 2019b, and references therein; Freestone *et al.* 2018; Nenna 2014). Raw glass and production waste of HIMT dating to the fourth and fifth centuries CE have turned up in large quantities in southern France (Foy 2017). HIMT typically has a distinctive yellowish-green colour owing to the combination of high manganese and iron oxide contents. HIMT glass shares some of its characteristics with the glass from the Wadi Natrun and Roman Sb decoloured glass. Like the earlier Egyptian groups, HIMT glass has relatively high soda levels and high heavy element impurities in combination with low lime contents (Table 1). For the present purpose I adopt the definition advanced by Ian Freestone of a titanium oxide cut-off at 0.2% (Freestone *et al.* 2018).

An extensive survey of British glass has demonstrated that the production of HIMT glass replaced the earlier Roman antimony glassmaking tradition in the fourth century, possibly due to shortages in the supply of antimony as the decolourant (Foster and Jackson 2009; Foster and Jackson 2010). Freestone and colleagues even go so far as to suggest that HIMT glass might have been produced by the same glassmakers as Roman antimony-decoloured glasses (Freestone *et*

al. 2018). HIMT glasses are easily distinguished due to their exceptionally high iron, manganese and heavy element concentrations (Table 1), features that were probably introduced in part by the Nilotic sands in northern Egypt and in part by adding a manganiferous material for colouring purposes (Freestone *et al.* 2018; Nenna 2014). None of the sands analysed by Degryse and colleagues which derive mostly from the Sinai, the area around Cairo and further south (Degryse 2014) contain the right combination of elements that would result in anything remotely similar to HIMT glass, which may point to a provenance in northern Egypt instead. Ostrakine and Pelusium have been proposed as possible candidates for primary production centres of HIMT glass (Nenna 2014). Some sand samples collected by Picon and colleagues along the northern Egyptian coast (Nenna 2014) appear to show an elemental make-up suitable for producing HIMT glasses, especially if we assume that the manganese-rich additive also introduced substantial amounts of other transition metals such as iron, titanium, zirconium and chromium (Freestone *et al.* 2018).

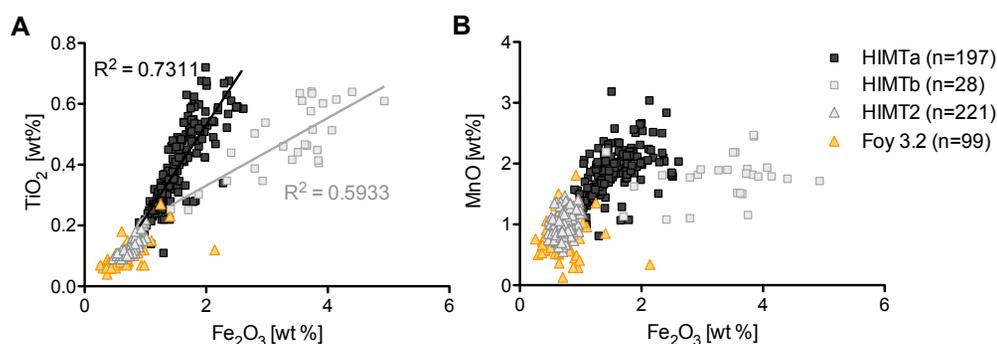


Fig. 5:

Differentiation between HIMTa, HIMTb (high Fe), HIMT2 and Foy 3.2. (a) HIMTa and HIMTb show different iron to titanium ratios, while both HIMT2 and Foy 3.2 have significantly lower levels of heavy mineral contaminants; (b) different manganiferous additives with higher iron contents relative to manganese were used for HIMTb. Data sources: (Ceglia *et al.* 2019; De Juan Ares *et al.* 2019b; Foster and Jackson 2009; Freestone *et al.* 2018) for HIMT a & b; (Foster and Jackson 2009) for HIMT 2; (Balvanović *et al.* 2018; Cholakova and Rehren 2018; Foy *et al.* 2003b; Gallo *et al.* 2014; Maltoni *et al.* 2015) for Foy 3.2.

HIMT has since been further separated into HIMTa and an iron-rich HIMTb variant (Fig. 5a; Ceglia *et al.* 2015; Freestone *et al.* 2018). Freestone and colleagues (2018) emphasised that the main distinguishing features are the differential iron to titanium ratios. Based on the study of a late Roman glass assemblage from Portus Ilicitanus (Picola, Alicante) in Spain, we have recently proposed a threshold for the Fe_2O_3 to TiO_2 ratio of 5.4 to distinguish the two HIMT variants (De Juan Ares *et al.* 2019b). The two sub-types are found to a greater or lesser extent throughout the

Mediterranean and Europe contingent on the chronology of the sites from which glass assemblages were retrieved. The statistical evaluation of these data allowed us to establish a temporal evolution from HIMTa to HIMTb glasses. The absence of HIMTb from Northern Europe suggests that this sub-type may have been produced and circulated when these former Roman provinces had already fallen away from the empire, which may have affected the supply of fresh glass. We can thus deduce that while HIMTa generally dates to the fourth and fifth centuries (Freestone *et al.* 2018), the HIMTb variant seems to have emerged only at the beginning of the fifth century CE (De Juan Ares *et al.* 2019b). The appearance of HIMTb indicates furthermore the exploitation of different manganese-rich deposits with higher iron to manganese ratios (Fig. 5b). To what extent this may explain the temporal difference between HIMTa and HIMTb and/or difference in the glassmaking recipe is unclear. The precise compositional ramifications of the additives are beyond the scope of the present discussion, but clearly merit further investigation.

HIMT2 & Foy 3.2 (série 3.2)

Foster and Jackson (2009) identified another sub-group, which they labelled HIMT2, despite its notably lower iron ($\text{Fe}_2\text{O}_3 < 1\%$), titanium ($\text{TiO}_2 < 0.2\%$) and manganese (average $\text{MnO} < 1\%$) concentrations. If we accept the reasoned baselines for these key elements, then HIMT2 is much closer to the so-called *série 3.2* (Foy *et al.* 2003b; Freestone *et al.* 2018). The two groups are not particularly well defined. *Série 3.2* and Foster and Jackson's HIMT2 display similar iron to titanium ratios, but lower absolute levels of the two elements than HIMT glass in the narrow sense (Fig. 5a). Similarly, neither group shows the same high variability in MnO and Fe_2O_3 concentrations as HIMT glasses (Fig. 5b). This suggests that the manganese-rich material added to *série 3.2* did not contain as much heavy mineral contaminants as HIMT glass, implying that the base glass composition of *série 3.2* can more or less be taken at face value. In contrast, the manganese and antimony contents of the HIMT2 glasses from Britain are negatively correlated (Fig. 6a), pointing to an admixture of Roman antimony-decoloured glass, while phosphorus, potassium and zinc as well as copper and lead show weak positive correlations. These compositional features are indicative of some degree of recycling. HIMT2 can therefore not be considered a primary production group in its own right.

Compared to those of HIMT2, the glasses of *série 3.2* have on average slightly higher lime concentrations and lower silica-related impurities. *Série 3.2* bears some resemblance to Roman antimony glass in terms of the low alumina levels, but for its lack of antimony coupled with elevated manganese and somewhat higher

lime contents (Fig. 6b). HIMT2 and *série 3.2* are primarily fourth- to fifth-century glass types (Cholakova and Rehren 2018; Stojanović *et al.* 2015). The earliest occurrence of HIMT2 is currently attributed to 320-330 CE (Foster and Jackson 2009). So they are virtually contemporaneous with HIMT glass or even slightly earlier. Raw glass chunks of this composition have been found as late as the first third of the sixth century in a secondary workshop in Marseilles (Foy *et al.* 2003b). *Série 3.2* does not seem to be as widely distributed as HIMT. Up to now, small numbers of samples have been recognised among assemblages from the Balkans (Balvanović *et al.* 2018; Balvanović and Šmit 2020; Cholakova and Rehren 2018; Stojanović *et al.* 2015), Roman Britain (Foster and Jackson 2010), north-eastern Italy around Aquileia (Gallo *et al.* 2014; Maltoni *et al.* 2015), southern France (Foy *et al.* 2003b) and Carthage (Schibille *et al.* 2017). Only a single sample of a *série 3.2* composition (a colourless glass from Pechina) has thus far been identified among the numerous assemblages that we have analysed from the Iberian Peninsula (De Juan Ares and Schibille *in press*), and among the over 100 analysed samples from the island of Mallorca only four have *série 3.2* characteristics (unpublished data). Given the fact that *série 3.2* is roughly contemporary with HIMT with a possibly even longer overall lifespan (Foster and Jackson 2010; Foy *et al.* 2003b), a disruption in the supply of raw glass cannot explain its more limited distribution.

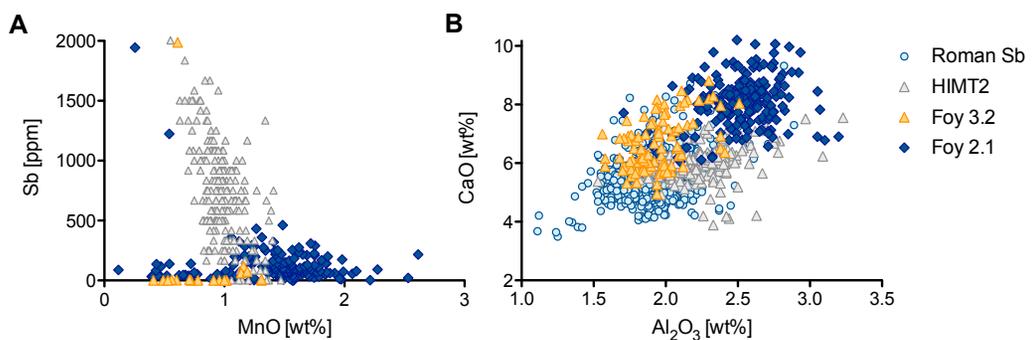


Fig. 6:

Compositional characteristics of HIMT2, Foy 3.2 and Foy 2.1. (a) HIMT2 and to a lesser extent Foy 2.1 have elevated antimony levels, markers of some recycling. In the case of HIMT2 antimony and manganese are negatively correlated, Foy 3.2 typically has no or very low levels of antimony; (b) lime and alumina levels of HIMT2, Foy 3.2 and Foy 2.1 compared to Roman Sb glass. Data sources: (Ceglia *et al.* 2019; De Juan Ares *et al.* 2019b; Foster and Jackson 2009; Freestone *et al.* 2018) for HIMT; (Foster and Jackson 2009) for HIMT2; (Balvanović *et al.* 2018; Cholakova and Rehren 2018; Foy *et al.* 2003b; Gallo *et al.* 2014; Maltoni *et al.* 2015) for Foy 3.2; (Ceglia *et al.* 2019; Foy *et al.* 2003b; Schibille *et al.* 2016) for Foy 2.1; (Baxter *et al.* 2005; Degryse 2014; Gratuze 2018; Jackson 2005; Paynter 2006; Silvestri 2008; Silvestri *et al.* 2008) for Roman Sb.

Just like HIMT, *série 3.2* has been interpreted as a continuation of the Roman antimony glassmaking tradition (Cholakova and Rehren 2018). This may reflect the gradual phasing out of antimony during the fourth century CE and its replacement by manganese as the decolourant of an otherwise similar base glass. Judging from the trace element make-up (e.g. Ti, Zr, Ba) and the lack of a clear correlation between manganese and iron, the manganese-rich material added to *série 3.2* as decolourant appears to have been purer than that used for HIMT glasses. The result was an often truly colourless (e.g. samples from Roman Britain, Bulgaria, Spain) or faintly coloured glass with a yellowish, blueish or greenish tinge. Given the clear compositional differences between HIMT and *série 3.2*, the two glasses were most certainly made from different raw materials in terms both of the sand deposits and the manganese ore.

Glass group Foy 2.1 (*série 2.1*)

Compositional similarities of the late antique Egyptian glass groups were furthermore recognised in a mostly fifth- to sixth-century glass type, the so-called Foy *série 2.1* (Cholakova *et al.* 2016; Cholakova and Rehren 2018; Foy *et al.* 2003b; Schibille *et al.* 2017). Glass samples belonging to *série 2.1* (Foy *et al.* 2003b) have been identified in the archaeological record of the south of France, Spain, Italy, northern Africa and Anglo-Saxon Britain (De Juan Ares *et al.* 2019a; Foy *et al.* 2003b; Freestone *et al.* 2008a; Mirti *et al.* 2000; Mirti *et al.* 2001). The earliest glasses of a Foy 2.1 composition date to the second half of the fifth century, as judged from well-dated Visigothic contexts in Spain (De Juan Ares *et al.* 2019a). It is a glass type that was used extensively in the sixth and into the first half of the seventh century (Ceglia *et al.* 2019; Cholakova *et al.* 2016; Foy *et al.* 2003b; Schibille *et al.* 2016). Foy 2.1 shares some characteristics with HIMT in terms of elevated iron, manganese, titanium, and zirconium levels (Table 1). The absolute concentrations of these elements, however, always remain below those of HIMT, and it has been demonstrated that the two glass groups represent separate primary productions (Cholakova *et al.* 2016).

A distinction between Foy 3.2 and Foy 2.1 on the other hand often proves challenging. A large-scale comparison of primary data reveals that Foy 2.1 has generally higher manganese concentrations as well as silica-related impurities, in particularly higher magnesia (MgO ~1%), alumina (Al₂O₃ ~2.5%), titanium oxide (TiO₂ ~0.15%) and lime (CaO ~8%) contents (Table 1, Figs. 6 & 8). Foy and colleagues (2003b) have proposed a sub-division into *série 2.1* and a late seventh-century *série 2.2*. No raw glass chunks of this latter sub-type are known, and various compositional features such as elevated antimony, copper and lead imply

that Foy 2.2 is not a primary glass group but represents recycled material (Foy *et al.* 2003b). In contrast, raw glass fragments of a Foy 2.1 composition have been recovered from several secondary workshops in the south of France (Maguelone, Marseille, Porte-Vendres, Bordeaux; Foy *et al.* 2003b), from Serdica (Cholakova *et al.* 2016), as well as from the sixth-century shipwreck at Marzamemi off the coast of Sicily (Leidwanger 2018; personal communication Ian Freestone). Nonetheless, Foy 2.1 often exhibits some signs of recycling as well. Whereas Foy 3.2 appears to be a mostly immaculate primary glass, the concentrations of elements associated with secondary additives (Co, Cu, Sn, Sb, Pb) in almost all the published data on Foy 2.1 are not sufficiently low to suggest their addition as natural impurities of the silica source (Fig. 6a). The elevated concentrations of these secondary elements are no doubt indicative of systematic recycling, previously observed with respect to HIMT glass (Foy *et al.* 2003b). The scale and recurrent presence of recycling markers strongly support the hypothesis that recycling of cullet took place already at the primary production stage (Ceglia *et al.* 2019; Foy *et al.* 2003b). This increasing reliance on recycling over time may have been caused by a lack of raw materials, but may also simply be a sign of the more extensive availability of cullet.

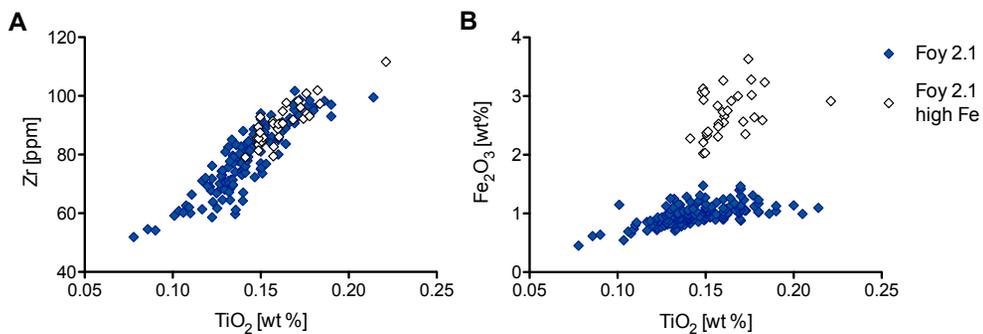


Fig. 7:

Comparison of Foy 2.1 and Foy 2.1 high Fe. (a) Zirconium and titanium concentrations of both Foy 2.1 variants are perfectly congruent; (b) iron versus titanium oxides show a clear break of correlations at a concentration of $1.5\% < \text{Fe}_2\text{O}_3$. Data sources: (Ceglia *et al.* 2019; Foy *et al.* 2003b; Schibille *et al.* 2016).

With the increasing number of available archaeometric data a Foy 2.1 high iron ($\text{Fe}_2\text{O}_3 > 1.5\%$) sub-group was recently identified (Schibille *et al.* 2016). Foy 2.1 and Foy 2.1 high Fe display the same linear dependence between titanium and zirconium typical of Egyptian glasses with a strong heavy mineral component (Fig. 7). The two sub-categories differ, however, in terms of their titanium and iron ratios, a phenomenon detected previously in relation to HIMTa and HIMTb

(Freestone *et al.* 2018). When one assesses the relationship between aluminium, iron, titanium and magnesium, the correlations seem to break down around the 1.5% iron oxide mark (Fig. 7b), suggesting that an iron-rich manganese additive was incorporated at the primary production stage in what was essentially the same raw glass as Foy 2.1. This confirms observations made by Freestone and colleagues (2018) in the context of HIMT glass that the manganese-rich additive potentially contributed significant amounts of iron and other trace elements. Unlike HIMT, however, the manganiferous material used in combination with a Foy 2.1 base glass does not appear to alter substantially any of the other transition metals or rare earth elements. Foy 2.1 high Fe has been recognised among assemblages from Bulgaria (Cholakova *et al.* 2016), Cyprus (Ceglia *et al.* 2019), France (Foy *et al.* 2003b), Italy (Mirti *et al.* 2000), Serbia (Balvanović *et al.* 2018), Visigothic Spain (De Juan Ares *et al.* 2019a) and in the context of a study of Byzantine glass weights dating to the mid- to late sixth century CE (Schibille *et al.* 2016). A raw glass chunk of Foy 2.1 high Fe composition is known from a late sixth- to early seventh-century context at Bordeaux (Foy *et al.* 2003b). This lends support to the interpretation that Foy 2.1 high Fe represents a distinct primary production group, even though glasses of this type display markers of recycling.

Magby – a high Mg Byzantine glass type

Closely related to Foy 2.1 is yet another Egyptian glass group that has been called Magby on account of its elevated magnesia concentrations and its definition as an independent primary glass production group in the context of sixth- to seventh-century Byzantine glass weights (Schibille *et al.* 2016). Judging from the elevated magnesium, potassium and phosphorus concentrations (Fig. 8a; Table 1) and the positive correlations between these elements, Magby glass most certainly contains an ash component. Given the compositional similarities between Magby and Foy 2.1 indicated by the perfectly superimposed trace element patterns (Fig. 8c), it seems likely that an ash-rich material was added to a natron-type glass without significantly changing the overall compositional trace element make-up associated with the silica source. Magby glasses, however, have higher iron to aluminium ratios than both Foy 2.1 and Foy 3.2 (Fig. 8b) which cannot be explained by a simple admixture of soda-rich plant ash to these natron-type groups. Instead, Magby glasses may be the result of a distinct yet related primary production that utilised the same or relatively similar silica sources but different manganese additives that were richer in iron, more like those used for Foy 2.1 high Fe and/or HIMT glasses. As has been observed in relation to Anglo-Saxon glass from Britain (Freestone *et al.* 2008a), Magby can be subdivided according to the manganese

concentrations into low MnO (< 0.5%) and high MnO (> 1.5%) variants, and possibly an intermediate third group, indicating different primary production events. Manganese is also associated with elevated strontium and barium contents.

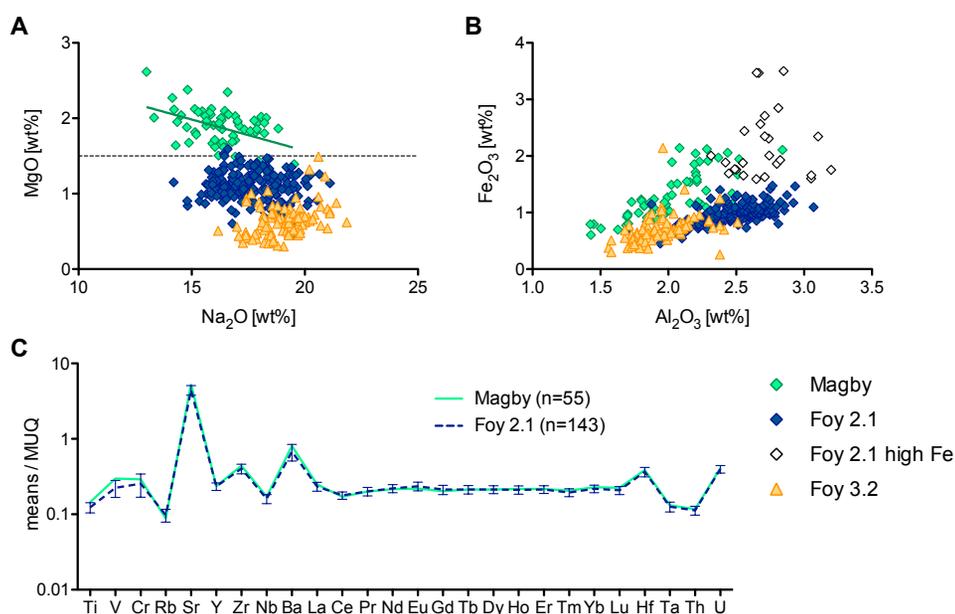


Fig. 8:

Compositional characteristics of the Magby group compared to other Egyptian late antique glass types. (a) Magnesia levels are notably higher in the Magby group compared to both Foy 3.2 and Foy 2.1, showing a slightly negative trend with soda, which rules out the use of a soda-rich plant ash typically encountered in the eastern Mediterranean; (b) comparison of the Magby glasses with Foy 2.1, Foy 2.1 high Fe, and Foy 3.2 in terms of their aluminium and iron oxide contents; (c) trace element patterns of Foy 2.1 and Magby normalised to the upper continental crust (Kamber *et al.* 2005), illustrating their close compositional relationship. Data sources: (De Juan Ares *et al.* 2019a; Freestone *et al.* 2008; Schibille *et al.* 2016) for Magby; (Ceglia *et al.* 2019; Foy *et al.* 2003b; Schibille *et al.* 2016) for Foy 2.1 & Foy 2.1 high Fe; (Balvanović *et al.* 2018; Cholakova and Rehren 2018; Foy *et al.* 2003b; Gallo *et al.* 2014; Maltoni *et al.* 2015) for Foy 3.2.

Glasses with Magby characteristics have been identified among contemporary assemblages from Anglo-Saxon Britain (Period II 550 - 700 CE) where they were termed high magnesia Saxon II glass (Freestone *et al.* 2008a), two samples from Caričin Grad in Serbia (Drauschke and Greiff 2010) as well as Merovingian France (Velde and Motteau 2013). The nature of the ash component and the form in which it was added to the batch is not entirely clear. The compositional dynamic range and relatively high strontium levels of the Anglo-Saxon samples had been interpreted as the result of the addition of a small quantity of a wood ash-rich material (Freestone *et al.* 2008a). At the time, the authors believed this to be a sign of shortages in the supply of fresh raw glass from the eastern Mediterranean

and a phenomenon specific to glass-working in Britain (Freestone *et al.* 2008a). However, Magby glasses have since turned up in considerable numbers in the archaeological record of Visigothic Spain (De Juan Ares *et al.* 2019a; unpublished data from Recópolis) and it was used for Byzantine glass weights in the eastern Mediterranean (Schibille *et al.* 2016). The wide geographical distribution of these glasses that gradually emerges from diverse datasets suggests that the Magby phenomenon does not fit with a regional model of production and recycling. Instead, it is more likely that an ash-rich material was incorporated in the primary production phase. It may have simply derived from fuel ash, since the soda contents exhibit a slight negative relationship with both magnesia and potash (Fig. 8a).

How can the use of a plant ash component in Magby glasses during late antiquity be explained? Arguments usually revolve around the deficiencies in mineral soda and/or shortages in fresh glass supplies (Freestone *et al.* 2008a; Schibille *et al.* 2016). Trying to narrow down what may have caused these shortages is difficult. A number of contributing factors, however, have been tentatively proposed. Religious and political turmoil in northern Egypt during the second half of the sixth century may have restricted access to some of the more prolific natron sources in the region (Shortland 2004; Shortland *et al.* 2006). Similarly, climatic shifts producing higher precipitations may offer another piece of the puzzle (Picon *et al.* 2008). Having said that, it is important to stress that Egypt had a long history of plant ash glass production that may never have ceased entirely, even though natron from evaporitic deposits in the Wadi Natrun had become the dominant source of the alkali flux sometime in the eighth century BCE until at least the late eighth century CE (Phelps *et al.* 2016; Sayre and Smith 1961; Shortland *et al.* 2006; Tite *et al.* 2006). Examples of Roman and late antique plant ash-based glasses have been retrieved from the Wadi Natrun (Picon *et al.* 2008), Lake Mareotis (Nenna 2007), Bubastis (Rosenow and Rehren 2014) and Armant in Upper Egypt (Rosenow and Rehren 2018). A plant ash recipe furthermore underlies a specific type of emerald green glass identified among first-century CE assemblages from various European sites (Jackson and Cottam 2016, and references therein) and as far afield as Begram in Afghanistan (Brill 1999). Some strongly coloured and opacified glasses often exhibit signs of a plant ash component, for example some of the red, translucent green and orange tesserae from the fourth-century Roman Villa of Noheda in Spain exhibit some of the characteristics of plant ash glass (Schibille *et al.* 2020b). None of the earlier Roman samples, however, provides a close compositional match for the Magby group. A possible exception is the later plant ash glasses (PA II) from Armant in Upper Egypt (Rosenow and Rehren 2018) that show comparable compositional features in terms of both the plant ash constituent and the silica source. Unfortunately, the dating of the samples from

Armant is rather uncertain, ranging from the third to the seventh century CE. These finds nonetheless open up the possibility of a continuous production of plant ash-type glasses in Egypt, albeit on a small, local or regional scale.

Compositions and working properties over time

Roman and late antique glasses from Egypt are typically rich in soda, and no systematic differences are apparent up to the fourth or early fifth century CE. The high soda contents have been explained by the geographical proximity of the Egyptian primary glass production centres to the different soda sources in northern Egypt that were exploited during ancient times (Nenna *et al.* 2000; Shortland *et al.* 2006). Starting with Foy 2.1 in the second half of the fifth century, there is a general decline in soda levels, concurrent with an increase in lime concentrations. The same observations were made in relation to glass produced in Syria-Palestine (Freestone 2020, and references therein). It has been suggested that Egyptian glass had a distinct advantage over Levantine glass in terms of its workability and cost-effectiveness at the secondary production stage (Freestone *et al.* 2018; Freestone 2020). The working temperature and viscosity curve of the different Egyptian glass groups (Roman Sb, HIMT, HIMT2, *série 3.2*, *série 2.1*, Magby) can be estimated using the model furnished by Fluegel (Fluegel 2007, GlassViscCalc_6). Unfortunately, the template does not allow for an accurate calculation of the viscosity of archaeological glasses, because various minor and trace elements are outside the application limits of the model. Nonetheless, the average base glass compositions (Table 1) produce a good approximation for comparative purposes, because the major and minor elements (silica, soda, lime, alumina, potash, magnesia, iron and titanium) decisively influence the viscosity of the glass batch (Fig. 9). According to these calculations, the late antique glasses from Egypt (HIMT, HIMT2, Foy 3.2 and Foy 2.1) have a marginally lower viscosity curve than Roman antimony glass, and all Egyptian glasses have a significantly lower viscosity than the average Levantine glass. At the working point indicated by a dotted line there is an estimated temperature difference of around 45°C between Roman Sb and Levantine glasses, and of almost 70°C between Levantine glass and HIMT2, which has the lowest estimated viscosity. The variance between the various late antique glasses from Egypt is within 15°C, which is unlikely to be a decisive factor for the different recipes and raw materials.

A 40°C difference has been observed between HIMT and fourth-century Levantine glass from Jalame (Freestone *et al.* 2018). As noted by the authors, the lower working temperature would have significantly reduced the cost due to smaller fuel expenses, which in turn may have been deliberately signalled by

tinting HIMT glass a yellowish green. According to this interpretation, the distinct yellowish green colour served the purpose of ‘commodity branding’, so that the secondary glass workers at the other end of the Mediterranean could more easily identify these glasses with advantageous working properties (Freestone *et al.* 2018). To what extent commodity branding as proposed by Freestone and colleagues (2018) actually affected the differential distribution of Egyptian and Levantine glass groups is not clear. As mentioned above, glass of the *série 3.2* composition ranges in colour from colourless to bluish green, and the same applies to the glasses of *série 2.1*. Hence, an intentional differentiation by colour for product recognition does not appear to be applicable to these primary production groups. What is more, there seems to be a temporal dimension underlying the differential supply of Levantine and Egyptian glass reaching the western Mediterranean. In a comprehensive study of Visigothic glass assemblages in combination with some late Roman glasses from Alicante, we were able to trace fundamental changes in the geographical scope of glass supplies to the Iberian Peninsula (De Juan Ares *et al.* 2019a). Until the middle of the sixth century Spain apparently procured glass almost exclusively from Egypt, and Levantine glass is virtually absent from fifth- and early sixth-century contexts. The supplies of glass in Sicily seem to follow similar chronological and geographical patterns (Schibille and Colangeli 2021). Levantine raw glass may simply not have reached the western Mediterranean on the same scale as Egyptian glass types, thus not creating a situation of real market competition in which a differentiation between Egyptian and Levantine products was required. Veritable market competition necessitates choice and assumes that access to the market is comparable. However, since only little Levantine glass reached the western Mediterranean during this time there was no need to distinguish Egyptian glasses unless, of course, Egyptian glass groups had gained such a substantial competitive advantage that Levantine glasses were ousted from the Iberian and Sicilian glass markets. In other words, the observed strongly skewed distribution of HIMT glass may be the consequence of a competitive advantage, in terms of both material properties and marketing. Be this as it may, the data from the Iberian Peninsula and Sicily give the strong impression that Egypt supplied the bulk of the raw glass for the secondary glass workshops in the western Mediterranean for two and a half centuries, from the fourth to the middle of the sixth century CE. In this context, it would be of great interest to investigate how this compares to the supply of earlier Roman antimony-decoloured glass from Egypt in comparison to Roman manganese-decoloured glass from the Levant.

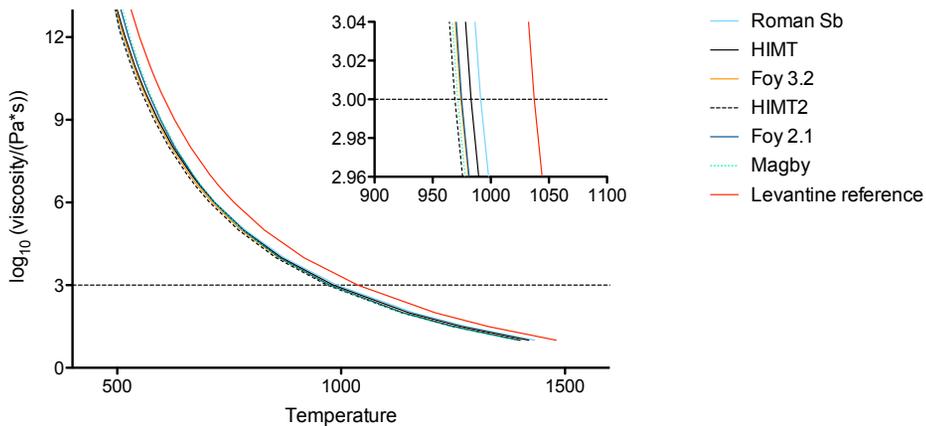


Fig. 9:

Viscosity curves as a function of temperature (in °C) for the average compositions of the different Egyptian glass groups (Roman Sb, HIMT, HIMT2, Foy 3.2, Foy 2.1) and a Levantine reference group (Levantine I; Phelps *et al.*, 2016). Viscosity model from (Fluegel 2007). Compositional data from Table 1 of major and minor elements (Na_2O , MgO , Al_2O_3 , SiO_2 , K_2O , CaO , TiO_2 and Fe_2O_3) were used for calculations. However, the Fe_2O_3 content of the HIMT group had to be capped at 1% due to application limitations of the model. The insert shows a scaled zoom highlighting the differences at working temperature.

The beginnings of Islamic glass production

According to current knowledge, Magby is the last pre-Islamic raw glass fabricated in Egypt in the sixth and possibly the early seventh century CE. The first type of glass that can be considered Islamic was probably manufactured from the middle of the seventh century CE. There is no independent archaeological information about production sites or glass workshops in Egypt dating to the early Islamic period, and we rely on detailed typological studies and the analytical evidence of glass weights and vessel stamps to trace the developments of the early Islamic glass industry in Egypt. Since these weights and stamps often bear the names of Egyptian officials (e.g. finance director, governor, prefect), they can be dated and provenanced with some certainty, which has significant implications for our model of the primary production of glass and its transformation in Egypt during the early Islamic period.

In a recent comprehensive analytical study of Islamic glass weights, vessel stamps and commodity weights (Schibille *et al.* 2019), we traced the transformation of the Egyptian glass industry from the monetary reform of the Umayyad caliph ‘Abd al-Malik (685-705 CE) to the reforms of the Ayyubid sultan al-Kâmil. The last glass weights included in our investigations bear the name of the caliph al-

Nasir (1180 - 1225 CE). The early glass weights and stamps up to the Fatimid period generally carry the imprint of the names of the finance director, governor or prefect of Egypt (Ollivier 2019). This custom was apparently no longer adhered to after the eleventh century, and post-Fatimid glass weights usually bear the name of the Abbasid caliph even though the caliph was no longer the *de facto* ruler of Egypt. It is nonetheless assumed that they were Ayyubid emissions made in Egypt (Balog 1966), and the compositional characteristics confirm this interpretation. The function of the glass discs is controversial. It is still disputed today whether they served as coin weights, money weights or money tokens, a dispute which has sparked a lively debate among numismatists (Balog 1966; Bates 1981; Fenina 2016). The problem is that while Umayyad and Abbasid glass weights correspond closely to the weights of the *dīnār*, *dirham* and their fractions and their inscriptions often refer to their direct connection with the official currencies, this relationship is less clear during the Fatimid and Ayyubid periods (Fenina 2016). The inscriptions on the glass discs no longer specify their function, and their weights are considerably more variable than those of earlier periods, while they seem to have been produced in larger numbers during the Fatimid period (Fenina 2016). Since they most certainly served some commercial and, by extension, fiscal function, it is reasonable to assume that the manufacture of the weights and vessel stamps was under the control of the office of the finance director and the official mint of Egypt in one way or another (Grohmann 1925; Noujaim-Le Garrec 2004).

285 individual objects (glass weights, vessel stamps and commodity weights) from the collections at the Bibliothèque nationale et universitaire in Strasbourg (BNU, $n = 223$) and the Department of Islamic Arts in the Musée du Louvre ($n = 62$; Noujaim-Le Garrec 2004) were selected and analysed. Where possible, the vessel stamps and their support were analysed separately, as were inclusions and patches of different colours. The total number of our analyses thus adds up to $n = 360$. Our study found that between the seventh and twelfth centuries CE the glass industry in Egypt experienced a dramatic transformation, which coincided with changes in the administration and governance of the early Islamic caliphate. In other words, in some important respects the organisation of the primary glass production in Egypt seems to have been contingent on the local administration. The data on the weights and stamps up to the reign of the Fatimid caliph al-Hakim (996-1020 CE) (Schibille *et al.* 2019) reinforced the compositional and temporal patterns observed by Bernard Gratuze some 30 years ago (Gratuze 1988). This, however, is only part of the story. The more refined temporal resolution of our study provides evidence for the continuity of a centralised production model from the seventh/eighth century through to the early eleventh century CE, with a marked change occurring only in the course of the eleventh century. Moreover, the analysis of a

substantial set of mosaic tesserae from the Great Umayyad Mosque in Damascus has revealed a further, hitherto unrecognised compositional group closely allied to natron-type Egypt 1 as identified and defined on the basis of glass weights.

Natron type Egypt 1A-C & Egypt 2

Prior to 871 CE, practically all glass was made of a natron-type composition. The exception is a single dinar weight (VStras 103) in the name of the emir ‘Ubayd-Allāh ibn al-Mahdī who had been appointed governor and director of finance of Egypt by the caliph Hārūn al-Rašīd (who reigned from 786 to 809 CE; Ollivier 2019). This weight, dated to the last years of the eighth century, has a plant ash base glass that is most certainly of Mesopotamian origin. The high resolution compositional data enabled us to separate four discrete compositional natron-type glass groups that follow a strict chronological sequence: Egypt 1A (< 725CE), 1B (720-780 CE), 1C (8th century) and Egypt 2 (775-870 CE). They can be distinguished from each other and from all other Egyptian natron glass categories on the basis of their TiO₂, Al₂O₃ and SiO₂ contents (Fig. 10). The characterisation and delineation of Egypt 1A and Egypt 1B was developed via a multi-step process that set a threshold of titanium oxide for Egypt 1B at 0.4% (Fig. 11; equivalent to approximately TiO₂/Al₂O₃ = 0.093). This cut-off is justified by the clear break in the absolute titanium values between the two sub-categories (Egypt 1A max = 0.37%; Egypt 1B min = 0.41%; Schibille *et al.* 2019). Egypt 1A is accordingly defined by fairly high aluminium, titanium and zirconium contents and low calcium (CaO ~ 3%), while Egypt 1B has even higher levels of accessory elements (Al, Ti, Fe, Zr) and equally low lime content (Table 2).

Egypt 1 and Egypt 2 glasses exhibit similar concentration ranges of elements usually related to heavy minerals (Ti, Fe, Zr, Hf) to the earlier Egyptian glass groups, but they show different correlations between, for instance, titanium and aluminium or zirconium (Fig. 10 & 11). Moreover, Egypt 2 has substantially higher lime contents and lower alumina than the Egypt 1 sub-groups. The most distinctive feature of the Egypt 2 compositional group, however, is the exceptionally low strontium to lime ratio (Fig. 11a). The low strontium relative to calcium concentrations of the Egypt 2 glasses (Sr/CaO < 25) suggest a geologically aged calcitic limestone as the principal source of lime, and by extension a continental silica source rather than seashells introduced as part of sands from the coastal regions of Egypt (Degryse 2014; Freestone *et al.* 2003a). Glass finds corresponding to an Egypt 2 composition and dated on typological grounds to the eighth to ninth centuries have been recovered from a glass workshop at el-Ashmunein in Middle Egypt (Bimson and Freestone 1987; Freestone *et al.* 2003a; Freestone

et al. 2009a). Whether raw glass was itself produced in el-Ashmunein (Foy *et al.* 2003a) is uncertain, but its compositional and isotopic features are consistent with an inland silica source and primary production location. By contrast, the high elemental strontium contents in groups Egypt 1A, B and C are fully consistent with the use of shell-bearing raw materials, possibly in the form of coastal sands, for the manufacture of these glasses (Fig. 11a). The even higher strontium levels in Egypt 1C compared to all other glasses (in the absence of manganese which would augment the absolute values) may be attributed to the variability of the strontium content in shells (Degryse 2014).

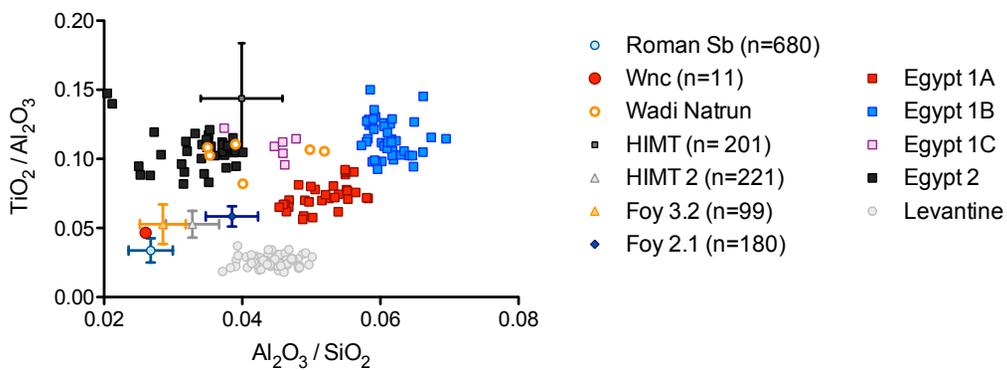


Fig. 10:

Major early Islamic natron-type glass compositional groups from Egypt. Ratios of TiO_2 to Al_2O_3 and Al_2O_3 to SiO_2 in [wt%] reflect heavy minerals, feldspar and quartz contents in the glassmaking sand, and separate the different Egyptian glass groups clearly from the Levantine primary production groups. Data sources: (Phelps *et al.* 2016) for Levantine I and II; (Picon *et al.* 2008) for Wadi Natrun; (Baxter *et al.* 2005; Degryse 2014; Gratuze 2018; Jackson 2005; Paynter 2006; Silvestri 2008; Silvestri *et al.* 2008) for Roman Sb; (De Juan Ares *et al.* 2019b; Foster and Jackson 2009; Freestone *et al.* 2018) for HIMT; (Ceglia *et al.* 2019; Foy *et al.* 2003b; Schibille *et al.* 2016) for Foy 2.1; (Balvanović *et al.* 2018; Cholakova and Rehren 2018; Foy *et al.* 2003b; Gallo *et al.* 2014; Maltoni *et al.* 2015) for Foy 3.2; (Schibille *et al.* 2019) for Egypt 1 & Egypt 2.

Despite certain compositional similarities, it must be stressed that Egypt 1 and early Roman glass types from the Wadi Natrun are entirely different. Egypt 1 and glass from the Wadi Natrun have in the past been systematically conflated because they both have low lime and high alumina concentrations (Freestone *et al.* 2002a; Freestone *et al.* 2002b; Freestone 2003; Freestone 2005; Freestone 2006; Freestone *et al.* 2008a; Rehren and Cholakova 2010; Rosenow and Rehren 2018). As repeatedly emphasised by Marie-Dominique Nenna, however, the known glass furnaces in the Wadi Natrun date to the first and second centuries CE, and there is no archaeological evidence of primary workshop activities in this

area dating to the early Islamic period (Nenna 2014). Besides, alumina and lime concentrations are no longer sufficient to define or discriminate between glass groups. Considering trace element data in more detail, it is possible to differentiate the Wadi Natrun glass from Egypt 1 as defined on the basis of the Islamic glass weights. Not only do the Wadi Natrun samples differ in terms of their alumina, lime and soda concentrations, but they show above all very different titanium to zirconium ratios (Fig. 11b). In other words, there is no unambiguous evidence to suggest a common provenance for these glasses and/or a continuous primary glass production in the Wadi Natrun from the Hellenistic into the early Islamic periods.

Glass group	Date	Na ₂ O	MgO	Al ₂ O ₃	SiO ₂	P ₂ O ₅	Cl	K ₂ O	CaO	TiO ₂	MnO	Fe ₂ O ₃	Sr	Zr
Egypt 1A	pre-725	16.6	0.64	3.75	72.4	0.09	1.02	0.59	3.08	0.28	0.03	1.13	201	91.5
(n=32)	stdev	1.2	0.07	0.26	1.7	0.05	0.09	0.14	0.36	0.05	0.01	0.15	15	13.6
Egypt 1B	720 – 780	16.0	0.87	4.38	71.6	0.083	0.98	0.50	3.07	0.50	0.042	1.82	201	185
(n=45)	stdev	1.0	0.08	0.21	1.2	0.026	0.08	0.07	0.17	0.06	0.002	0.35	13	40
Egypt 1C	8 th c.	15.9	0.81	3.14	70.3	0.16	0.96	0.73	5.64	0.34	0.44	1.27	497	136
(n=6)	stdev	0.4	0.12	0.25	1.0	0.07	0.08	0.09	1.16	0.03	0.47	0.11	123	9
Egypt 2	~775 – <815 CE	16.5	0.47	2.00	69.7	0.10	1.08	0.33	8.51	0.20	0.045	0.84	139	120
(n= 12)	stdev	1.0	0.09	0.31	1.9	0.05	0.13	0.09	1.32	0.03	0.083	0.31	17	25
Egypt 2	815 – > 815 CE	13.4	0.70	2.52	70.1	0.11	1.04	0.51	9.57	0.27	0.44	1.18	187	181
(n=24)	stdev	0.6	0.15	0.20	1.4	0.05	0.10	0.25	0.54	0.03	0.47	0.32	21	27
Damascus Egypt 1A		18.7	0.64	3.45	69.8	0.28	1.12	0.49	3.59	0.27		1.47	218	103
(n=401)	stdev	0.8	0.06	0.21	1.8	0.46	0.08	0.08	0.89	0.03		1.16	46	16
Damascus Egypt 1Ax		18.7	0.5	2.59	72	0.31	1.15	0.44	3	0.24		0.98	158	105
(n=199)	stdev	1.1	0.06	0.25	1.5	0.2	0.13	0.09	0.73	0.03		0.1	66	15

Table 2:

Average compositions and standard deviations of early Islamic natron-type glass groups from Egypt. Metal oxides and chlorine are given in [wt%], Sr and Zr are given as elements [ppm]. Data sources: (Schibille *et al.* 2019) for Islamic glass weights from Egypt, (Schibille *et al.* forthcoming) for Damascus.

Similarly, attention needs to be drawn to some late antique glass samples that have been attributed to Egypt 1. These include some samples from Armant (Rosenow and Rehren 2018) and Cyprus (Ceglia *et al.* 2015; Ceglia *et al.* 2019) and a handful of Byzantine glass weights dated to the sixth and seventh centuries CE (Schibille *et*

al. 2016). A glass chunk (A-20) from Armant in Upper Egypt and three Byzantine glass weights attributed to someone with the name of Hadrianos are more closely related to Wadi Natrun (Wnd) than to Egypt 1A when one considers their zirconium and titanium contents (Fig. 11b). The three Byzantine weights also have uncharacteristically low strontium to lime ratios (Fig. 11a). Two Byzantine glass weights with a cruciform monogram (BM 19,0601.15 and BnF AA VA 19) which closely match Egypt 1A contain manganese in excess of 1%. Elevated manganese concentrations are uncommon for Egypt 1 glasses, and the precise composition of the base glass of these two weights before the addition of the manganese colourant is impossible to establish insofar as both samples show high levels of contaminants (Schibille *et al.* 2016). Another Byzantine weight (BnF Froehner verre 34) appears to be closely related to Egypt 1A, but for its higher strontium to calcium ratio (Fig. 11a). It is therefore not unreasonable to conclude that the aforementioned late antique samples do not belong to the prototypical Egypt 1 category.

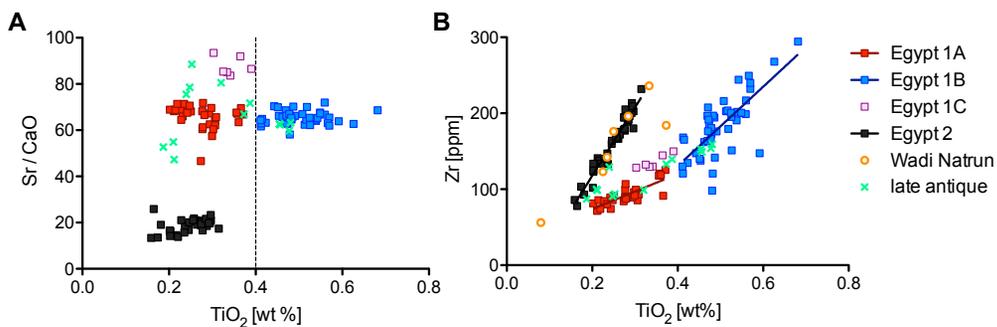


Fig. 11:

Comparison of the Islamic natron-type Egypt 1 and Egypt 2 glasses with earlier natron glass groups from Egypt. (a) Sr/CaO ratios versus TiO₂ highlight the distinctive nature of the early Islamic natron-type glass groups from Egypt; (b) zirconium to titanium oxide correlations distinguish Egypt 1 from the Wadi Natrun compositional groups, while there are some compositional similarities between Islamic Egypt 1A and 1B, Byzantine glass weights and late antique samples from Cyprus. Data sources: (Picon *et al.* 2008) for Wadi Natrun; (Schibille *et al.* 2016) for Byzantine glass weights; (Rosenow and Rehren 2018) for Armant; (Ceglia *et al.* 2019) for Cyprus; (Schibille *et al.* 2019) for Egypt 1 & Egypt 2.

From the study of glass assemblages from Tebtynis and Fustat (Foy *et al.* 2003a) and the Sinai Peninsula (Kato *et al.* 2009) we know that Egypt 1A was already in use by the middle of the seventh century (Foy *et al.* 2003a). The chronological difference between Egypt 1A and Egypt 1B is not as clearly reflected in the vessel glass, but the evidence still suggests a temporal evolution from Egypt 1A to Egypt 1B (Schibille *et al.* 2019). This temporal sequence is in apparent contradiction to

the finds from Cyprus (three out of five samples attributed to Egypt 1; Ceglia *et al.* 2015) and a Byzantine glass weight (BM 1983,11-8,3; Schibille *et al.* 2016) which have been dated to the seventh century at the very latest. Since these four samples cannot be distinguished compositionally from Egypt 1B (> 720 CE), a common source of silica and, by extension, a common provenance must be assumed, which may suggest an earlier beginning for Egypt 1B glass production than the one we observe in relation to the Islamic glass weights. Based on the available data, this issue cannot be conclusively resolved at present, but a number of observations are worth considering. Archaeological dating is subject to considerable uncertainty. The samples from Cyprus are dated broadly from the fifth up to the middle of the seventh century CE (Ceglia *et al.* 2015), and it is not clear whether later contaminations of the archaeological context may be a possibility. The Byzantine glass weight with an Egypt 1B composition is more problematic as the issuing of Byzantine glass weights is believed to have ceased in the second half of the seventh century CE (Schibille *et al.* 2016). A possible explanation may be the nature of this particular Byzantine glass weight itself, since it cannot be dated with any certainty due to the fact that it is imprinted with an indistinct box monogram (Fig. 12). It belongs to a debased sub-type that has been dubbed ‘arabo-byzantine’, believed to have been an Arabic copy that was possibly issued privately by Coptic merchants after the Arab conquest of Egypt (Balog 1958; Entwistle 2002; Entwistle 2016).



Fig. 12:

Byzantine glass weight stamped with an indistinct box monogram. Diameter 2.56 cm; weight: 3.72 g; Registration number 1983,1108.3 (Entwistle 2016, cat.no. 751, p. 86). © The Trustees of the British Museum. Shared under a Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International (CC BY-NC-SA 4.0) licence.

Its weight (3.73 g) deviates substantially from the official weight unit of the gold solidus nomisma (4.50 g) or, in fact, the new weight standard of the dinar (4.25 g). So there is indeed the distinct possibility that this Byzantine glass weight may have been issued in the eighth century by the Coptic community for local use.

The early eighth-century mosaic decoration of the Great Mosque in Damascus (705 – 715 CE) may yield indirect information on the relative dating of Egypt 1A and Egypt 1B insofar as none of the 908 tesserae analysed corresponds to an Egypt 1B composition (see below). The finds from Damascus contrast with the later mosaics from Khirbat al-Mafjar (dated to 736 – 746 CE), where four out of 16 tesserae have an Egypt 1B signature (Fiorentino *et al.* 2018; Fiorentino *et al.* 2019a). While this does not prove beyond doubt that Egypt 1B had not yet been manufactured at the beginning of the eighth century, any significant scale of production of Egypt 1B at the time is very unlikely, which seems largely to vindicate our chronological model of early Islamic natron-type glass from Egypt. As regards the dating of Egypt 1C (n = 5), four samples have been provisionally attributed to the eighth century, even though three of the weights are anonymous (VStras 138, 140, 141; Ollivier 2019). One commodity weight in the name of Hatim bin Haratma (MAO 1134) dates to the beginning of the ninth century (809 – 811 CE; Noujaim-Le Garrec 2004). Due to their unofficial nature, it has been assumed that these weights were issued by a provincial centre (Morton 1985). They all show signs of recycling, which may further reflect their unofficial character (Fig. 13).

The transition from Egypt 1B to Egypt 2 appears more straightforward. According to the data on Islamic glass weights, Egypt 1B is superseded by Egypt 2 in the last quarter of the eighth century (Schibille *et al.* 2019). Analytical data of early Islamic glass assemblages from Tebtynis and Fustat (Foy *et al.* 2003a) and the Sinai Peninsula (Kato *et al.* 2009) lend further support to this temporal pattern. Among the glass finds from Tebtynis and Fustat, Egypt 1A and 1B (Picon's groups 9 and 8, respectively) are exclusively associated with Umayyad contexts and typologies, while Egypt 2 finds (Picon's group 7) are dated to the late eighth and ninth centuries CE (Foy *et al.* 2003a). Similarly, Kato's N2-a2/Egypt 1B from Raya is attributed to the eighth and group N2-b/Egypt 2 to the ninth century CE (Kato *et al.* 2009). Hence, Egypt 1A and 1B are predominantly Umayyad glasses, even though the use of Egypt 1B for glass weights lasted until about 775 CE (Schibille *et al.* 2019). Egypt 2, in contrast, can be considered an Abbasid glass type. Reference must be made here to a number of glass finds from Israel, mostly recovered from Ramla, which have Egypt 2 characteristics and which have been dated to the first half of the eighth century CE on comparative grounds (Gorin-Rosen 2011; Phelps *et al.* 2016). This stands in stark contrast to the data on

Islamic glass weights and the observations made on Egyptian assemblages. It is obvious that the interpretation of analytical data depends on archaeological data, and that it can be fundamentally strengthened (or weakened) by the precision of the dating. The dating of Islamic glass weights is reasonably robust, and it may thus be worth critically re-evaluating the available archaeological and typological evidence. Of course, only a small proportion of all extant Islamic glass weights have been analysed and there is always the possibility that glass was stored and/or the primary production of the raw glass was not contemporary with its further processing and the manufacture of the weights. I would nonetheless argue that the data on Islamic glass weights and their temporal sequence are the strongest available data yet, and that they reflect contemporary developments in primary glass production – otherwise a higher degree of mixing and recycling might be expected.

The presence of colourants (Cu, Pb, Sn) above a threshold of 100 ppm or decolourants (Mn, Sb) at levels exceeding their typical background levels of about 250 ppm for manganese and 30 ppm for antimony, in combination with an accumulation of elements associated with glass-working (Fe) and fuel ash (K, P), have previously been interpreted as indicators of recycling (Barfod *et al.* 2018; Freestone 2015, and references therein). From a comparison of the traces of the colouring elements (Mn, Cu, Zn, Sn, Sb, Pb) we can thus get a clear sense of the relative degree of recycling of the different Islamic natron glasses from Egypt. In the majority of the groups the colouring elements remain below the threshold of 100 ppm (250 ppm for Mn), and in most cases even below 30 ppm (Fig. 13). There is therefore little evidence of recycling. The only exception is Egypt 1C which has consistently elevated contents of transition metals such as manganese, copper and lead. There is furthermore a slight, but consistent increase in all recycling markers in a later subtype of Egypt 2 (> 815 CE) with reduced soda contents of about 13.4% Na₂O compared to the earlier Egypt 2 examples (< 815 CE), containing on average 16.5% Na₂O (Table 2). The former includes a couple of vessel stamps which were tentatively dated to the second half of the tenth century (VStras 187, VStras 188) and which were most certainly recycled. The overall decline in soda contents of Egyptian natron-type glass over the ninth century is indicative of minor changes in glassmaking recipes, which in turn may point to increasingly limited access to the mineral soda deposits in Egypt. The combination of lower soda levels and a higher incidence of recycling could be a reflection of an Egyptian glass industry in crisis or one that was directly affected by an unsettled political situation. It foreshadows the end of natron-glass production which coincides with the disintegration of Abbasid rule in Egypt.

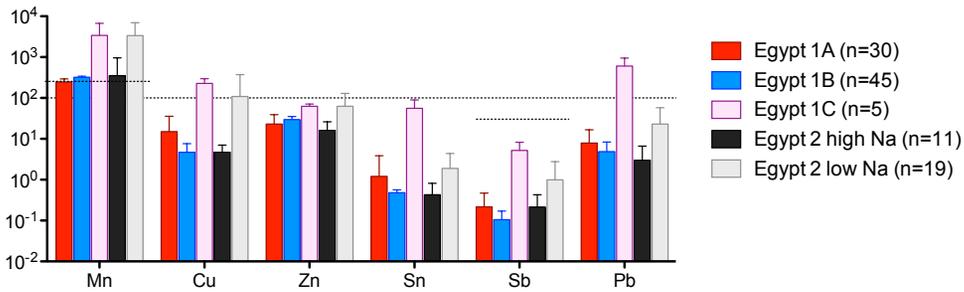


Fig. 13:

Recycling markers (Mn, Cu, Zn, Sn, Sb, Pb) within the different early Islamic natron-type glass groups. Data source: (Schibille *et al.* 2019). Dashed lines indicate the threshold that identifies cut-offs for Mn = 250 ppm and Sb = 30 ppm, and all other elements at 100 ppm.

The demise of Egyptian natron glass production is complete with the establishment of the Tūlūnid regime in Egypt. The last glass weight of an Egypt 2 composition dates to the first year of the governorship of Ahmad ibn Tūlūn (868 CE), marking the end not only of natron glass production and the end of Abbasid rule in Egypt, but also the beginning of a 100-year interlude from the time of which virtually no Egyptian glass weight or stamp is known to exist (Ollivier 2019). Glass weights re-emerge after the Fatimid conquest of al-Fustat in 969 CE, when Egypt became the centre of the Fatimid caliphate until the end of the dynasty in 1171 CE (Power 2018; Sanders 1998). Substantial social, cultural, political and, in fact, technological transformation had taken place in the meantime. Egyptian glass production no longer used natron but had reverted to the exclusive use of plant ash as the main fluxing agent. The precise moment is uncertain, but it is certain that under the Fatimids glass weights were made from soda-rich plant ash glass.

Natron type Egypt 1Ax – glass mosaics from the Great Mosque in Damascus

Before we embark upon a detailed discussion of Islamic plant ash glasses from Egypt, the compositional properties of the mosaic tesserae from the Great Mosque in Damascus deserve special attention. A surge in monumental building campaigns at the end of the seventh and the beginning of the eighth centuries during the reigns of the Umayyad caliphs 'Abd al-Malik (691/92 CE) and his son al-Walīd I (705 - 715 CE) meant a dramatic increase in demand for architectural glass (windows, mosaics, lamps) within a relatively short period of time (Leal 2020). This surge includes the construction of the Great Umayyad Mosque in Damascus, commissioned by the caliph al-Walīd I in 705/706 CE and completed by 715 CE (George 2021). The Great Mosque, the largest congregational mosque

of its day, was decorated with a vast expanse of glass mosaics literally inside and out, covering much of the wall surface (Fig. 14). Tenth-century Arab sources claim that the mosaic tesserae and workmen for the original eighth-century decoration came from the Byzantine Empire (James 2017, and references therein). The cost of the building is said to have been several times the annual poll tax of Syria (Flood 2001, p. 2) and to have required an estimated 170 tons of glass for the mosaics (see chapter 2). Even though the mosaics have been extensively restored and repaired on several occasions, with the earliest documented restorations occurring in the eleventh and twelfth centuries CE, and much of the decoration has been completely lost (Flood 2001; George 2021; James 2017; Walker 2004), many of the remaining tesserae represent original material from the early eighth century.



Fig. 14:

Damascus - Umayyad (Great) Mosque - west arcade - قشمد - يومال اعماجلا - قشمد اورلا - قشمد اورلا - قشمد اورلا.
 (©Photo: Judith McKenzie/Manar al-Athar; <http://www.manar-al-athar.ox.ac.uk>)

In a collaborative research project (IRAMAT-CEB, Musée de Louvre, C2RMF), we recently analysed 908 mosaic tesserae from the Great Mosque in Damascus, including strongly coloured and partially opacified mosaic tesserae as well as gold-leaf and silver-leaf ones (Schibille *et al.* forthcoming). Of the analysed samples,

54 tesserae have elevated magnesium, potassium and phosphorus contents, indicative of the use of plant ash as the main fluxing agent. These tesserae are thought to stem from later restorations, as no comparative plant ash glass is known from the early eighth century. Another possibility is that this is material from the mosaic panels that were executed in the eleventh to twelfth centuries CE (George 2021). Similarly, six gold leaf tesserae of an alkali lead glass almost certainly do not constitute original eighth-century material. The bulk of the analysed tesserae, however, correspond to natron-type glass that can be assumed to have formed part of the original early eighth-century mosaic decoration. About 65% of the natron tesserae examined exhibit compositional features strongly reminiscent of the Egypt 1A production group, pointing to a contemporary Egyptian provenance. This material therefore represents extremely interesting comparative data, offering indirect insights into the early Islamic glass industry in Egypt.

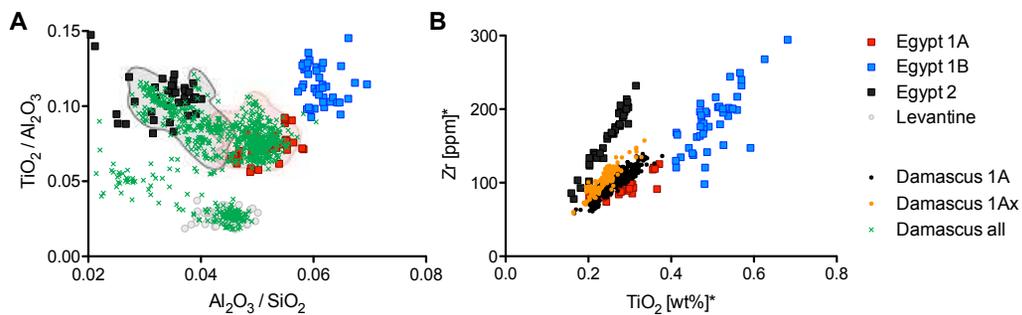


Fig. 15:

Comparison of the Damascus tesserae with contemporary primary production groups from Egypt and the Levant. (a) $\text{TiO}_2/\text{Al}_2\text{O}_3$ versus $\text{Al}_2\text{O}_3/\text{SiO}_2$ ratios confirm the group affiliations of the majority of the Damascus tesserae with Egyptian primary production groups; outlines correspond to the 95% kernel density ranges for Egypt 1A and Egypt 1Ax, generated using the open-access RESET statistical tools (<https://c14.arch.ox.ac.uk/resetdb/db.php>); (b) titanium and zirconium are positively correlated and separate the Damascus Egypt 1Ax from Egypt 2, highlighting its similarities with Egypt 1A (asterisks indicate reduced and normalised compositions). Data sources: (Schibille *et al.* 2019) for Egypt 1 & Egypt 2; (Brems *et al.* 2018; Freestone *et al.* 2008b; Phelps *et al.* 2016) for Levantine; (Schibille *et al.* forthcoming) for Damascus.

The Damascus tesserae are characterised by elevated titanium oxide concentrations ($\text{TiO}_2 > 0.2\%$) but highly variable alumina contents, ranging from about 2% to 4% in their reduced and normalised composition. As a group, the tesserae exceed the range of the early Islamic Egypt 1A glass group (Table 2). Therefore, I have subdivided the assemblage using a somewhat arbitrary threshold of 3.2% Al_2O_3 , which is derived from the lower limit of the Egypt 1A glass weights data minus

two standard deviations. The group of tesserae with $\text{Al}_2\text{O}_3 > 3.2\%$ is perfectly congruent with the Egypt 1A reference group represented by the data on the Islamic glass weights (Fig. 15). No perfect compositional match was found for the tesserae with lower alumina contents that have been tentatively called Egypt 1Ax. Their overlap with Egypt 2 in terms of the ratios of $\text{TiO}_2/\text{Al}_2\text{O}_3$ and $\text{Al}_2\text{O}_3/\text{SiO}_2$ is coincidental and resolves when the absolute zirconium and titanium concentrations are considered (Fig. 15b). The Egypt 1Ax tesserae also have much lower calcium contents (typically $\text{CaO} < 4\%$) and proportionally higher strontium levels than Egypt 2 (Table 2). Instead, Egypt 1Ax appears to be closely related to Egypt 1A. The two groups appear to form a compositional continuum in terms of the accessory elements. They are almost completely identical with respect to their normalised trace and rare earth elements, and both are consistent with the Egypt 1A reference group (Fig. 16). Zirconium to titanium oxides of both groups of tesserae from Damascus and the glass weights show very similar behaviour, but for slightly higher average zirconium to titanium ratios in the Egypt 1Ax sub-type (Fig. 15b). This may be due to local variations in the distribution of minerals within the same silica source as a result of different forces during sediment deposition (Brems *et al.* 2015; Brems *et al.* 2018). It is thus quite conceivable that one and the same sand deposit is more or less depleted in accessory minerals, depending, for example, on the depth of extraction. There can be no doubt that the two groups are intimately related, leading to the conclusion that a geographically and geologically similar, if not the same, silica source was exploited. In contrast, there is a clear difference in the trace element profile of Egypt 1B, which has overall higher silica-related impurities (Fig. 16).

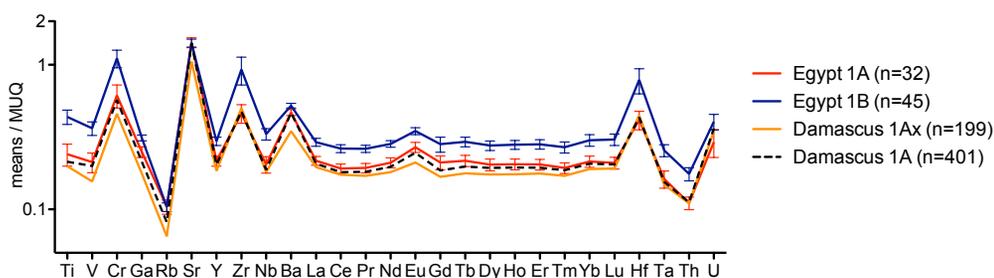


Fig. 16:

Average trace element patterns of Damascus 1A and 1Ax (Schibille *et al.* forthcoming) compared to Egypt 1A and Egypt 1B reference groups (Schibille *et al.* 2019). Data were normalised to the upper continental crust (Kamber *et al.* 2005). Standard deviations are given as error bars.

Particularly remarkable are the high soda levels of the Egyptian tesserae from Damascus. The soda contents are on average 2 wt% higher than in the Egypt 1A reference group of early Islamic glass weights (Table 2) or of other vitreous objects such as vessels (Phelps *et al.* 2016). This is all the more surprising since a general decline in soda contents was observed over the course of the first millennium CE, in both Levantine and Egyptian productions (Freestone 2020). The high levels of soda in the mosaic tesserae suggest that access to suitable natron sources in Egypt was not yet restricted and that natron was still relatively abundant. Glass that is higher in soda is easier and faster to melt. In the case of the tesserae from Damascus, the working temperature is estimated to be about 40°C lower than that of the glass weights, judging by the model provided by Fluegel (2007) and the average compositions given in Table 2. This difference in temperature offers considerable advantages, especially with regard to a large-scale commission. The quantities needed for the mosaic decoration of the Great Mosque in Damascus are enormous and time was of the essence. In view of the material requirements for his various building projects, it is plausible that al-Walīd I directly commissioned the manufacture and shipping of mosaic tesserae from Egypt. This may also explain the new compositional group, Egypt 1Ax, which has so far been identified only among the mosaic tesserae from the Great Mosque. From archival material such as the *Aphrodito Papyri* that record the official correspondence between Qurra ibn Sharik, then governor of Egypt (709 to 714 CE), and the prefect of the district of Aphrodito in Upper Egypt we know that artisans, craftsmen and materials were requested from Egypt to help with the construction of the Mosque in Damascus (van Lohuizen-Mulder 1995). These resources formed part of the annual tax payments by the provinces to the central caliphal government (George 2021, pp. 77-81). Whether this included master mosaicists is a matter of speculation, but large quantities of mosaic tesserae were undoubtedly part of the ‘material aid’ or annual tax payments.

There is evidence to suggest that tesserae or intermediate products (e.g. coloured glass cakes) rather than raw glass were manufactured in Egypt and from there shipped to the Levantine coast and on to Syria. The regional compositional groups (Levantine, Egyptian) remain distinct and well defined. There is no sign of substantial mixing between the vitreous materials from the two regions, thereby confirming independent secondary working. What is more, the colours are distributed unevenly between the Egyptian and Levantine base glasses, a phenomenon we have already observed in connection with the palatial complex at Khirbat al-Minya at Lake Tiberias in Israel (Adlington *et al.* 2020). None of the red or cobalt blue samples with notable cobalt levels (Co > 200 ppm) and only one of the gold tesserae correspond to Egypt 1A. Black tesserae on the other hand are

predominantly made from Egypt 1A. These colour differences suggest different secondary working practices and/or a lack of access to colorants, for example with respect to suitable cobalt sources. Furthermore, the trace elements associated with the lead component in the Egyptian tesserae (Egypt 1A or Egypt 1Ax) from Damascus and Khirbat al-Minya with lead oxide levels of $\text{PbO} > 2\%$ indicate a common lead source. The fairly consistent lead to bismuth ratio in the Egypt 1A and Egypt 1Ax tesserae independent of the colour (green, yellow) is not found to the same extent in the Levantine tesserae (Fig. 17). One possible interpretation of the positive correlation between bismuth and lead in the Egyptian tesserae is that the same lead-bearing raw materials were used for the production of lead coloured glasses, and that different colours were made in a single secondary workshop.

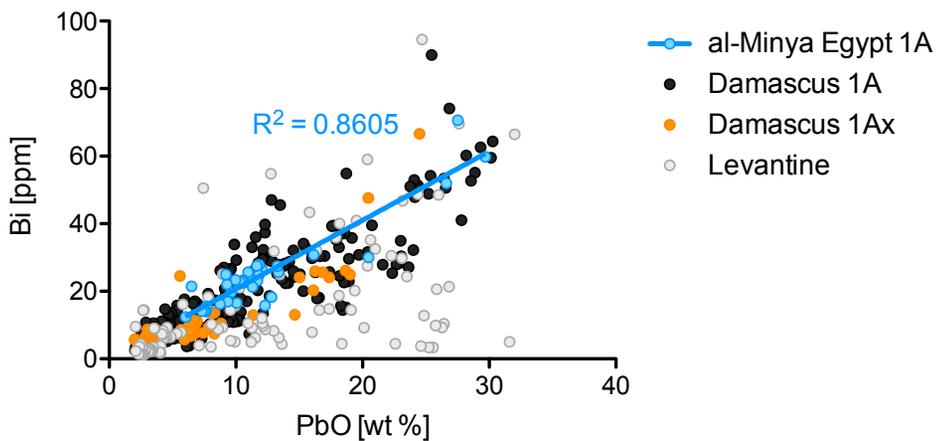


Fig. 17:

Bismuth compared to lead oxide contents in all tesserae from Khirbat al-Minya and the Great Umayyad Mosque of Damascus with $\text{PbO} > 2\%$. Data sources: (Adlington *et al.* 2020) for al-Minya; (Schibille *et al.* forthcoming) for Damascus.

Egyptian glass has long been used for the production of mosaic tesserae. Egyptian Foy 2.1 glass, for example, makes up the bulk of the sixth-century mosaic decoration of the church of Hagia Sophia in Istanbul (unpublished data). The combined data from the Great Mosque in Damascus (Schibille *et al.* forthcoming) and the clear parallels with contemporary Khirbat al-Minya (Adlington *et al.* 2020) give the impression that Egyptian glass was more commonly used than Levantine glass in early Islamic mosaics despite the proximity of both Damascus and Khirbat al-Minya to the primary glassmaking sites on the Levantine coast. The production of strongly coloured glass in Egypt stretches back to the Ptolemaic and Roman periods (Nenna *et al.* 2000; van Lohuizen-Mulder 1995), and Egypt had a long history of mosaic making. According to textual sources, the Mosque

of 'Amr ibn al-'As in Fustat, said to be the oldest mosque in Egypt (641-642 CE), was decorated with wall mosaics (van Lohuizen-Mulder 1995), and a mosaic workshop was allegedly active in Egypt during the time of al-Walīd I (Ritter 2017, p. 208). Egypt may thus have been the leading producer of glass mosaics at that time. The existence of the Egypt 1Ax sub-group, which is similar to Egypt 1A and which has not been identified elsewhere, is strong evidence that the manufacture and supply of tesserae for the decoration of the Great Mosque in Damascus may have been a special large-scale commission, possibly at the explicit request of al-Walīd I himself. Al-Walīd allegedly spared no expense. In the late tenth century, the geographer al-Muqaddasī makes reference to the enormous costs of the construction of the Great Mosque (cited in Flood 2001, p. 215). The need for copious supplies of glass for various monumental building campaigns may have fuelled the Egyptian glass industry which still produced a surplus of material and was still capable of supplying the wider eastern Mediterranean market. This may in turn reflect the decisive role of the central government and the caliph himself in the intensification of production and in changing distribution patterns. From the second half of the seventh century the economic and cultural focus was on Greater Syria and its capital Damascus. All this may have changed when the Tūlūnids created an autonomous regime in Egypt that was largely independent of the central caliphal government that had since moved to Baghdad and Samarra.

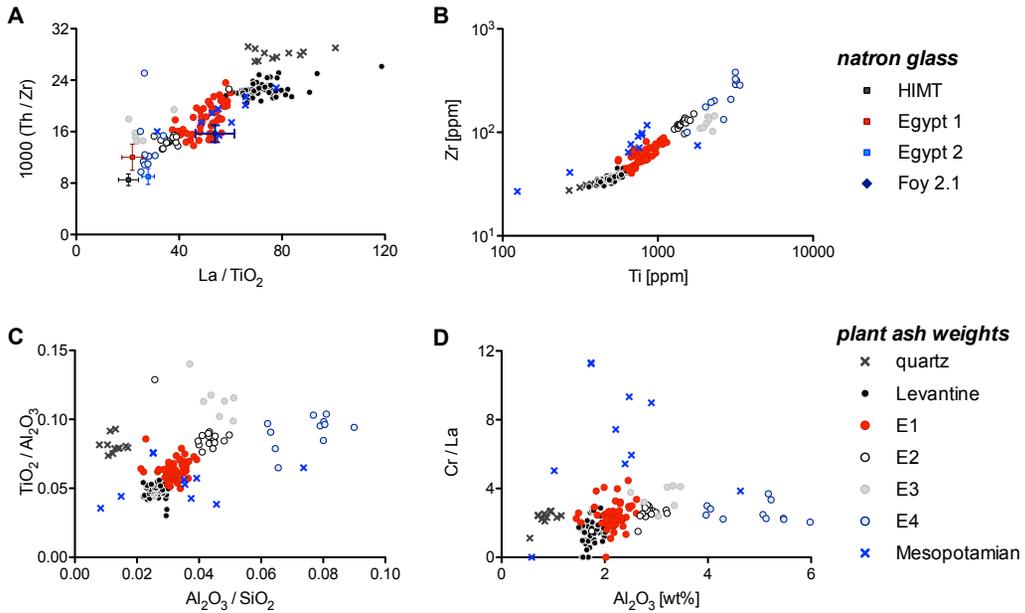
The earliest plant ash glasses from Egypt

At the time Ibn Tūlūn established the Tūlūnid dynasty in Egypt in 868 CE, the finance officer of Egypt was Ibn al-Mudabbir Ibn Tūlūn, who was notorious for levying new taxes, including new natron taxes (Treadwell 2017). In the fifteenth century al-Maqrīzī mentions that al-Mudabbir 'had the natron sources guarded that had previously been open to all and appropriated the revenue' (al-Maqrīzī, *Khitat*, I, 39; French translation in Bouriant 1895, p. 298). It is likely that these restrictions on the extraction of natron and the concomitant rise in its price had a profound impact on the glassmaking industries (Becker 1903). Judging from the Islamic glass weights, Ibn Tūlūn's reign indeed marks the end of natron glass production in Egypt and the beginning of a 100-year gap in the manufacture of official glass weights. This cessation of the production of official glass weights in Egypt may be directly linked to the general disintegration of Abbasid rule. When glass weights reappeared in the archaeological record of Egypt after the Fatimid conquest, they were made from a plant ash base glass. The primary glassmaking industry in Egypt had evidently changed in the meantime. The transformation of the industry is reflected in the compositional diversity of Fatimid and Ayyubid glass weights.

Different compositional groups of plant ash glass were in circulation at the same time, some of them having been imported into Egypt from the Levantine coast and Mesopotamia (Schibille *et al.* 2019; Schibille 2022).

Plant ash glasses E1 – E4

Through a detailed characterisation and comparison of the compositional data, the plant ash glass weights can be classified into seven compositional groups, four of which probably represent Egyptian productions (E1-4; Table 3). The differentiation between the different plant ash glasses requires a multidimensional evaluation of elements associated with both the silica source and the fluxing agent. Compositional features that have been shown to distinguish natron-type and Late Bronze Age glass (Shortland *et al.* 2007) serve as starting point. For example, the typically high concentrations of titanium and zirconium in earlier Egyptian natron-type glass can equally be used as a tool to distinguish Egyptian from Levantine plant ash glass. A diagram showing the ratios of thorium to zirconium and lanthanum to titanium oxide (Fig. 18a) highlights the potentials of this approach which has been used to distinguish between natron-type glasses of Levantine and Egyptian provenance (Freestone *et al.* 2018). The group singled out as Levantine plant ash glass on account of its compositional resemblance to Levantine plant ash glass from Tyre (Freestone 2002; Schibille *et al.* 2019) has systematically higher Th/Zr and La/TiO₂ ratios, while groups E2, E3 and E4 lie at the other end of the spectrum, very close, in fact, to natron glass Egypt 1 and Egypt 2 as well as HIMT. Plant ash group E1 occupies an intermediate position between the two extremes and an unambiguous attribution is difficult. Levantine and E1 plant ash glass are similar in many respects (Table 3). The two groups differ primarily in the average concentrations of titanium, zirconium and thorium, and in a higher degree of recycling in the E1 group (Fig. 19). E1 thus appears to be sufficiently distinct from the Levantine category, while at the same time exhibiting similarities with other Egyptian groups to suggest an Egyptian origin. The threshold of TiO₂/Al₂O₃ at 0.055 proposed recently (Schibille *et al.* 2019) provides a good estimate to distinguish Levantine plant ash glasses from Egyptian ones, but may not suffice on its own. To delineate the two populations further, the La/TiO₂ ratio proved to be a useful discriminant to separate glasses from Egyptian and Levantine sources.

**Fig. 18:**

Compositional differences between the Islamic soda-rich plant ash glass weights from Egypt. (a) Separation of Levantine plant ash glass from the Egyptian groups in terms of their Th/Zr and La/TiO₂ ratios (Th, La and Zr in [ppm], and TiO₂ in [wt %]), note the close relationship of E2, E3 and E4 with natron glass HIMT (De Juan Ares *et al.* 2019b) and Egypt 1 and Egypt 2 (Schibille *et al.* 2019); (b) covariations of zirconium and titanium in the different plant ash groups, only group E3 deviates from a common regression line; (c) TiO₂/Al₂O₃ and Al₂O₃/SiO₂ ratios confirm different plant ash glass populations; (d) elevated Cr/La ratios separate the Mesopotamian plant ash glass from the rest of the glass weights which exhibit a relatively wide range of alumina contents. Data sources: (Schibille *et al.* 2019); Schibille and Gratuze groups E2-E4 unpublished data.

The attribution of the Egyptian plant ash glass groups is exclusive rather than affirmative, meaning that we can exclude potential sources rather than positively and definitively attribute the glass to an Egyptian origin. The classification is further complicated by the high variability of the glass and the limited number of samples per group. The majority of the Egyptian plant ash glasses have constant zirconium to titanium ratios, while the absolute amounts of the two elements increase considerably from group E1 to E4 (Fig. 18b). The glasses of E3 represent a possible exception to the rule by having somewhat higher titanium to zirconium ratios than the other samples. In the absence of evidence to the contrary, it is nonetheless assumed that E3 is also an Egyptian plant ash glass. Glass group E2 has moderate alumina and fairly high titanium and zirconium values (Fig. 18), and most of the samples affiliated with E2 have considerably higher boron contents

compared to the other groups (Table 3). Group E4 shares some similarities with natron-type Egypt 1 and the Roman glass from Lake Mareotis mostly on account of its high alumina ($\text{Al}_2\text{O}_3 > 4\%$) relative to silica content (Fig. 18c), with strong positive correlations ($R > 0.8$) between alumina and titanium, iron and the lighter lanthanides (La, Ce, Pr, Nd, Sm). Also, the trace and rare earth elements are higher than in any of the other groups. This implies that the silica source of the E4 glasses was rich in accessory minerals such as monazites and zircons. The relatively high variability of the silica-related impurities furthermore suggests that group E4 as defined here may in fact contain two or more sub-categories of high alumina plant ash glasses. The limited number of samples ($n=11$), however, prevents a further refinement of the group characteristics and affiliations. These variations may reflect the overall smaller scale of production of plant ash glasses compared to natron-type glasses.

Type	Date	Na ₂ O	MgO	Al ₂ O ₃	SiO ₂	P ₂ O ₅	Cl	K ₂ O	CaO	TiO ₂	MnO	Fe ₂ O ₃	Li	B	Cr	Sr	Zr
Mesopotamian (n=10)	795-1094 stdev	13.8 1.0	3.94 1.00	2.22 1.05	66.4 2.8	0.23 0.06	0.69 0.09	2.80 0.45	6.70 0.73	0.12 0.07	0.87 0.55	1.59 0.83	18.9 5.6	113 32	50.1 30.6	443 66	75.6 25.7
quartz (n=11)	996-1129 stdev	14.3 0.9	3.47 0.21	0.86 0.17	67.2 1.3	0.41 0.11	0.89 0.11	2.66 0.47	9.00 1.01	0.07 0.01	0.13 0.27	0.40 0.08	7.57 1.29	107 10	12.3 2.6	472 81	33.1 3.1
plant ash Lev (n=53)	952-1129 stdev	12.7 1.2	3.03 0.36	1.79 0.14	67.9 1.3	0.32 0.04	0.83 0.13	2.58 0.29	8.87 0.83	0.09 0.01	1.06 0.48	0.64 0.42	5.54 1.21	85.7 10.8	9.71 4.52	507 102	36.4 3.2
plant ash E1 (n=51)	952-1154 stdev	12.6 0.7	2.73 0.42	2.15 0.25	67.7 1.2	0.39 0.11	0.79 0.08	2.33 0.38	8.83 0.80	0.14 0.02	0.99 0.60	0.83 0.18	6.77 2.14	93.8 13.0	16.3 5.0	508 69	61.4 11.7
plant ash E2 (n=16)	996-1129 stdev	14.7 1.0	2.38 0.32	2.80 0.31	65.7 1.8	0.51 0.22	0.93 0.09	1.77 0.49	8.81 1.65	0.24 0.02	0.49 0.18	1.27 0.29	7.52 1.57	214 77	22.5 2.9	502 170	123 13
plant ash E3 (n=7)	1035-1129 stdev	12.3 1.2	2.67 0.41	3.09 0.32	67.8 1.3	0.43 0.10	0.81 0.22	2.46 0.45	7.79 1.15	0.35 0.02	0.48 0.41	1.46 0.15	6.67 0.51	67.3 18.1	30.9 6.7	617 134	124 16
plant ash E4 (n=11)	1035-1149 stdev	14.3 2.4	2.05 0.60	4.89 0.58	65.3 11.3	0.42 0.13	1.01 0.17	2.14 0.55	6.13 1.64	0.45 0.08	0.97 0.54	1.78 0.41	7.81 1.99	99.7 54.0	31.7 7.7	454 125	238 35

Table 3:

Averages and standard deviations of compositional groups of Islamic glass weights from Egypt. Metal oxides and chlorine are given in [wt %], Li, B, Cr, Sr and Zr are given in [ppm]. Data sources: (Schibille *et al.* 2019); Schibille and Gratuze, groups E2-E4 unpublished data.

A small group of Mesopotamian plant ash glasses (n=10) can easily be differentiated thanks to a combination of characteristics, including typically higher MgO (> 3.5%) and lithium (> 10 ppm), as well as low P₂O₅ (< 0.3%) contents coupled with high chromium to lanthanum ratios (Cr/La > 5) (Table 3, Fig. 18d). Chromium as a marker for Mesopotamian glasses was first singled out in the context of Late Bronze Age glasses (Shortland *et al.* 2007), but this seems to hold at least partly true also for Islamic plant ash glasses (see chapter 3). Another minor group (n=11) is tentatively called ‘quartz’, based on its low levels of mineral contaminants (Fig. 18). Because of the pure nature of these samples and the lack of any distinguishing features, it is not possible to assign a definitive provenance to the ‘quartz’ group. Given their relatively high lime and low lithium content, an eastern Mediterranean origin seems more likely than a Mesopotamian one, even though the samples have relatively high magnesium oxide values.

Recycling and chronological evolution

Together, these compositional parameters allow us gradually to develop a framework of regional variations of plant ash glasses from the three major glass-producing regions. Recycling practices, however, potentially obscure a precise distinction between groups. For example, a clear cut-off between the Levantine and E1 categories may be hampered by the fact that almost all E1 glasses show elevated levels of recycling indicators, such as colouring and opacifying elements (Fig. 19) that are indicative of an addition of recycled material. Their chemical composition may thus have been influenced by the combination of several glass types. By far the most intriguing element in this respect is antimony which had not been in use since the fourth or maybe fifth century CE (Lobo *et al.* 2013; Tite *et al.* 2008). The elevated levels of antimony in some of the E1 and E2 glass weights are associated with increased lead contents, suggesting the incorporation of antimony opacified glass fragments, possibly in the form of mosaic tesserae (Mirti *et al.* 2001). The existence of several late Abbasid glass weights with patches of antimony white containing up to 5% Sb₂O₃ combined with an Egypt 2 base glass (Schibille *et al.* 2019) provides strong independent evidence for the deliberate incorporation of recycled opaque material at the secondary working stage. The addition of some recycled cullet during primary production is also likely. The Levantine plant ash glass weights, on the other hand, do not display any obvious signs of recycling, with values of copper, lead and tin generally well below 100 ppm (Fig. 19). This probably reflects the consignment of fresh raw glass from the Levantine coast and a relatively heavy dependence of Egyptian glass workers on Levantine imports during this period.

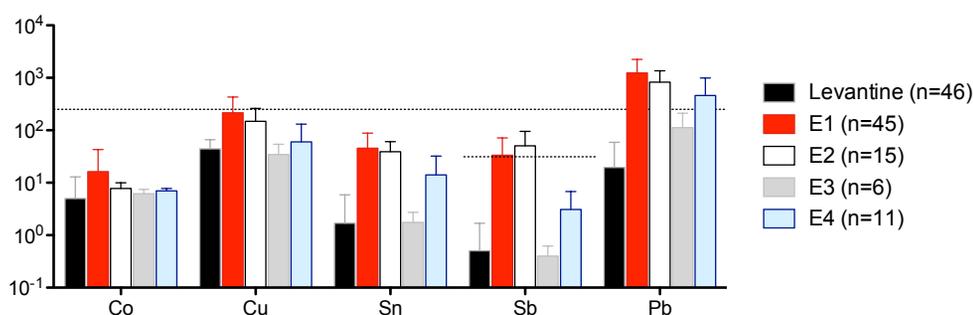


Fig. 19:

Recycling markers within the different plant ash glass weights from Egypt. Dashed lines indicate the thresholds of 100 ppm and 30 ppm for antimony.

The Levantine glasses are among the earliest Fatimid glass weights alongside E1, dating to the reign of the first Fatimid caliph, al-Mu‘izz li-din Allah (953-975 CE), who succeeded in conquering Egypt in 969 CE and who established Egypt and its new capital Cairo as the centre of the Fatimid caliphate (Sanders 1998). During the caliphates of al-Mu‘izz and his successor al-‘Aziz, the majority of glass weights was made from Levantine and E1 plant ash glass in roughly equal proportions, while there are isolated cases of recycled natron types Egypt 1A (MAO 999, 1148) and Egypt 2 (BNU 154, 165). This is the first time that we see relatively large quantities of raw glass being imported into Islamic Egypt. None of the earlier Levantine natron-type glasses have been found in Egypt in significant quantities. The Levantine and E1 plant ash categories dominate the late tenth and eleventh centuries CE and are phased out in the first half of the twelfth century CE (Table 3). The last glass weight made from a Levantine plant ash glass identified so far is in the name of al-‘Amir (1101-1129 CE), while E1 type glass was still detected in a single weight from the reign of al-Zafir (1149-1154 CE). These two main groups were joined at the very end of the tenth or the early eleventh century (996-1020 CE) by what appears to be a minor plant ash glass group, E2, then by E3 and E4 which were introduced during the caliphate of al-Mustansir (1035-1094 CE). All three plant ash formulas E2, E3 and E4 remain in circulation until the middle of the twelfth century, when the optical properties and colour range of the glass change dramatically.

The colour palette had already expanded considerably since the Fatimid period, when colourless and translucent yellow, amber, purple, dark blue and (seemingly) black weights were added to the previously dominant natural greenish and bluish aqua colours (Noujaim-Le Garrec 2004; Ollivier 2019). From the reign of al-Ḥākim (996-1020 CE) onwards, we occasionally see opacified glass weights that

eventually become the norm during the Ayyubid period, and that include opaque white, grey and aqua as well as pale celadon green and turquoise (Balog 1966). These samples contain large quantities of additives (lead and tin) which act as colouring and opacifying agents.

Tin-oxide opacified glass weights

The analysis of 33 fully opaque glass weights from the second quarter of the twelfth through to the first quarter of the thirteenth centuries allowed us to establish the use of tin oxide for the manufacture of mostly white and aqua (greenish or bluish) opaque glasses alongside the occasional turquoise object. This group of samples has been labelled *Celadon* because of their resemblance to the jade green celadon colour. Tin-based opacifiers (i.e. tin oxide white and lead stannate yellow) gradually supplanted antimony compounds in the making of opaque glasses sometime in the fourth century CE both in Europe and in the Near East (Tite *et al.* 2008; Turner and Rooksby 1959; Turner and Rooksby 1961; for a recent review with an extensive list of references see Matin 2019). In the Islamic world lead-tin yellow was identified in combination with natron Egypt 1A glass in the form of patches on a small number of Fatimid glass weights (Schibille *et al.* 2019), as well as in mosaic tesserae from the Great Mosque in Damascus, early eighth-century Khirbat al-Minya (Adlington *et al.* 2020) and Khirbat al-Mafjar in Palestine (Fiorentino *et al.* 2018), Qusayr' Amra in Jordan (Verità *et al.* 2017b) and Samarra in Iraq (Schibille *et al.* 2018a). The earliest occurrence of tin-based opacifiers in connection with Islamic plant ash glass is currently attributed to ninth-century Samarra (Schibille *et al.* 2018a) and Nishapur (Wypyski 2015). There are, however, earlier Sasanian plant ash glasses from Ctesiphon that were already opacified by tin- and lead-tin-oxide compounds (see chapter 3).

The opaque glass weights contain as much as 33% lead oxide and up to 27% tin oxide (Fig. 20a), although the median for lead oxide is approximately 24% and for tin oxide about 6%. Lead contents of over 60% were found in yellow and green patches of a series of polychrome weights provisionally attributed to the Fatimid period (BNU 1450, 1451, 1453). These colourful speckles are somewhat exceptional in that they appear to represent simply a mixture of lead, tin and silica with only minor levels of soda and lime (Schibille *et al.* 2019). As such the yellow and green phases are similar to a yellow vitreous pigment known as *anima* that is usually present in the crystalline form of $\text{Pb}(\text{Sn},\text{Si})\text{O}_3$ (Moretti and Hreglich 1984). All other fully opaque glass weights reflect a different colouring technique and crystalline phases. The weights contain on average a combined alkali (Na_2O , MgO , K_2O) load of about 14% and a mean lead to tin ratio of about 5 (Fig. 20a).

The relatively constant lead to tin ratios suggest that lead and tin were added together, presumably as a single component (lead-tin calx), to the glass batch in the secondary glass-working stage. Judging from the parallel negative slopes of both silica and soda normalised to their respective average values in comparison to the lead concentrations, lead and tin were probably added to a pre-existing glass rather than a mixture of silica and alkali (Fig. 20b).

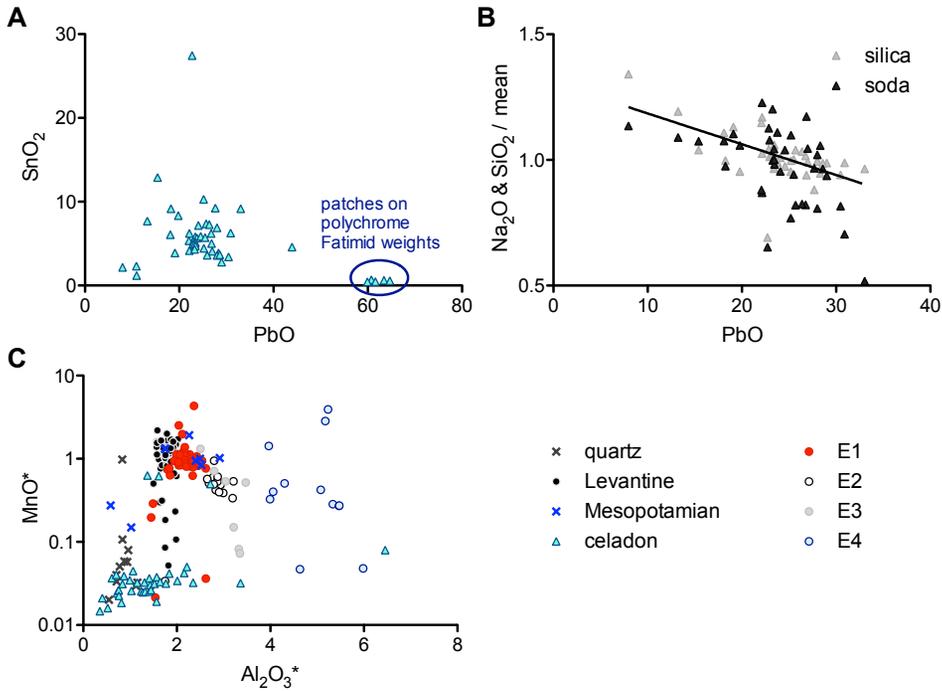


Fig. 20:

Compositional characteristics of early Islamic tin oxide opacified glass weights from Egypt. (a) Lead and tin concentrations of the fully opaque glass weights are relatively constant, while the yellow patches on otherwise translucent Fatimid weights appear to represent the lead-stannate yellow pigment called *anima*; (b) silica and soda data normalised to their average values versus absolute lead concentrations show a similar negative trend, suggesting that lead was added to a pre-formed glass rather than a mixture of raw materials; (c) manganese and aluminium oxide levels of the lead-tin opacified weights underscore the differences between the celadon weights and the other plant ash glass weights. Asterisks indicate reduced and normalised data. Data sources: Schibille and Gratuze unpublished data.

Lead-tin oxide was commonly used to produce a deep yellow colour subject to the stoichiometric requirement of Pb_2SnO_4 ($\text{Pb}/\text{Sn} \geq 3.5$) (Matin *et al.* 2018; Matin 2019). High lead contents and lead to tin ratios are therefore unexpected in opaque white glass. However, experimental results have shown that yellow Pb_2SnO_4 or $\text{Pb}(\text{Sn},\text{Si})\text{O}_3$ crystals decompose during heat treatment to form secondary white

tin oxide particles (SnO_2 cassiterite) within the glass melt if it is sufficiently high in alkali, converting the yellow pigment into an opaque white (Matin *et al.* 2018; Matin 2019). Assuming that lead and tin were added together to an alkali glass in the form of lead-tin calx then the obvious conclusion is that this process was set in motion. While high Pb/Sn ratios are rather uncommon in first millennium white glass, some recent studies have demonstrated that they were relatively typical of Islamic ceramic white glazes of the eighth to tenth centuries in Egypt as well as in Greater Syria and Mesopotamia (Matin *et al.* 2018; Matin 2019; Tite *et al.* 2008). A small amount of Egyptian ceramic lustre ware from Fustat with a lead-tin opacifier and Pb/Sn values ≥ 3.5 dates to the last quarter of the tenth or first quarter of the eleventh century CE (Mason and Tite 1997). The earliest known occurrence of lead-tin oxide white with Pb/Sn values ≥ 3.5 in glass is patches on an otherwise translucent amber-coloured glass weight (BNU 637) that dates to the reign of al-Mustansir (1035-1094 CE), thus at least a generation or two later than the use of this compound in ceramic glazes. The earliest fully white opaque glass weights analysed in our study are from the reign of al-Hafiz in the second quarter of the twelfth century (1129-1149 CE). There is therefore good reason to suggest that the high lead contents in opaque white glass were inspired by glazing techniques, some of which clearly pre-date the use of high lead concentrations in white opaque glasses (Matin 2019).

The lead-tin opacified glass weights have highly variable base glass compositions that are different from the other Islamic glass weights. The reduced and normalised alumina concentrations range from 0.35% to 6.45% (Fig. 20c) and titanium oxide from 0.05% to 0.63%, i.e. a concentration range that covers more than one order of magnitude. They also have variable zirconium to titanium ratios, indicating that different silica sources were used for the production of these opaque glass weights. The samples with low to medium alumina concentrations ($\text{Al}_2\text{O}_3 < 2\%$) generally have low mineral impurities that point to the use of a relatively pure silica source, as well as limited contamination caused by the lead-bearing component. This appears to confirm the mixing of the lead-tin calx with a pre-formed glass, which would minimise the contamination of the batch from the melting crucibles, which could otherwise be expected due to the highly corrosive nature of lead. The alkali values are likewise variable. Reduced and normalised soda contents range from about 10% to 19%, magnesia from 0.7% to 3.9% and potash from 0.9% to 3.3%. These variations in terms both of the silica and the alkali sources demonstrate that the production of opaque white glass was not standardised. Instead, different recipes and different raw materials underlie the lead-tin opaque glass weights analysed in our study.

The very low manganese content (median MnO < 0.03%) of most opacified glass weights accentuates the unique character of the opaque glass weights in relation to the other plant ash glass groups (Fig. 20c). Considerable amounts of manganese (MnO > 0.5%) are present particularly in the Mesopotamian, Levantine and E1 groups, and to a lesser extent in the E2 glasses, suggesting its deliberate addition to these glasses independent of the final colour. The addition of manganese during the early Islamic period appears to have been a practice related to primary glassmaking, as evidenced by the data from the primary glassmaking furnaces at Tyre (Freestone 2002) and the workshop at Baniyas (Freestone *et al.* 2000; Freestone *et al.* 2003a) and Raqqa (Henderson *et al.* 2004). The absence of manganese in the lead-tin opacified glass weights therefore provides further evidence that they represent a distinct production. It has been stated that the use of manganese increased during the early Islamic period, and that notable contents of MnO are typical of Islamic glasses (Swan *et al.* 2017, and references therein). Contrary to these observations, our weights data demonstrate that most of the glasses of group E4, for instance, do not contain significant levels of manganese oxide (MnO < 0.5%). Manganese does not appear to be systematically elevated either in the natron-type Egypt 1 and Egypt 2 glasses or in the plant ash glasses from Egypt (e.g. E3, E4). The use of manganese in Islamic plant ash glass may be related to geographical, chronological and/or technological variations that require further investigation.

Trace element discriminants of Egyptian glass

Classifying early Islamic plant ash glasses from Egypt into distinct compositional groups derived from regionally distinct raw materials continues to be one of the most complex and difficult of tasks, given the high variability and distinct shortage of comparative data on plant ash glass of proven provenance. As a result, the majority of the evidence is circumstantial and exclusive rather than inclusive. Provisional conclusions can be drawn based on the differences in glass assemblages from sites in Syria-Palestine and Mesopotamia, as well as the compositional characteristics of Egyptian natron-type glass. The pre-Islamic compositional groups from Egypt (Roman Sb, Foy 3.2, HIMT, Foy 2.1, Magby) have been relatively well established and are known to have high zirconium and titanium contents as well as specific hafnium isotope signatures, which can be ascribed to silica sources determined by the sediments of the River Nile that are characterised by clinopyroxene and amphibole originating from the volcanic rocks of the Ethiopian plateau (Barfod *et al.* 2020; Degryse 2014; Freestone *et al.* 2009a;

Nenna 2014). Thorium to zirconium and lanthanum to titanium ratios in particular have proved successful in separating Egyptian from Levantine natron glass. These findings can be extrapolated to plant ash glass reliably to identify an Egyptian origin (Fig. 18). Defining a clean threshold between plant ash E1 and contemporary Levantine plant ash glass, however, remains challenging, because of their similar zirconium to titanium ratios, owing presumably to the Nile-derived sediments that have an effect also on the eastern Mediterranean coastline from Egypt to Israel and beyond (Barfod *et al.* 2020; Degryse 2014). Hence, the determination of compositional differences requires a combination of several elements (Al, Ti, Zr, La, Th) and especially their normalised fractions (ratios). Similarities between the E1-E4 plant ash glass groups and their compositional resemblance to some of the natron-type categories (HIMT, Egypt 1, Foy 2.1), which strongly differ from the published data on glass assemblages affiliated with Levantine and Mesopotamian glassmaking, corroborate the existence of a common, most likely Egyptian origin for the raw materials used in their production.

Even though these compositional parameters seem to provide an effective way of differentiating between Egyptian plant ash glasses, further work and more trace element and isotopic data are required to fully understand the range of variability of Egyptian (and other) plant ash glasses and the implications of these variations in terms of the scale and location of production. The elevated boron levels of plant ash group E2, for example, suggest the adoption of a different recipe in terms of the alkali fluxing agent in addition to a silica source distinct from the other groups. Plant ash group E4 has exceptionally high mineral contaminants, pointing to the rather indiscriminate use of ‘dirty’ silica sources. The so-called quartz group, in contrast, is fairly clean and an affiliation with any of the glass production regions is consequently almost impossible. More data are needed to further refine these groups.

Egyptian glass and its market

The compositional data on glass assemblages contain information not only about the possible provenance but also about the extent of the markets, and, by extension, changes in trading networks. Detecting and quantifying changes in the Egyptian glass industry over time hinge on the quantity and reliability of the archaeological and compositional evidence to make sure that the data are sufficiently representative of the general trends in the production and circulation of individual glass groups. The number of data from the Roman and late antique periods is considerable, but we still do not have an equivalent number of data for the early Islamic period. Hence, the conclusions drawn from the Roman and late

antique material are inevitably more robust than for the early Islamic period, but some valid interpretations can be advanced nonetheless.

There can be no doubt about the large-scale and centralised nature of the glass industry in Egypt from the first to the fourth centuries CE. While the production and distribution of Roman antimony-decoloured glass may have been restricted and attached to luxury glassware in the first century CE, its use diversified and dominated a global glass market in the second and third centuries CE. We notice a transformation of the primary glassmaking industry in the fourth century with the appearance of new glass types in Egypt, first in the form of the comparatively clean Foy 3.2 type, where manganese replaced antimony as the main decolouring agent. More or less simultaneously, the abundant HIMT group appears with much higher levels of impurities and a distinct yellow-greenish colour. HIMT glass was traded widely and has been found both as raw glass chunks as well as finished objects throughout the Mediterranean and Europe, with the exception of the Levantine coast. It was by far the most prevalent glass used in the fourth to fifth centuries from Great Britain to Spain, from Sicily through Tunisia to Asia Minor. The prominent yellow-greenish colour of HIMT has been associated with market forces and the principles of commodity branding (Freestone *et al.* 2018), but it may also reflect a shift in aesthetic preferences. Different variants of the Foy 2 family (Foy 2.1, Foy 2.1 high Fe, Magby) followed in the fifth and sixth centuries. All of these late antique glass groups still fed an international, Mediterranean-wide glass market, which suggests that the scale of production continued to be substantial and oriented towards export.

The most significant change, however, came with the Arab conquest of Egypt and the Levant. The eighth- and ninth-century natron-type glass groups Egypt 1 and Egypt 2 were still produced on an industrial scale, but the geographical distribution of these early Islamic glasses is severely reduced. Only a very few isolated fragments of Egypt 1 and Egypt 2 base glass have thus far turned up in the western Mediterranean (e.g. Spain, Sicily, Italy). At the same time, enormous quantities of Egypt 1 and Egypt 2 were evidently exported to the Levant and Syria (Adlington *et al.* 2020; Phelps *et al.* 2016). The establishment of Damascus as the capital of the Umayyad Caliphate apparently realigned the gravitational forces of the empire and reoriented exchange patterns and the movement of goods within the eastern Mediterranean, making Greater Syria the core economic region. This is not to say that long-distance connections no longer existed, but the international trade in bulk glass seems to have contracted considerably between the seventh and the ninth centuries CE in favour of more regional trading networks.

The disintegration of the Abbasid rule in Egypt at the end of the ninth century seems to have dealt a near death blow to the glass industry; at least this is what the evidence from the glass weights suggests. It is not clear to what extent the technological changes and recipes of glassmaking were linked causally or merely incidentally to the complete transformation of the early Islamic social orders and state bureaucracy. The early Islamic state had inherited from the Roman and Sasanian Empires the sophisticated fiscal system of public taxation which ensured economic prosperity and stability (Kennedy 2015). This system of public taxation effectively collapsed in the first half of the tenth century CE, an event which had a profound impact on the political and social orders (Kennedy 2010). After 870 CE, the much reduced and fragmented Abbasid caliphate led to the emergence of a new elite, no longer loyal to the imperial centre in Samarra or Baghdad, but to local entities (Kennedy 2004). In Egypt this fragmentation resulted in the virtually independent Tūlūnid emirate (868-905 CE). From the first year of his appointment as deputy governor of Egypt in 868 CE, Ahmad ibn Tūlūn issued a number of commodity weights and vessel stamps but seemingly no coin weights (Balog 1976; Ollivier 2019). The Tūlūnids apparently still recognised the caliphal prerogative to control the production of coinage (Ilish 1979; Treadwell 2017). Tūlūnid coins issued at Fustat, Ramla, Aleppo, Antioch and possibly Damascus were accordingly struck in the name of the Abbasid caliph (Bianquis 1998). The absence of glass coin weights from the archaeological record of Egypt seems to imply that they too may have required caliphal authority.

Large quantities of glass weights are known again from the Fatimid period when they were produced from plant ash glass, at least half of which was imported from the Levantine coast. The compositional data on the Egyptian glass weights and the archaeological evidence from the primary glassmaking centre at Tyre (Freestone 2002; Phelps *et al.* 2016) suggest that the production of early Islamic plant ash glass was again occurring on a relatively large scale and targeted on export markets. The Cairo Geniza documents offer an additional source of information that a large shipment of glass was sent from Tyre to Fustat at the beginning of the eleventh century CE (Gil 1997). Similarly, the cullet and raw glass (1 ton of cullet, 2 tons of raw glass) recovered from the eleventh-century merchant ship sunk off the southwest coast of Turkey known as Serçe Limani (Bass *et al.* 2009) attest to the bulk exchange of vitreous material and to the Levantine coast as the most likely point of departure (Brill 2009; Henderson *et al.* 2020). In summary, the evidence from Palestine largely demonstrates the continuity of a centralised large-scale model of primary glass production and far-flung international trade at least until the eleventh century CE (Phelps 2018).

The situation of the glass industry in Egypt in the tenth century is less clear as no primary production sites are documented and because of the 100-year gap between the Tūlūnid and Fatimid periods. The chemical composition of a fragment of a large dark blue ring weight (VStras 119) which bears the name of Ahmad ibn Tūlūn and the precise date of the year 868 CE still represents the old natron glassmaking tradition of the Egypt 2 type (Schibille *et al.* 2019). The final replacement of natron by plant ash as the main fluxing agent had evidently not yet taken place in Egyptian glassmaking. Unfortunately, no compositional data on glass weights or stamps from the later Tūlūnid period, the Abbasid interlude (905-935 CE) or the Ikhshīdids dynasty (until 968 CE) are currently available. The exact point in time when plant ash glassmaking took hold in Egypt can therefore not be determined with any precision. The Fatimid glass weights represent the earliest securely dated plant ash glasses the Egyptian provenance of which seems reasonably certain. Although some of the E1 plant ash glasses show signs of recycling, they nonetheless form a relatively coherent compositional group indicative of a single source. Supply diversifies in the eleventh century, when the glass weights exhibit much greater compositional variability and considerable levels of mineral impurities. This reveals a significant transformation of the organisation of primary (and possibly secondary) glassmaking in Egypt and a shift away from a single source of raw glass to multiple suppliers which probably operated on a much smaller scale. Fluctuations in the composition of glass are necessarily the result of a reduced scale of production of plant ash glass that is inherently more variable than natron-type glass due to the variability of the ash component. The heterogeneity of the compositional make-up of Egyptian plant ash glass assemblages may thus be a reflection of the changing nature and scale of the primary production of glass. The cause of these changes may not be a simple reorganisation of the glass industry, but may be the direct result of more global geopolitical and economic changes in the eastern Mediterranean.

Islamic glassmaking in Greater Syria (Bilâd al-Shâm): distribution patterns

The developments of the glass industry and trade in vitreous materials in Greater Syria, formerly the diocese of *Oriens* recast as Bilâd al-Shâm, followed patterns different from those in Egypt, although there are also some significant similarities. The technological and economic transformations need to be seen against the historical background of the Bilâd al-Shâm that was to become the political centre of the Umayyad Caliphate with Damascus as capital, and the decentralised nature of the Umayyad administration (Walmsley 2000). No new towns were founded in Greater Syria immediately after the Muslim conquest, and the new Muslim elites took up residence in the urban centres and estates left behind by the Byzantines, who had fled to Constantinople (Kennedy 2007, pp. 95-97). This meant that many of the old urban centres, such as Damascus, Aleppo and Jerusalem, survived and often even thrived after the Muslim conquest (Kennedy 1992). At the same time, many of the coastal cities (e.g. Antioch, Beirut, Tyre) that had already been in decline long before the Muslim invasions fully recovered only in the Fatimid period after 969 CE (Kennedy 1985; Kennedy 1992). The gradual decline of the coastal towns may underlie a Mediterranean-wide trend of dwindling numbers of shipwrecks from the middle of the fourth century onwards, as indicated in Andrew Wilson's evaluation of the chronological distribution of Mediterranean shipwrecks (n=1646; Wilson 2009). Far from implying an acute economic downturn, however, zooming into regional patterns and counting shipwrecks off the southwest coast of Turkey have revealed more localised economic phenomena and a period of economic growth and prosperity from the second half of the fourth through to the early seventh centuries CE (Leidwanger 2017). This dramatic surge in economic maritime activities in the eastern part of the Mediterranean has been attributed to the foundation of Constantinople as the new capital of the Roman Empire which must have greatly affected the flow of resources (Leidwanger 2017). It seems likely that the establishment of Damascus as the capital of the Umayyad Caliphate (c. 661 – 750 CE) had a similar effect on the economy and on

maritime trade networks. In particular, the commercial activities between Egypt and Syria-Palestine appear to have flourished in the seventh century and continued to do so well into the eighth century CE (Reynolds 2018; Walmsley 2007a). The implementation of a unified monetary system at the end of the seventh century may also have had a beneficial impact on trade and exchange. ‘Abd al-Malik’s monetary reforms which included the opening of a mint in Damascus in 691 CE and the introduction of a new weight standard (4.25 g for the dinar compared to 4.5 g for the earlier gold solidus) in 696 CE shifted the structures and dynamics of the monetary economy considerably. The new, lighter all-epigraphic gold coin, the dinar, almost immediately supplanted the solidus, thus creating an empire-wide Muslim currency and unifying the Umayyad Caliphate into a single currency zone, which up to this point had been divided into a Byzantine (Greater Syria) and Sasanian (Mashriq) system (Bacharach 2010; Treadwell 2009; Walmsley 2007a). The new currency no doubt facilitated the wider movement of coinage and interregional transactions, which may have benefited economic expansion and commercial contacts (Treadwell 2009; Walmsley 2000; Walmsley 2007a).

Glassmaking and glass-working in the Bilâd al-Shâm – the archaeological evidence

Our knowledge of glass production in Greater Syria during the late antique and early Islamic periods is appreciably better than that of Egypt mainly due to ongoing research initiatives and rescue excavations by the Israel Antiquities Authorities (see publications by Yael Gorin-Rosen). A number of primary production installations dating from the Roman imperial period to the eighth century CE were discovered. Evidence for the primary production of glass was found in Beirut (Lebanon) in the form of tank furnaces that were dated to the Hellenistic and early Roman period (first century BCE – first century CE; Henderson 2013; Kowatli *et al.* 2006). However, there is considerable doubt about this early dating (M.-D. Nenna, personal communication). As regards the late antique and early Islamic periods, several primary production centres have been archaeologically recorded in Israel (Fig. 2). Recently, the manufacture of raw glass was confirmed at fourth-century Jalame (Gorin-Rosen conference presentation) and excavations at Apollonia have yielded the remains of four tank furnaces dating to the sixth to seventh centuries CE (Freestone *et al.* 2008b; Tal *et al.* 2004). The remnants of 17 tank furnaces dedicated to the primary production of glass with capacities of eight to ten tons each were discovered at Bet Eli‘ezer near Hadera (Freestone *et al.* 2000; Gorin-Rosen 1995; Gorin-Rosen 2000). Their activity is attributed to the eighth century CE (Brems *et al.* 2018). At the nearby site of Horbat Biz’a,

further evidence of primary and secondary production was recently identified, dating to the late antique and early Umayyad periods (Gorin-Rosen 2012). All these furnaces seemingly produced large quantities of natron-type glass. Evidence for the primary production of plant-ash glass is known from the excavation of four tank furnaces at Tyre dating to the tenth to eleventh centuries (Aldsworth *et al.* 2002; Freestone 2002) and from the debris and furnace floor fragments discovered at eighth- to ninth-century Raqqa (Henderson 1999; Henderson *et al.* 2005a; Khalil and Henderson 2011). A failed glass slab of about nine tons that was discovered *in situ* in Bet She'arim may in fact represent an early attempt to mix a Levantine coastal sand (rich in calcareous material) with plant ash as the fluxing agent, and it is now generally dated to the ninth century CE (Freestone and Gorin-Rosen 1999). Some of the primary glassmaking centres were associated with secondary glass workshops such as at Jalame (Brill 1988), Apollonia (Freestone *et al.* 2008b; Tal *et al.* 2004), Horbat Biz'a (Gorin-Rosen 2012), and Raqqa (Henderson 1999; Henderson *et al.* 2002; Henderson *et al.* 2004; Henderson *et al.* 2005a). Secondary workshops at some distance from primary production sites have likewise been documented, for instance, at Ramla (Tal *et al.* 2008), Bet Shean (Gorin-Rosen 2000), Tel Aviv (Freestone *et al.* 2015b) and at Beit Ras/Capitolias in northern Jordan (Abd-Allah 2010).

A wealth of chemical and isotopic data has also been generated in the last two decades from vitreous materials collected from primary production sites in Syria-Palestine as well as some secondary workshops and consumer sites. The growing body of data from primary workshops has allowed us to refine the geochemical characteristics of glasses produced in Greater Syria and to trace the distribution patterns of raw glass by way of comparison with these established primary production groups. However, we should note that the melt of a single large primary furnace has been shown to be compositionally remarkably heterogeneous (Brems *et al.* 2018; Freestone *et al.* 2008b; Tal *et al.* 2004). Secondary glass-working processes can at the same time bring about compositional changes due to contaminations, the mixing of different raw glasses and/or cullet, and the potential loss of volatile elements (Freestone 2015; Paynter 2008; Tal *et al.* 2008). Hence, as emphasised by Ian Freestone (Freestone *et al.* 2015b), the study of materials from secondary workshops contributes important additional information about what caused these changes, the nature of supply in the secondary glass-working stage and the scale of production. For example, with respect to a refuse deposit associated with the seventh- to eighth-century secondary glass workshop in Tel Aviv, Freestone and colleagues identified three well-defined raw glass types that were apparently worked in the same workshop with minimal mixing and recycling between them (Freestone *et al.* 2015b). This may reflect changing supply lines

and/or the ability of the glass workers to distinguish clearly between the different primary production groups used simultaneously in the same workshop.

Roman and late antique glass groups of Levantine origin

Roman manganese-decoloured and naturally coloured glass

The compositional data on the glass from the primary furnaces in Beirut have unfortunately not been published in full. With about 67.7% – 73.7% SiO₂, 15.3% – 19.5% Na₂O, 7.2% – 8.6% CaO, 0.4% – 1% K₂O, 0.4% – 0.7% MgO, and 2.2% – 2.6% Al₂O₃ (Bradford *et al.* 2018) its averaged composition appears to correspond to a natron-type base glass made from a relatively pure silica source typical of the Levantine coast and a mineral natron as the fluxing agent. In fact, most of the Roman naturally coloured or manganese-decoloured glass is thought to have been produced in Syria-Palestine (Degryse 2014), in contrast to Roman antimony-decoloured glass, the Egyptian origin of which has now been firmly established (Barfod *et al.* 2020).

What follows is a brief discussion of Roman and late antique glass groups manufactured in the Levant. Defining clean groups of Roman manganese-decoloured and naturally blue green glasses proves more difficult than in the case of the Roman antimony-decoloured glass due to the limitations of published data. The sensitivity of some of the analytical techniques that were applied to glass assemblages is often not sufficient to detect small quantities of antimony, given that the threshold above which antimony indicates contamination through recycling or mixing is in the order of 30 ppm. Therefore, the selection criteria could not always be applied as stringently as originally hoped. Moreover, in order to augment the number of samples, some of the *Mn* and *low Mn* samples of Jackson and Paynter (2016) were included in this group despite having antimony oxide contents of about 75 ppm (Sb₂O₅ = 0.01%). It was deemed that this level of contamination would not significantly alter the properties of the base glass. These samples were thus added to obtain a larger dataset and more reliable and representative average values for the base glass. In contrast, samples with suspiciously low alumina (Al₂O₃ < 2%) and/or high titanium oxide (TiO₂ > 0.12%) were excluded from the selection of published data of Roman Levantine glass, broadly defined to include material from the first to fourth centuries CE (Degryse 2014; Gratuze 2018; Jackson and Paynter 2016; Schibille and Freestone 2013; Schibille *et al.* 2017; Silvestri *et al.* 2005; Silvestri 2008; Silvestri *et al.* 2008). Applying these criteria, we are left with a group of 239 samples of mostly colourless and weakly coloured glasses with varying contents of manganese oxide

(0.01% – 2.3%). They exhibit more or less identical base glass compositions and are thus probably made from the same or closely related glassmaking sand. The average major and minor element composition is given in table 4. Compared to Roman antimony-decoloured glasses, the Roman Levantine samples tend to have lower soda, higher lime and alumina and on average higher potash levels (Fig. 21). These characteristics suggest the use of a silica source relatively rich in feldspar and poor in heavy minerals, like the famous Belus river sand that was said to have been exploited in Levantine glass production (Brill 1988; Freestone and Gorin-Rosen 1999; Freestone *et al.* 2000).

Glass group	Date	Na ₂ O	MgO	Al ₂ O ₃	SiO ₂	P ₂ O ₅	Cl	K ₂ O	CaO	TiO ₂	MnO	Fe ₂ O ₃	Sr	Zr
Roman Mn (138 < n < 239)	1 st – 4 th	16.1	0.54	2.62	69.6	0.13	1.1	0.65	7.92	0.07	0.74	0.4	425	37.4
	stdev	1.3	0.10	0.24	2.3	0.04	0.18	0.23	0.76	0.02	0.56	0.15	62	10.7
Jalame (n=50)	4 th	15.7	0.59	2.73	69.9	0.14		0.78	8.74	0.09	0.65	0.44	567	51.7
	stdev	0.9	0.12	0.17	1.6	0.03		0.13	0.67	0.02	0.94	0.19	83	100
Apollonia (n=30)	6 th – 7 th	14.2	0.68	3.25	71.2	0.05	0.81	0.62	8.43	0.09	0.02	0.50	444	44.9
	stdev	1.1	0.28	0.18	1.4	0.03	0.09	0.19	0.79	0.02	0.005	0.11	66	6.1
Bet Eli‘ezer (26 < n < 79)	8 th	12.3	0.59	3.38	74.4	0.07	0.68	0.48	7.35	0.11	0.02	0.69	389	44.4
	stdev	1.2	0.13	0.3	1.5	0.02	0.07	0.08	0.7	0.03	0.004	0.24	34	8.5

Table 4:

Averages and standard deviations of Roman and late antique glass groups from the Levant. Major and minor oxides and chlorine are given in [wt %], Sr and Zr are given in [ppm]. Data sources: (Degryse 2014; Gratuze 2018; Jackson and Paynter 2016; Schibille *et al.* 2012; Schibille *et al.* 2017; Silvestri *et al.* 2005; Silvestri 2008; Silvestri *et al.* 2008) for Roman Mn; (Brill 1999) for Jalame; (Brems *et al.* 2018; Freestone *et al.* 2008b) for Apollonia; (Brems *et al.* 2018; Freestone *et al.* 2000; Freestone *et al.* 2015b; Phelps *et al.* 2016) for Bet Eli‘ezer.

The use of a coastal sand from the eastern Mediterranean is further supported by the strontium and neodymium isotope signatures. Strontium and neodymium isotopic data are available for 73 of the samples from the Roman Lev group as defined above (Barfod *et al.* 2020; Degryse 2014). The ⁸⁷Sr/⁸⁶Sr ratios vary from 0.70858 to 0.70932, with the majority of samples just below the value of present day seawater (⁸⁷Sr/⁸⁶Sr = 0.709165 +/- 0.000020 indicated by a dashed line in Fig. 22; Stille and Shields 1997). Hence, the strontium isotopic values are consistent with Holocene seashell being the main source of lime in these Roman glasses (Brems *et al.* 2018; Freestone *et al.* 2003a; Freestone *et al.* 2009a). The minor variations in the strontium isotope data may be attributed to slightly different proportions of limestone and seashell in the sand source (Degryse and Schneider 2008; Freestone *et al.* 2003a; Freestone *et al.* 2009a) and/or contamination by

the furnace environment (Brems *et al.* 2018; Chen *et al.* 2021). The neodymium isotopic ratios (ϵ_{Nd}) range from -6.6 to -3.8 (Fig. 22) and are likewise broadly consistent with the use of Levantine sand sources. Neodymium isotopes of 16 beach sand samples collected along the Levantine coast (Degryse 2014; Henderson *et al.* 2020) are distributed between $\epsilon_{Nd} = -1$ to $\epsilon_{Nd} = -7$ (Fig. 22). These considerable variations may be explained by climatic fluctuations and dilution phenomena (Degryse *et al.* 2010a; Freestone *et al.* 2009a).

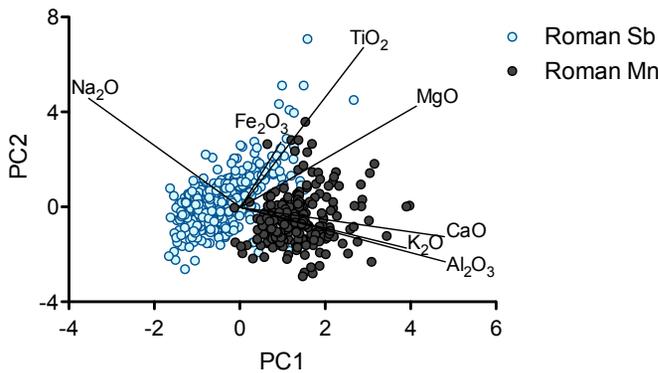


Fig. 21:

Principal component analysis (PCA) of Roman naturally coloured and Mn-decoloured glass from the Levant in comparison with Roman Sb decoloured glass. Data sources: (Degryse 2014; Gratuze 2018; Jackson and Paynter 2016; Schibille *et al.* 2012; Schibille *et al.* 2017; Silvestri *et al.* 2005; Silvestri 2008; Silvestri *et al.* 2008) for Roman Lev; (Baxter *et al.* 2005; Degryse 2014; Gratuze 2018; Jackson 2005; Paynter 2006; Silvestri 2008; Silvestri *et al.* 2008) for Roman Sb. Please note that the coefficient vectors are given on an enlarged scale (10x).

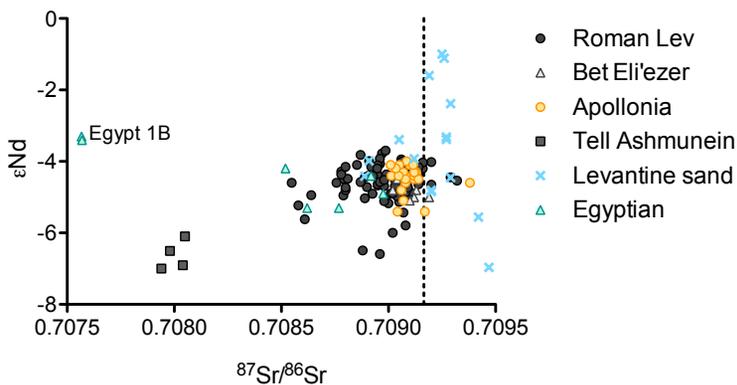


Fig. 22:

Strontium and neodymium isotopic composition of 73 glasses from the Roman Lev group in comparison with data from the furnaces at Apollonia and Bet Eli'ezer as well as Tell Ashmunein. Data sources: (Degryse 2014) for Roman Lev group; (Brems *et al.* 2018) for Apollonia, Bet Eli'ezer and Tell el-Ashmunein; (Barfod *et al.* 2020) for Egyptian glass, including Roman Sb, Foy 2.1 and Egypt 1B & 1C; (Brill and Stapleton 2012; Degryse and Schneider 2008; Degryse 2014; Henderson *et al.* 2020) for sand sources from the coastal regions. The dashed vertical line marks the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio at 0.709165 of present day seawater.

For comparative purposes, strontium and neodymium isotopic data from the tank furnaces at Apollonia and Bet Eli‘ezer as well as the eighth- to ninth-century secondary glass workshop at Tell el-Ashmunein in Egypt (Egypt 2) were included (Brems *et al.* 2018; Freestone *et al.* 2003a; Freestone *et al.* 2009a), as were recently published data on some Roman antimony-decoloured, Foy 2.1 and Egypt 1 samples (Barfod *et al.* 2020). These additional neodymium and strontium isotope data qualify the variability of the Roman Mn glasses. Both Egypt 1B and Egypt 2 (Tell el-Ashmunein) have significantly lower $^{87}\text{Sr}/^{86}\text{Sr}$ ratios, which in the case of Egypt 2 is indicative of limestone as the main source of calcium (Brems *et al.* 2018; Freestone *et al.* 2003a; Freestone *et al.* 2009a). The low strontium ratios of Egypt 1B are somewhat surprising since the Sr/CaO ratios are relatively high and consistent with the use of a shell-bearing coastal silica source (see previous chapter). There are hardly any differences in the ϵ_{Nd} signatures of all natron glasses from Egypt and the Levant due to the use of Nile-derived sand sources (Fig. 22). The sand sources collected from the semi-desert area in Syria, by contrast, have substantially lower ϵ_{Nd} signatures reflective of geologically older silica sources of continental origin (Henderson *et al.* 2020). The investigation of hafnium isotopes has recently been shown to be an effective way of differentiating between Egyptian (Roman Sb, Foy 2.1, Egypt I) and Levantine glasses (Roman Mn, Jalame, Apollonia) (Barfod *et al.* 2020), providing conclusive evidence for the use of different silica sources and thus different primary production locations. This confirms the interpretation that the Roman Mn and naturally coloured glasses, along with the glass from Jalame and Apollonia, were made using sands from the Levantine coast. It should be kept in mind, however, that there are altogether only limited isotopic data available, and the implications of regional variations are therefore not yet fully understood.

The glass from fourth-century Jalame

Thirty years ago, the study of the vitreous material from the glass factory at Jalame provided the most comprehensive set of data on glass produced on the Levantine coast, using sand from the nearby Belus River in the Bay of Haifa (Brill 1988). A primary production furnace has recently been discovered, confirming that Jalame was indeed a primary as well as secondary glassmaking site (Phelps *et al.* 2016). The fourth-century glass from Jalame has often been conflated with the material from the primary glassmaking factories at Apollonia, probably dating to the sixth and seventh centuries, into the so-called Levantine I group (Freestone *et al.* 2000). Ian Freestone suggested that glass production in the region around Apollonia may have replaced that in Jalame as early as in the fifth century CE (Freestone 2020).

The two compositional groups have since been disentangled into distinct primary production categories based mainly on differential calcium to aluminium, and soda to silica ratios (Phelps *et al.* 2016). In fact, the Jalame glass cannot easily be distinguished from the Roman Levantine group in terms of the major and minor elements. However, allowing for a significant chronological overlap between the Roman glasses and the assemblage from Jalame, the average compositions indicate a general decline in soda contents and an increase in potash, lime and possibly alumina levels from the earlier Roman Mn and naturally coloured glass to the fourth-century glass from Jalame (Table 4; see also Freestone 2020). The most obvious difference between the two chronological groups is the lime concentration which in Jalame is considerably higher than in the average Roman Mn glass.

Late antique Apollonia glass – Levantine I

The decline in soda concentrations and the augmentation of aluminium oxide values relative to the silica content become more pronounced in the glasses from the sixth- to seventh-century primary glass furnaces at Apollonia (Fig.23). The glass from Apollonia has on average about 1% - 2% less soda than Jalame and Roman Levantine glass (Table 4). The Jalame and Apollonia glasses can be distinguished on the basis of their lime to alumina and soda to silica ratios (Phelps *et al.* 2016), which further underscore the similarities between the Roman Levantine group and Jalame glass (Fig. 23a). The close relationship between the Roman and Jalame assemblages may ultimately not be surprising, since the two groups overlap chronologically, and a better temporal resolution and full range of minor and trace elements would be required to delineate the Roman Levantine glasses more precisely. The main difference between Apollonia and the two earlier glass groups is the higher alumina content, while the lime and silica levels as well as the heavy mineral concentrations remain largely unchanged over time (Table 4). These variations relate to the carbonate and feldspar fractions of the silica source used as raw material and their relative proportions in the sand. The lower soda levels, on the other hand, are indicative of different mixing ratios of network former to fluxing agent. The general compositional characteristics of the three Levantine groups can thus be described and to some extent distinguished, but this applies only to the groups as a whole and not to individual samples. Assigning a single data point to one of the Levantine glass groups remains a challenge.

Another distinguishing feature between the glass from the primary production centre at Apollonia and the Jalame and Roman groups is the presence or absence of manganese oxide. Both the Roman and Jalame glass populations contain concentrations of manganese that are systematically above the natural impurity

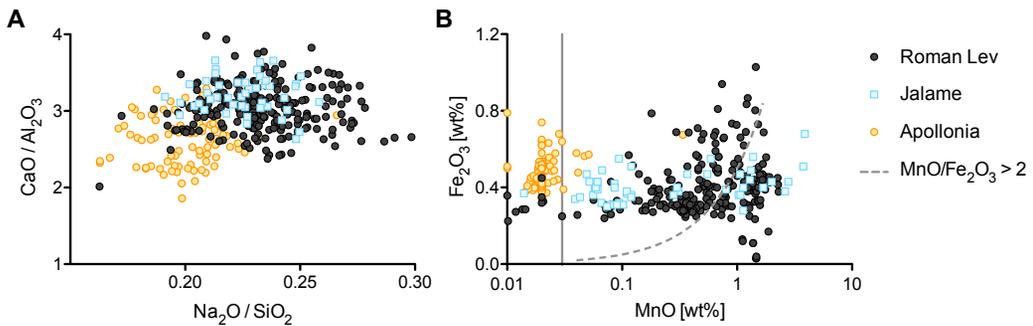


Fig. 23:

Apollonia glass in comparison with Roman Levantine and Jalame assemblages. (a) CaO/Al₂O₃ versus Na₂O/SiO₂ separates the Apollonia glasses clearly from both the Jalame and Roman glass groups, the main difference being the higher alumina contents of the Apollonia glass compared to the earlier glass groups; (b) iron compared to manganese oxide levels of the Roman, Jalame and Apollonia glasses. Vertical line at MnO = 0.03% indicates the cut-off between natural impurities of the raw materials and contaminations through recycling. The curved line corresponds to MnO/Fe₂O₃ = 2 as a guideline above which manganese becomes effective as a decolourant according to (Silvestri *et al.* 2005). Data sources: (Degryse 2014; Gratuze 2018; Jackson and Paynter 2016; Schibille *et al.* 2012; Schibille *et al.* 2017; Silvestri 2008; Silvestri *et al.* 2008) for Roman Lev; (Brill 1999) for Jalame; (Brems *et al.* 2018; Freestone *et al.* 2008b; Phelps *et al.* 2016) for Apollonia.

levels of silica sources (MnO > 0.03%). By contrast, none of the Apollonia primary raw glass chunks shows an elevated manganese (or antimony) content (Fig. 23b). More specifically, the majority of the Jalame glasses have manganese oxide concentrations that exceed the background (sand) levels (MnO > 0.03%), but are below the threshold where it can be considered an effective decolourant (indicated by the dashed curve in Fig. 23b). These low concentrations of manganese do not necessarily indicate its intentional use as decolourant, but rather suggest recycling and the incorporation of some manganese-containing cullet. Only 15 out of 50 samples from Jalame qualify as manganese-decoloured glasses by having MnO/Fe₂O₃ > 2. Proportionately more samples belonging to the Roman group (a third to half of the glasses) have levels of manganese oxide indicative of its deliberate addition as decolouring agent. The decline in the use of manganese as decolourant in Levantine glass production sometime in the fourth or fifth century has already been observed by Foy and colleagues (Foy *et al.* 2003b), who found that manganese is no longer present in Levantine glass after the fifth century CE. The proportional differences between the Roman and Jalame glasses suggest that this trend is noticeable already in the fourth century. The absence of manganese can therefore serve as an additional marker for glass from Apollonia (Freestone 2020).

The glass from the Apollonia tank furnaces has been extensively characterised in terms of its geochemical and isotopic characteristics in the scientific literature (Brems *et al.* 2018; Freestone *et al.* 2000; Freestone *et al.* 2008b; Freestone 2020; Phelps *et al.* 2016; Tal *et al.* 2004). The 30 samples from different contexts in Apollonia considered here range between 12-16% soda and 68-74% silica, about 3-3.6% alumina and 7-11% lime (Table 4). Apollonia-type Levantine glasses have turned up in the archaeological record across the entire Mediterranean region, from Jordan (Abd-Allah 2010; Al-Bashaireh *et al.* 2016; Barfod *et al.* 2018), numerous consumer sites in Israel (Freestone *et al.* 2008b; Phelps *et al.* 2016; Tal *et al.* 2008), Cyprus (Ceglia *et al.* 2015; Ceglia *et al.* 2019; Freestone *et al.* 2002b), Turkey at Labraunda (unpublished data), France (Cabart *et al.* 2017; Lassaunière *et al.* 2016; Pactat 2013) and the Iberian Peninsula (De Juan Ares *et al.* 2019a). Virtually pristine Apollonia-type Levantine I glass emerged as the main glass supplied to sixth- and seventh-century Visigothic Spain (De Juan Ares *et al.* 2019a). Surprisingly, a survey of published data on glass finds from the Italian peninsula identified only a few individual samples that can be confidently assigned to the Apollonia type of the sixth and seventh centuries (e.g. Schibille *et al.* 2018b). About six samples from Grado on the northern Adriatic coast (Silvestri *et al.* 2005) match the Apollonia primary production group. There may also be a small number of recycled Apollonia-type glasses among the assemblage from Santa Maria della Scala in Siena (Hellemans *et al.* 2019), from Piazza Bovio in Naples (De Francesco *et al.* 2014), a glass workshop in Catania (Di Bella *et al.* 2015) and a very few mosaic tesserae from Naples (Schibille *et al.* 2018b, and references therein). Some Apollonia-type natron glasses were among the vitreous finds from medieval Sicily, mostly from Palermo and Castronovo, and seventh- to eighth-century Mazara del Vallo on the western coast of Sicily (Schibille and Colangeli 2021). In contrast, the earlier glasses of Syro-Palestinian origin, including Roman Mn, naturally coloured and, to a lesser extent, Jalame-type glasses are relatively abundant throughout Italy (e.g. Gliozzo 2017, and references therein).

The discrepancy in the relative quantities of Levantine glasses in Italy suggests changing supply patterns between the fourth/fifth and sixth centuries. In his doctoral thesis Matt Phelps has noted a difference in the distribution of earlier Levantine glasses compared to glass of the Apollonia production group, stating that during the (late) Roman period Levantine glass was ubiquitous throughout the empire, but that its distribution in the fifth and sixth centuries was more limited to the eastern Mediterranean (Phelps 2017, pp. 97-98). At the time no late antique glass assemblage from the Iberian Peninsula had been analysed. In Iberia we found a preponderance of Apollonia-type Levantine I glass starting around the middle of the sixth century CE (De Juan Ares *et al.* 2019a). The dominance of Levantine glass is particularly

marked in Visigothic contexts in the last quarter of the sixth and first quarter of the seventh centuries CE, but is apparently sustained until the end of the seventh, possibly as late as the early eighth century CE. Similar supply patterns are also emerging in Sicily (Schibille and Colangeli 2021), and Apollonia-type Levantine I glass was used in France until the eighth century CE (Pactat 2020). It thus appears to be less a matter of a difference between the eastern and the western Mediterranean, than of the existence of a variegated patchwork of supply routes connecting different regions that were no longer united in a common Mediterranean-wide empire. One possible reason for the lack of sixth- to seventh-century Apollonia-type Levantine glass in mainland Italy is that the peninsula may simply have been an extensive repository for Roman glass, which was systematically and extensively recycled during the late antique and medieval periods. This is certainly something that was observed in relation to the reuse and recycling of Roman mosaic tesserae in various medieval contexts (Schibille and Freestone 2013; Schibille *et al.* 2018b) even in the city of Rome itself. In contrast, the Visigothic city of Recópolis, located on the river Tajo in the province of Guadalajara, Castilla La Mancha, was not founded until 578 CE (Olmo Enciso 2008). Here, Levantine glass makes up practically all the vitreous finds collected from workshop 1 which is contemporaneous with the foundation of the city of Recópolis and which was active until the middle of the seventh century CE (unpublished data). The Levantine samples retrieved from workshop 2, dated a little later to the seventh century, mostly show signs of recycling. Thus, in order to furnish the newly founded city with vitreous materials one or more shipments of new raw glass appear to have been imported to Recópolis in the last quarter of the sixth century. Fresh glass may still have arrived in the seventh century, but the archaeo-vitreous record of Iberia increasingly exhibits signs of recycling (see chapter 4).

The previous sections have outlined the general trends in the primary production of glass on the Levantine coast prior to the Arab conquest which began in 634 CE (Kennedy 2007). In the absence of a more precise dating of the Apollonia tank furnaces which are broadly dated to the sixth to seventh centuries (Freestone *et al.* 2008b; Tal *et al.* 2004), it is not entirely clear whether or not primary production activities at Apollonia continued beyond the Arab invasion. In any case, the changes that we see in the chemical makeup of glass produced in Syria-Palestine, such as decreasing soda levels concurrent with increasing lime, alumina and silica contents, had already begun in the fourth century, as reflected in the compositional differences between Jalame and earlier Roman glasses, and even more so between Jalame and Apollonia.

The decline in soda levels is frequently explained by limited supplies of natron from Egypt (Freestone *et al.* 2000; Phelps *et al.* 2016; Shortland *et al.* 2006).

However, the soda levels in contemporary Egyptian glasses appear to be temporarily affected as well. Magby glass has on average a slightly lower soda content (about 16.3%) compared to earlier groups such as Roman Sb, HIMT and Foy 3.2 (Table 1), although this may be related to the incorporation of an ash component that reduced the relative soda levels and increased the potash concentrations. The soda levels of Foy 2.1 vary from 14.2% to 21% (average $\text{Na}_2\text{O} \sim 17.7\%$), but whether there is a chronological dimension to this wide range is impossible to say at this point due to the insufficiently precise dating of most assemblages. No chronological shift is evident from our data on Visigothic glasses in Spain (De Juan Ares *et al.* 2019a) or the Byzantine glass weights (Schibille *et al.* 2016). The soda concentrations of the Egypt 1 and Egypt 2 groups remain around the 16% – 16.5% mark and drop off noticeably only after the first quarter of the ninth century CE (see chapter 1). For a brief period at the beginning of the eighth century we even see an increase in the soda levels in Egyptian tesserae recovered from the Great Mosque in Damascus. It is thus unlikely that the exploitation of the natron sources in Egypt were impaired in the long term, and the fluctuations seen during late antiquity may instead be related to climatic variations (Picon *et al.* 2008; Shortland 2004; Shortland *et al.* 2006). Different factors must therefore account for the persistent decline in the soda levels in Levantine glasses. The ceramic evidence indicates continued trade between Egypt and southern Syria-Palestine on a relatively large scale into the Umayyad and the Abbasid periods (Reynolds 2018; Walmsley 2007a). Consequently, changing trade networks cannot explain the gradual decline in soda levels either. To what then can we attribute the reduced use of soda in Levantine glass production? Part of the explanation may be the scale of glass production in Egypt during the late antique and early Islamic periods. An increase in local demand for natron in Egypt, caused possibly by large-scale commissions from the central caliphal government, may have led to restrictions on the export of raw materials from Egypt to the Levant. In short, the reason for the decreasing natron imports may not be a decline in trade or problems at the source, but limited availability due to Egypt's booming glass industry.

The beginnings of Islamic glass production

Early Islamic natron glass from Bet Eli'ezzer – Levantine II

The incredible speed of the Arab conquest of the eastern Mediterranean - by 640 CE the whole of Syria and Palestine was under Muslim rule, followed by Egypt in 642 CE - and the fact that the archaeological record does not show many traces or destruction layers that can be unambiguously associated with the events of the

conquest suggest that the impact of the Arab expansion on settlement patterns and daily life was minimal (Milwright 2010; Robinson 2010; Walmsley 2007b). The Arab conquest also appears to have had no immediate discernible consequence for the primary production of glass. There is little or no obvious change in the organisation or scale of glass production, or in the use of raw materials before the late eighth or early ninth century CE (Henderson *et al.* 2004; Phelps *et al.* 2016). Large-scale primary production of natron-type raw glass continued throughout the seventh and eighth centuries, as judged by the evidence from Bet Eli‘ezer near Hadera, where the foundations of 17 tank furnaces were unearthed (Brems *et al.* 2018; Freestone *et al.* 2000; Gorin-Rosen 1995; Gorin-Rosen 2000). The glass finds from Bet Eli‘ezer were previously termed Levantine II (Freestone *et al.* 2000) and the furnaces were initially dated to the sixth to eighth centuries CE (Freestone *et al.* 2000; Gorin-Rosen 1995; Gorin-Rosen 2000). Since no pre-Islamic finished artefacts from Syria-Palestine correspond compositionally to the Bet Eli‘ezer furnace glass, there is good reason to believe that this Levantine II type is in fact an Islamic glass dated perhaps to the seventh and more likely to the eighth century CE (Freestone *et al.* 2015b). Four samples recovered from the consumer site at Umm el-Jimal in Jordan are largely consistent with a Levantine II composition and have been loosely attributed to the Byzantine period (Al-Bashaireh *et al.* 2016). In one instance the context was dated on grounds of a ‘considerable amount of Umayyad ceramics’ (Al-Bashaireh *et al.* 2016, p. 810), so the exact dates are not entirely clear and there seems to be a distinct possibility that the chronological range of the assemblage extends into the eighth century.

Bet Eli‘ezer-type glass is very similar to the glass from Apollonia in terms of its chemical characteristics as well as its strontium and neodymium isotopic signature (Brems *et al.* 2018; Freestone *et al.* 2015b; Phelps *et al.* 2016). The main distinguishing features of Bet Eli‘ezer glass are low soda concentrations in relation to silica contents and low lime relative to alumina (Table 4; Fig. 24). It also tends to have lower potash concentrations compared to Jalame and Apollonia glasses. The low soda to silica ratios suggest differences in the recipes in terms of the relative proportions of fluxing agent to network former, while the lime and alumina ratios and potassium oxide contents reflect differences in the mineralogical characteristics of the silica source used (Freestone *et al.* 2000). Bet Eli‘ezer is located further inland than Apollonia and Jalame, and it has been proposed that general geopolitical and economic changes may have caused a re-orientation away from the Mediterranean coast (Phelps *et al.* 2016). Recently a closely related compositional group was identified among the vitreous refuse material from a secondary glass workshop in Tel Aviv dating likewise to the seventh to eighth

centuries CE (Fig. 24; Freestone *et al.* 2015b). To what extent this was the product of an independent glass production is not clear, as only four samples have been identified to date.

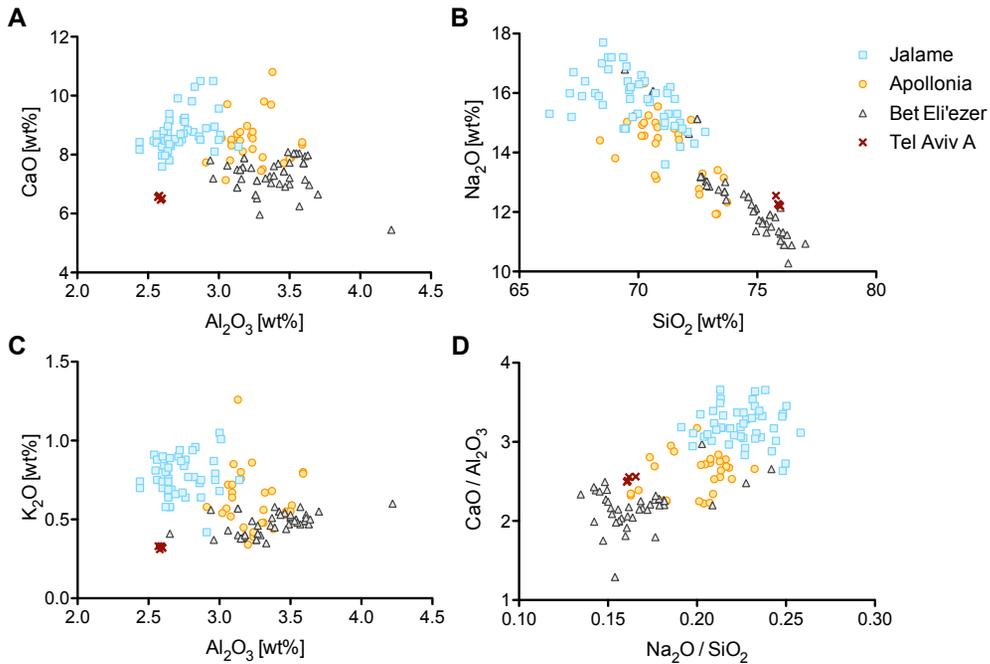


Fig. 24:

Compositional characteristics of the Bet Eli'ezer glass in comparison with the glass from Jalame and Apollonia. (a) Lime and alumina levels imply differences in the mineralogical composition of the glassmaking sands of the different Levantine groups; (b) soda versus silica contents reflect different proportions of natron to silica and thus different glassmaking recipes; (c) potassium and aluminium oxides confirm differences in the silica source; (d) ratios of lime to alumina and soda to silica separate Bet Eli'ezer clearly from earlier Levantine glasses. Data sources: (Brill 1999) for Jalame; (Brems *et al.* 2018; Freestone *et al.* 2008b) for Apollonia; (Brems *et al.* 2018; Freestone *et al.* 2000; Freestone *et al.* 2015b) for Bet Eli'ezer; (Freestone *et al.* 2015b) for Tel Aviv.

Despite the large-scale production of glass at Bet Eli'ezer (17 tank furnaces with an estimate capacity of eight to ten tons each), this type of glass has not been widely reported from regions outside Syria and Palestine, and even among Levantine assemblages it is surprisingly rare. Bet Eli'ezer glass was detected among the early Islamic finds from Ahihud, Jerusalem and Ramla (Phelps *et al.* 2016; Tal *et al.* 2008). There may also be some Bet Eli'ezer-type specimens among the eighth-century assemblage from Raya on the Sinai Peninsula (Kato *et al.* 2009), a few isolated samples from Jordan (Al-Bashaireh *et al.* 2016; Rehren *et al.* 2010), and possibly some individual samples in France (e.g. at the Abbey of

Hamage, Inès Pactat, personal communication). Phelps and colleagues proposed that the glass produced in Bet Eli‘ezer was destined for a local market and that trade routes had changed more profoundly after the Arab conquest (Phelps *et al.* 2016). However, even if one assumes that the primary production activities at Bet Eli‘ezer were relatively short-lived, spanning only 50 to 100 years (Freestone *et al.* 2000), the scale of production is still in apparent contradiction to the scarcity of archaeological finds of this type of glass. The exceptionally high silica content of the Bet Eli‘ezer glass means that the working temperatures and range are not as advantageous as those, for instance, of Jalame or Apollonia glasses, let alone any of the Egyptian glass groups. The viscosity curve of the Bet Eli‘ezer glass is considerably higher with an estimated temperature difference at the working point of a whopping 70°C compared to Jalame glass and of about 50°C compared to the glass from Apollonia (Fig. 25). Freestone and colleagues believe that these physical properties required an adjustment of the glass-working techniques (Freestone *et al.* 2000). It is thus worth considering whether this type of silica-rich glass may have been used less for vessel production and more for cast or moulded architectural glasses that became particularly popular during the Abbasid period and that may have required specialised glass-working skills (Leal 2020).

An interesting case in point are the glass floor tiles that were in demand during the Abbasid period. Naturally aqua-coloured glass floor tiles (Fig. 26) were found, for example, in the reception room of a palace belonging to Hārūn al-Rašīd at Raqqa (about 796-809 CE), in the early ninth-century Qaṣr al-Ḥayr al-Sharqī residence in eastern Syria (Carboni 2003; Ritter 2019; Ritter 2020) as well as the caliphal palace of Samarra (Lamm 1928, fig. 66; Ritter 2019; Ritter 2020). These rectangular tiles (about 16.6 x 11.6 cm) of translucent naturally coloured glass (greenish and bluish aqua to turquoise) have a smooth upper surface and semi-globular nubs on the underside (Fig. 26), and they were presumably produced by casting into moulds (Ritter 2019). Entire glass floors constructed of these translucent glass tiles seem to have been an early Abbasid invention (Leal 2020; Ritter 2019). Even though only fragments of these glass tiles have thus far been documented, the variations in the vitreous material, shapes and profiles of the nubs suggest different secondary production events and possibly workshops (Ritter 2019). Paving entire reception halls, including the lower wall zones, with glass tiles would certainly have required substantial amounts of glass. Interestingly, the preliminary analysis of a square bottle in the Glassware and Ceramics Museum of Iran which was assembled from numerous Abbasid nubbed glass tiles (Ritter 2019) revealed a chemical composition consistent with the Bet‘Eliezer Levantine II compositional group with typical low soda, high alumina and moderate lime levels (personal communication Davoud Agha-Aligol). It is an intriguing thought that

the glass produced at Bet‘Eliezer may have been destined mainly for these types of cast architectural decorations. As long as no further analyses of the composition of these glass tiles are carried out, this hypothesis must remain speculative.

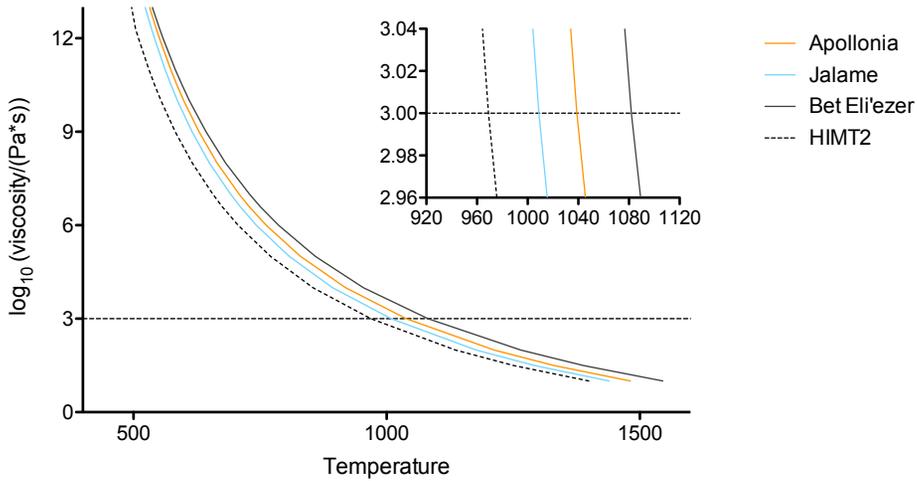


Fig. 25: Viscosity curves as a function of temperature (in °C) for the average compositions of different Levantine glass groups, including glass from Jalame, Apollonia and Bet Eli'ezer. Compositional data from table 4 (and table 1 for HIMT2) of major and minor elements (Na_2O , MgO , Al_2O_3 , SiO_2 , K_2O , CaO , TiO_2 and Fe_2O_3) were used for the calculations. Roman Manganese and naturally coloured glass was not included, because the viscosity curve is identical to that of glass from Jalame. Viscosity model from (Fluegel 2007). The insert shows a scaled zoom highlighting the differences at working temperature.

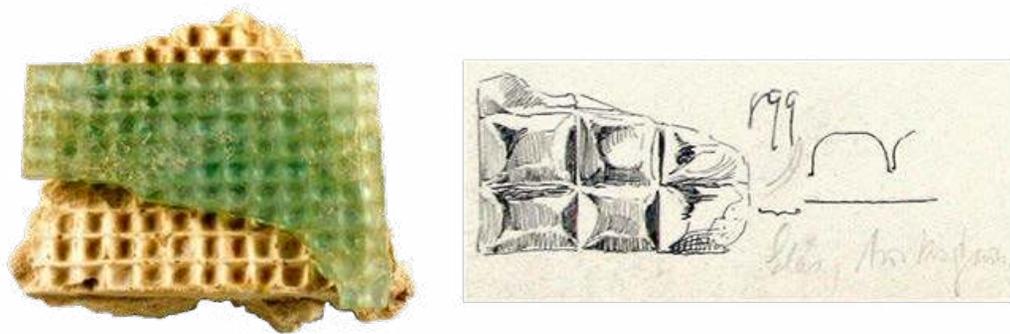


Fig. 26: Examples of Abbasid glass tiles. (a) Fragment of a glass tile embedded in plaster from the palace of caliph al-Mu‘tasim Billah (833-842 CE). Mona al-Moadin in *Discover Islamic Art*, © Museum with no Frontiers, 2021. http://islamicart.museumwnf.org/database_item.php?id=object;ISL;sy;Mus01;9;en; (b) drawing of glass tile fragment and profile recovered from the caliphal palace at Samarra during the Herzfeld excavations in 1912. © Ernst Herzfeld Papers, FSA_A.06_07.19 (detail), Freer Gallery of Art and Arthur M. Sackler Gallery Archives, Gift of Ernst Herzfeld, 1946.

The early Islamic mosaic tradition in Greater Syria

Glass from Bet'Eliezer does not appear to have been extensively used for the production of mosaic tesserae, even though the turn of the eighth century CE can be considered a *Golden Age* of Islamic mosaic making when, within about a generation, major construction programmes were undertaken that included vast surfaces of mosaic decorations, notably those of the Dome of the Rock (684? - 691? CE) and the al-Aqsa Mosque (709? – 715 CE) on the Temple Mount in Jerusalem, the Great Mosque in Damascus (705 - 715 CE), the Great Mosque of Aleppo (possibly begun around 715 CE), as well as the Holy Mosque in Mecca (redecorated between 705 and 715 CE) and the Prophet's Mosque in Medina (restored between 706 and 709 CE; Grafman and Rosen-Ayalon 1999; James 2017; Leal 2020). Architectural glass was also extensively used in Umayyad palatial residences: glass tesserae were found in the building south of the al-Ḥaram aš-Šarīf, at the Umayyad fort at Qaṣṭal, in Qaṣr al-Ḥair aš-Šarqī and Qaṣr al-Ḥair al-Ġarbī east and west of Palmyra (Syria), respectively, in Khirbat al-Mafjar (Jericho, Palestine) as well as in Khirbat al-Minya on the northern shore of Lake Tiberias in Israel (Baker 2004; Baker 2005; Grabar 1993; Ritter 2019, and references therein). Hundreds of fragments of coloured window glass (purple, blue, green, yellowish green and amber) were recovered from both the Qaṣr al-Ḥair aš-Šarqī (Salam-Liebich 1978) and Khirbat al-Minya (Ritter 2017). The lavish use of architectural glass, particularly mosaic decorations, meant that appropriate resources had to be mobilised. Using approximate values for both the size of the tesserae (0.75 cm³) and the density of glass (3 g/cm³),¹ the Great Mosque of Damascus alone with roughly 7,500 m² of mosaic decoration (Leal 2020) would have swallowed nearly 170 tons of glass. All the monumental Umayyad mosques in Greater Syria and the Hijaz region together would amount to an estimated mosaic surface of about 22,000 m² (for approximate calculations see Leal 2020), meaning that a total amount of almost 500 tons (167 m³) of glass was needed. This pertains only to mosaic decorations and only to the so-called Great Mosques and does not take into account the use of glass for windows or lamps, or the numerous smaller foundations or Umayyad palaces.

The quantities that were required for the various architectural campaigns in the first half of the eighth century would easily have exceeded the capacities of the tank furnaces at Bet'Eliezer several times over. This may have been one of the reasons why about two-thirds of the original Umayyad mosaic tesserae from the Great Mosque in Damascus and about half of the mosaics and most of the window glass

¹ To approximate the amount of glass needed for decoration I chose a median value for both the size of tesserae and the density of glass. Common soda glass has a density of the order of 2.5 g/cm³, while lead glass has densities of 3.1-5.9 g/cm³. The side-length of tesserae varies from 0.5 cm to 1.5 cm and they are not necessarily regular.

from Khirbat al-Minya were of contemporary Egyptian provenance (see chapter 1; for Damascus see Schibille *et al.* forthcoming; for Khirbat al-Minya see Adlington *et al.* 2020). Thus, the analytical evidence gained from the mosaic decoration and window glass fragments from the *qasr* of Khirbat al-Minya together with the mosaics from the Great Mosque in Damascus provides a nuanced and complex picture of the supply of glass for architectural decorations to Greater Syria at the beginning of the eighth century CE. We should note that no consensus has been reached as regards the dating of the *qasr* of Khirbat al-Minya, but judging from the compositional characteristics of the vitreous material, an early eighth-century date during the reign of al-Walīd I (705 - 715 CE) as opposed to al-Walīd II (743 -744 CE) is likely (for a discussion of the archaeological and historical evidence see the introduction to Ritter 2017; for analytical data see Adlington *et al.* 2020).

A comparison of the data on 270 mosaic tesserae from Khirbat al-Minya with 908 mosaic tesserae from the Great Mosque in Damascus shows a broadly similar distribution of the base glasses at the two sites. $\text{Al}_2\text{O}_3/\text{SiO}_2$ compared to $\text{TiO}_2/\text{Al}_2\text{O}_3$ ratios separate glass made with a silica source in the Levantine coastal region from glasses of Egyptian origin (Fig. 27a). The overwhelming majority of the Damascus tesserae corresponds to Egyptian glasses of the early Islamic period (Egypt 1A and Egypt 1Ax), and only about 19% of the natron-type tesserae match the compositional features of Levantine glasses. At al-Minya, the distribution between the two production regions is about 50:50. The Egypt 1A tesserae from al-Minya form a very tight cluster, much tighter than at Damascus, and none of the newly described Egypt 1Ax sub-type was identified. The two mosaic assemblages also agree in terms of the relative presence of minor glass groups that occupy an intermediate space between the two major categories. One population has low alumina contents ($\text{Al}_2\text{O}_3 < 2\%$), the other corresponds to Foy 2.1 on account of its slightly elevated titanium oxide levels (Fig. 27a). The similarities in the compositional make-up of the mosaic assemblages of the two sites underlines the representative nature of the two data sets on the basis of which a model of the production and supply of mosaic tesserae during the early Islamic period can be advanced.

A detailed classification of the Levantine tesserae from Damascus and al-Minya proves somewhat challenging, because in some of the tesserae calcium phosphate is present as opacifier, which has an impact on the lime to alumina ratios that are typically used to distinguish the different Levantine reference groups (Fig. 27b). The Levantine-type glasses from both mosaic assemblages cluster at the interface of the fourth-century Jalame and sixth- to seventh-century Apollonia reference groups and can therefore not be clearly affiliated with one or the other. Only a handful of tesserae may belong to the Bet'Eliezer Levantine II type. Using manganese

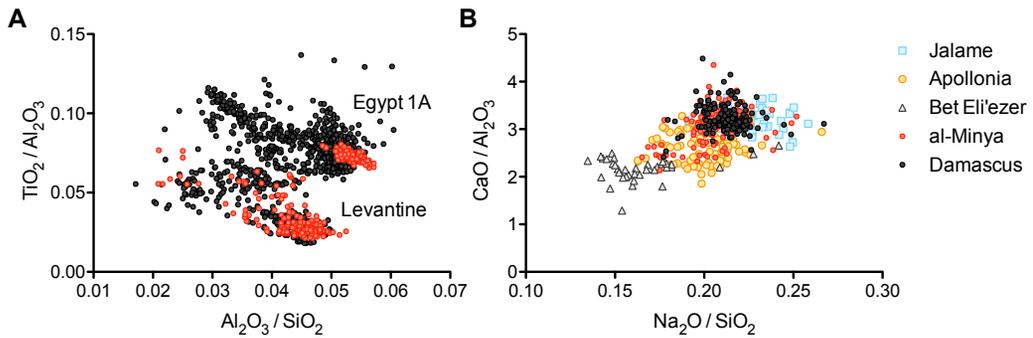


Fig. 27:

Compositional affiliations of the glass mosaic tesserae from the Great Mosque in Damascus and Khirbat al-Minya. (a) $\text{TiO}_2/\text{Al}_2\text{O}_3$ versus $\text{Al}_2\text{O}_3/\text{SiO}_2$ separate the Egyptian (Egypt 1A & 1Ax) from the Levantine tesserae; (b) lime to alumina and soda to silica ratios distinguish between different Levantine primary production groups from Jalame, Apollonia and Bet'Eliezer. The Levantine tesserae of both mosaic assemblages are consistent with either Apollonia-type Levantine I or Jalame glass and only a few samples match the later Bet Eli'ezer composition. Data sources: (Adlington *et al.* 2020; Brems *et al.* 2018; Freestone *et al.* 2008b; Phelps *et al.* 2016; Schibille *et al.* forthcoming).

concentrations as an additional marker to distinguish between Apollonia and earlier Levantine groups shows that the majority of Levantine tesserae from both al-Minya and Damascus contain manganese that exceeds the usual background levels of silica sources ($\text{Mn} > 250$ ppm), but is below the concentration at which it could be considered an effective colourant or decolorant (Fig. 28). In view of the fact that Apollonia glass does not usually contain manganese, it can be assumed that the base glass of the Levantine tesserae was a mixture of earlier glass groups that were combined through recycling processes. Broadly speaking, it seems that the base glass of strongly coloured and opacified tesserae is often a mixture of scrap glass in one form or another. Analytical data on Roman and late antique mosaic assemblages have shown that coloured mosaic tesserae are more variable than colourless or weakly coloured glasses in terms of elements such as aluminium, titanium and calcium (e.g. Paynter *et al.* 2015; Schibille *et al.* 2018b). The use of various additives to colour and opacify the glass makes it yet more difficult to identify the base glass accurately. The distinction between tesserae of Levantine glass and Egyptian Foy 2.1, for example, is occasionally blurred, because the compositional spectrum of Levantine mosaic tesserae can be more diverse than that of non-coloured glasses (Schibille *et al.* 2018b). What we can say with some certainty is that a large proportion of the base glass used for the Levantine tesserae (with the exception of a few Bet Eli'ezer Levantine II type samples) predates the foundation of the Great Mosque in Damascus as well as Khirbat al-Minya in the eighth century. The supply of tesserae to these Syro-

Palestinian sites was thus ensured mostly through imports of large quantities of fresh Egyptian material, alongside some recycled and/or reused samples.

The gold leaf tesserae are the exception to the rule. Apart from one sample (Egypt 1A), all the gold leaf tesserae belong to the Levantine, Foy 2.1 and low alumina glass types. They have surprisingly high manganese contents (MnO median = 3.5%), resulting in a variety of amber and purple hues (Fig. 32b). This colouring practice appears to be quite common in early Islamic tesserae in the Near East, but has never been identified in gold leaf tesserae from the western Mediterranean (Verità 2016). The antimony levels of the Levantine gold leaf tesserae can be attributed to impurities in the glass raw material. Hence they do not exhibit clear signs of recycling and may well have been re-used. The same applies to gold leaf tesserae with a Foy 2.1 and a low alumina base glass. Even though they tend to have slightly elevated antimony contents (Fig. 28), this is not uncommon for these types of Egyptian glasses. Neither manganese nor antimony can therefore be used as a discriminant between reuse and recycling, and it is impossible to tell at which point the Levantine and minor glass groups were fused together and made into mosaic tesserae. There is a distinct possibility that many of the tesserae made of older primary glass groups were in fact reused tesserae as opposed to freshly re-melted cullet turned into “new” tesserae. The collection and reuse of gold leaf tesserae may be particularly attractive due to their higher material value and higher production costs.

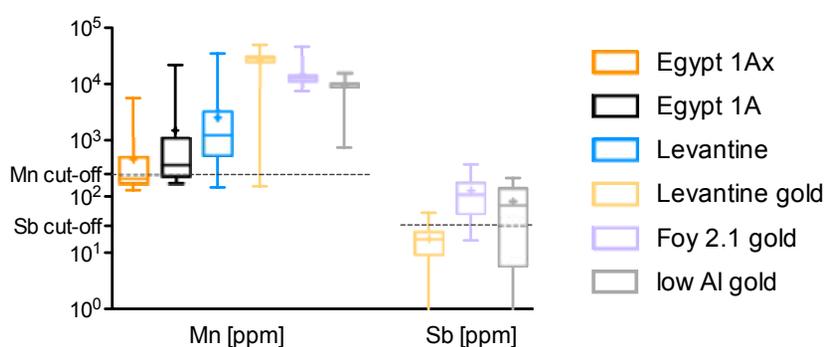


Fig. 28:

Manganese and antimony levels of the different base glass categories among the mosaic assemblages from the Great Mosque in Damascus and Khirbat al-Minya. A considerable number of samples show manganese contents above the threshold of natural contamination (Mn cut-off at 250 ppm), suggesting the incorporation of some recycled material during the life-cycle and secondary production of the glass tesserae, especially as regards the tesserae with a Levantine base glass composition. The gold leaf tesserae have exceptionally high manganese concentrations. Here, manganese was probably added deliberately for colouring purposes, whereas the antimony contents at impurity levels do not betray any recycling. Data sources: (Adlington *et al.* 2020) for al-Minya; (Schibille *et al.* forthcoming) for Damascus.

An interlude – the gold in gold leaf tesserae

Some authors have suggested that the composition of the gold (and silver) leaf can provide additional insights into secondary working processes and, due to a direct link with contemporary gold coinage, facilitate the distinction between reused and newly made tesserae (Neri *et al.* 2016). In a preliminary series of experiments, we have analysed the gold leaf of tesserae from Damascus (n=21) and Khirbat al-Minya (n=9) alongside earlier samples from the fourth-century Roman villa of Noheda in Spain (n=8), the sixth-century Church of St Mary at Ephesos (n=4) and Hagia Sophia in Constantinople (n=21). The tesserae from Damascus and Khirbat al-Minya have gold contents of between 77% and 97% (Fig. 29a), which is considerably lower than those of Byzantine gold coins of the sixth and seventh centuries and of early Umayyad coinage from Syria (Gondonneau and Guerra 2002; Jonson *et al.* 2014). Late seventh- and early eighth-century coins from the Islamic mints in North Africa as well as a single, anomalous Byzantine coin from the reign of Constantine IV labelled as Arab/Byzantine by the Barber Institute have comparably low gold contents (Jonson *et al.* 2014). North African mints apparently started to issue debased gold solidi, semisses and tremisses shortly after the Arab conquest of the region. The decline in gold levels resulted from an increase in silver and copper contents (Jonson *et al.* 2014). A clear debasement of gold coinage and parallel increase in silver contents (not copper) was observed in the eastern Mediterranean mints only later during the Abbasid caliphate (Gondonneau and Guerra 2002). Thus, there is a clear difference between the composition of the gold leaf of tesserae on the one hand and Byzantine and early Islamic gold coinage on the other hand. The gold content in the tesserae tends to be consistently lower and the silver higher than in the contemporary coins from the Near East and, to a lesser extent, the coinage from the North African mints (Fig. 29b). In fact, the sixth-century gold leaf tesserae from Ephesos and Hagia Sophia in Constantinople show a similarly broad range of gold contents from 85% to 98%, but these sixth-century tesserae have a higher median of about 96% compared to 92% of the al-Minya and 85% of the Damascus samples. The range of gold concentrations is much narrower in the fourth-century tesserae from the Roman villa at Noheda (91% - 98%), but some overlap with late antique and early Islamic tesserae occurs at the lower end of the spectrum (Fig. 29a). No chronological and geographical attribution of the gold leaf tesserae is thus possible based on the gold and/or silver contents.

Numerous numismatic studies have shown that the gold sources exploited by the Byzantines and early Umayyads were compositionally related and that Islamic gold coinage issued in North Africa and Syria during the Umayyad period relied heavily on the recycling of Byzantine gold coins (Gondonneau and Guerra 2002; Jonson *et al.* 2014). The similarities are reflected in the relatively narrow range

of platinum to gold ratios of all the sixth-century Byzantine mosaic tesserae, the Byzantine and Umayyad coinage as well as the majority of the tesserae from Damascus and Khirbat al-Minya (Fig. 29a). By contrast, the fourth-century tesserae from the Roman villa of Noheda, together with one tessera from Khirbat al-Minya with an Apollonia-type Levantine I composition (NS-T049), one gold leaf tessera from Hagia Sophia made from a Foy 2.1 base glass, and one Islamic coin of uncertain provenance (L463 in Gondonneau and Guerra 2002) have notably lower Pt/Au ratios. This is a clear indication that the gold used for these artefacts derived from a different primary source from that of all the other tesserae. The palladium to gold ratios further enabled us to separate the gold leaf of all the mosaic tesserae analysed from both the Byzantine and early Umayyad gold coinage (Fig. 29c). Palladium and platinum have proven to be reliable markers for the identification of ‘gold stocks’, as neither Pd/Au nor Pt/Au ratios appear to be affected by ancient metallurgical processes (Blet-Lemarquand *et al.* 2017). It is therefore very striking that the tesserae from Damascus, Khirbat al-Minya and Hagia Sophia are distributed along the same regression line of Pd/Au and Pt/Au ratios, which differs considerably from that of the Byzantine and Umayyad gold coinage. The compositional features of the mosaic tesserae under consideration therefore rule out a direct material link between the production of gold leaf used for the manufacture of tesserae and Byzantine or Islamic gold coinage in the sixth, seventh and early eighth centuries CE. At the same time, the majority of sixth- to eighth-century tesserae seem to derive from a common source of gold independent of the base glass composition. Both Levantine and Egyptian Foy 2.1 tesserae made use of the same type of gold, even though there are some outliers that have very different gold leaf features (Fig. 29).

The elevated silver concentrations in the gold leaf in comparison to gold coinage (Fig. 29b) may be the result of the use of non-purified native gold (Gondonneau and Guerra 2002; Jonson *et al.* 2014). As pointed out by Gondonneau and Guerra (2002, p. 578), the refining of gold is expensive and time-consuming. Producing gold leaf for the manufacture of gold tesserae certainly did not require gold of the same purity as the issue of gold coins and, if available, craftsmen may very well have preferred the use of native gold which was presumably less expensive by weight than the purer gold used in gold coinage. While the use of native gold can account for the increased silver content, copper above 1% is not normally present in native gold, but it does occur, mainly in volcanogenic massive sulphide and porphyry Cu-Au deposits (Liu and Beaudoin 2021). Another possible explanation for the presence of elevated copper in gold leaf tesserae (Fig. 29b) is that the craftsmen modified the colour of the gold leaf by using different gold-silver-copper alloys. Different silver and copper contents can produce a multitude of hues, from

whitish in silver-rich alloys to reddish in copper-rich ones (Cretu and Van Der Lingen 1999; Verità 2016). The intense amber and purple colour of the base glass of many of the gold leaf tesserae would seem to reinforce this interpretation.

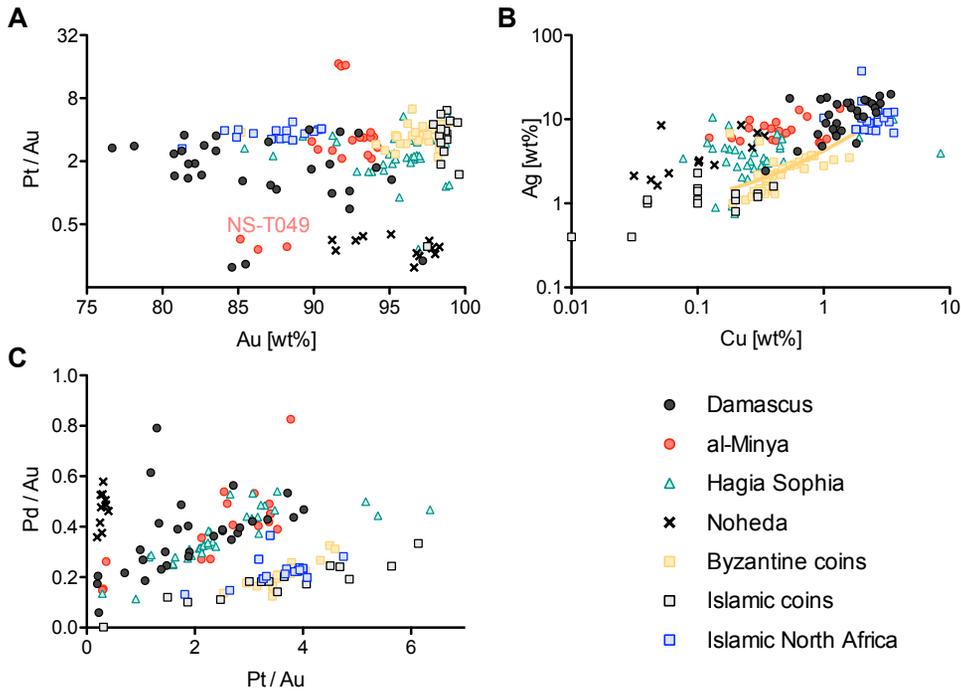


Fig. 29:

Compositional characteristics of the gold leaf of some tesserae from the Great Mosque in Damascus and Khirbat al-Minya compared to earlier tesserae from fourth-century Noheda (Spain), sixth-century Hagia Sophia in Constantinople and Byzantine and early Islamic gold coins. (a) Platinum to gold ratios versus gold contents highlight the similarities of Byzantine and Islamic gold sources, while the gold used for late Roman gold leaf tesserae clearly differs; (b) the relative concentrations of copper and silver are strongly correlated in the Byzantine and early Islamic coinage from North Africa, while the silver contents in the tesserae tend to be on average higher than in the contemporary gold coinage; (c) ratios of palladium and platinum to gold separate the Byzantine and Islamic coinage from all gold leaves of mosaic tesserae analysed. Data sources: (Gondonneau and Guerra 2002; Jonson *et al.* 2014; Neri *et al.* 2016; Schibille *et al.* forthcoming). Please note that the graphs include multiple analyses of the same samples.

Colours and opacifiers of the mosaic tesserae

Without going into too much detail, the colouring and opacifying technologies common to the mosaics from Damascus and Khirbat al-Minya reveal a number of interesting patterns. Calcium phosphate, presumably in the form of bone ash or powdered bone, was used as an opacifier mostly in combination with Egypt 1A

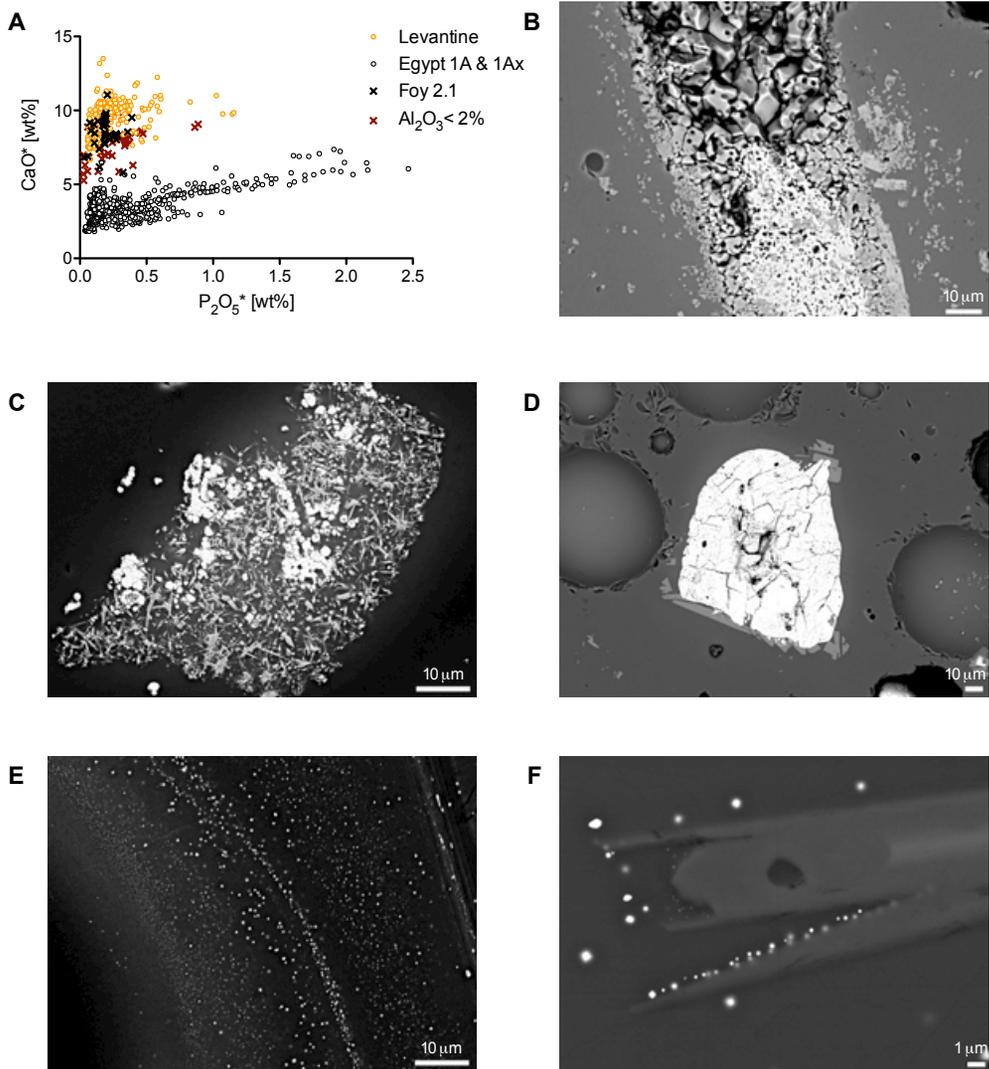


Fig. 30:

Main opacifiers detected in the mosaic tesserae from the Great Umayyad Mosque in Damascus. (a) Calcium versus phosphorus levels highlight the use of bone ash particularly in combination with Egypt 1A tesserae; (b) backscattered SEM image of aqua-coloured Egypt 1A tessera AFI 2295/62 A3 showing spongy calcium phosphate particles surrounded by a reaction zone consisting of bubbles and devitrification crystals (wollastonite); (c) SEM image of backscattered electrons showing clusters of lead stannate and secondary cassiterite crystals in yellow Egypt 1Ax tessera AFI 2295/38 G1; (d) manganese oxide inclusion with surrounding wollastonite devitrification crystals in SEM backscattered image of the beige Levantine tessera AFI 2295/68 A1, possibly indicating its deliberate addition for decolouring purposes; (e) backscattered SEM micrograph highlights heterogeneous distribution of metallic copper nanoparticles in red tessera AFI 2295/67 A"2a; (f) metallic copper nanoparticles develop around wollastonite particles in red tessera AFI 2295/67 A"3, implying the copper precipitated after the formation of the wollastonite crystals at temperatures below 850°C. All SEM images © Léa Brunswic C2RMF.

and Egypt 1Ax glass and only sporadically in the other primary glass groups (Fig. 30a). Calcium and phosphorus are positively correlated and their relative increase corresponds roughly to the ratio of 4:3 (in wt % of their oxides) that is equivalent to the calcium to phosphorus ratio of bone (hydroxyapatite $\text{Ca}_5(\text{PO}_4)_3(\text{OH})$).

Hydroxyapatite ($\text{Ca}_5(\text{PO}_4)_3(\text{OH})$) and β -rhenanite ($\beta\text{-NaCaPO}_4$) were identified by Raman spectroscopy and SEM-EDS in some of the aqua-coloured tesserae with an Egypt 1A composition from Damascus (Fig. 30b), and in the purple, olive and turquoise tesserae from Khirbat al-Minya (Adlington *et al.* 2020). Tesserae opacified with bone ash are known from the Petra church in Jordan that is broadly dated to the mid-fifth to early eighth centuries CE (Marii and Rehren 2009) and have since been recognised at various Levantine sites as well as in northern Italy (Neri *et al.* 2017, and references therein). The use of calcium phosphate was recently reported also for the mosaic assemblage recovered from the second phase (724–743 CE) of the Umayyad *qasr* of Khirbat al-Mafjar (Jericho, Palestine; Fiorentino *et al.* 2018; Fiorentino *et al.* 2019a) and the eighth-century Qusayr' Amra (Jordan; Verità *et al.* 2017b), both of which post-date the Great Mosque in Damascus and Khirbat al-Minya by a couple of decades.

Lead stannate is the yellow pigment and opacifier in the yellow and green tesserae, mostly in the form of euhedral crystals that range in size from a few tens of nanometres to tens of microns and that are often accompanied by small tin oxide (cassiterite) particles (Fig. 30c). Their angular shape indicates that these cassiterite crystals most probably resulted not from a deliberate addition of tin oxide, but from secondary decomposition of the yellow pigments during heat treatment. Tin-based opacifiers have been widely used since the fourth century CE (Bonnerot *et al.* 2016; Freestone *et al.* 1990; Neri *et al.* 2017; Tite *et al.* 2008). Copper in different oxidation states accounts for the green, turquoise and red colours, with the red samples systematically having higher iron contents than the green and turquoise tesserae. Nanoparticles of metallic copper appear to be responsible for the red tesserae as no cuprous oxide was detected by Raman in the tesserae from Damascus, meaning that the iron acts probably as reducing agent. The metallic copper particles are heterogeneously distributed and seem to precipitate preferentially along devitrification crystals of wollastonite (Fig. 30e–f). The red tesserae are predominantly made of Levantine base glass or one of the minor compositional groups, notably Foy 2.1 and HIMT (Fig. 31). Some of the red tesserae with variable compositions cannot be easily affiliated to any of the primary production groups due to the high levels of additives, especially iron, copper and lead. Different traditions for making deep red glass have existed concurrently since ancient times, utilising different combinations of raw

materials (Bandiera *et al.* 2020; Barber *et al.* 2009; Schibille *et al.* 2020b; Shugar 2000). The black samples owe their colour to high levels of iron oxide, with the exception of one black sample of Levantine composition that contains an excess of manganese (MnO = 4.5%). Iron is probably also responsible for the different olive shades (amber, beige, greenish) even though the absolute iron levels remain moderate (about 1%), indicating that the furnace conditions may have played a vital role.

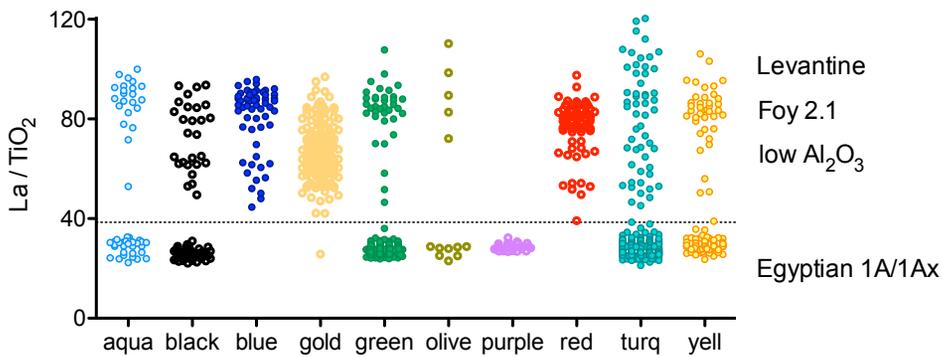


Fig. 31:

Colour distribution of the mosaic tesserae from the Great Umayyad Mosque in Damascus and Khirbat al-Minya as a function of their La/TiO₂ ratios. The horizontal line separates Egypt 1A and Egypt 1Ax from all other compositional groups represented, with the exception of HIMT, which has been omitted for simplicity. Please note that the cut-off ($\text{La/TiO}_2 < 38.5$) is an approximation for illustrative purposes and is not meant as an absolute threshold.

The distribution profile of the different colours shows that aqua, black, green, olive, turquoise and yellow tesserae have been produced from all the different base glasses (Levantine, Foy 2.1, Egypt 1), more or less relative to the total number of samples within each group (Fig. 31). None of the cobalt blue samples (Co > 200 ppm), none of the copper red tesserae and only a single gold leaf sample are of Islamic Egypt 1A or Egypt 1Ax base glass composition. Instead, these samples represent either Levantine I or one of the minor glass groups (Foy 2.1, low alumina, HIMT). The purple tesserae from Khirbat al-Minya containing on average 1.3% MnO were exclusively made from an Egypt 1A base glass. In contrast, the gold leaf tesserae with up to 5% MnO are all made from Levantine or Foy 2.1 compositions. In fact, the gold leaf tesserae with excess levels of manganese tend to be predominantly of the Levantine type, and only a handful of gold leaf tesserae with a Foy 2.1 signature have MnO > 2% (Fig. 32). Manganese oxide in the Foy 2.1 tesserae is associated with iron, indicating the use of an additive that introduced both elements to the glass batch. In contrast, the manganese-rich ingredient used

to colour the base of most Levantine gold leaf tesserae with a purplish amber hue did not contain any additional iron impurities. Manganese oxide inclusions were identified by backscattered SEM imaging in a beige-coloured sample (Fig. 30d) to which manganese may have been deliberately added as colourant/decolourant.

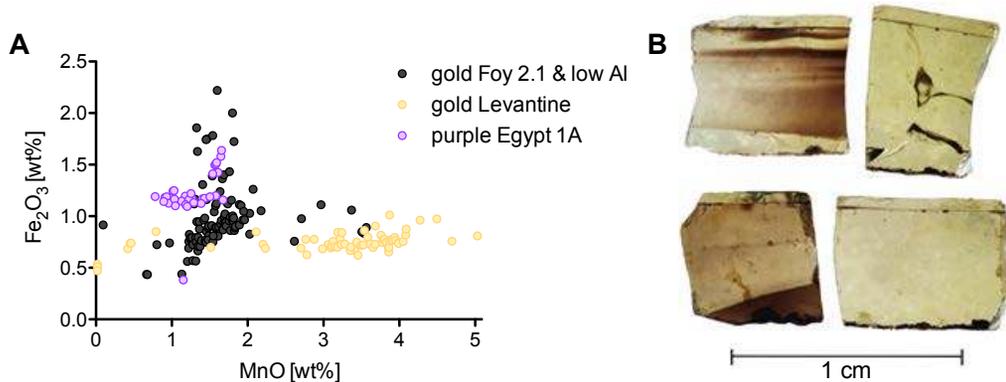


Fig. 32:

Gold leaf tesserae from Damascus and Khirbat al-Minya, in comparison with some purple samples from al-Minya. (a) Iron and manganese oxide concentrations clearly separate the Levantine and Foy 2.1 gold leaf tesserae from one another as well as the purple tesserae. (b) cross-sections of gold leaf tesserae from Khirbat al-Minya embedded in resin and polished: NS-T054/Levantine - 3.06% MnO, 0.72% Fe₂O₃ (upper left); NS-T051/Foy 2.1 - 3.54% MnO, 0.84% Fe₂O₃ (upper right); NS-T056/Foy 2.1 - 3.51% MnO, 0.85% Fe₂O₃ (lower left); NS-T060/Levantine - 3.12% MnO, 0.72% Fe₂O₃ (lower right).

In order to develop a purple colour, manganese needs to be present in its oxidised Mn³⁺ form, whereas Mn²⁺ is almost colourless. Hence, manganese acts as a decolouriser by oxidising the blue ferrous Fe²⁺ to the yellowish ferric Fe³⁺ (Möncke *et al.* 2014). It has been suggested that the ratio of iron to manganese plays a crucial role in the resulting colour and that an excess of manganese relative to iron oxide is required to create purple glass (Bidegaray *et al.* 2019). In the case of the purple tesserae from Khirbat al-Minya, more than half have Fe₂O₃/MnO ratios of about 1, suggesting that the oxidation state of manganese is more decisive than its absolute concentration and its relative amount compared to iron oxide (Fig. 32). Prolonged heat treatment may have aided the transformation of Mn(II) to Mn(III) (Möncke *et al.* 2014), an effect documented in the twelfth century by Theophilus in his *De Diversis Artibus* (Brepohl 2013). Theophilus describes the colour change after two hours of heat treatment from a yellow/tawny flesh-like colour to a light purple, which further intensifies into a red purple (*purpura rufa*) after four additional hours of heating (Brepohl 2013, Book II, chapter VIII, p. 150). What we can conclude from the colouring and decolouring properties of manganese is

that the redox conditions during the secondary working procedures of the purple and the Levantine gold leaf tesserae with a purple tinge must have been highly oxidising. The lower melting and working temperatures of Egypt 1A compared to Levantine glasses may in fact have benefited the formation of oxidised Mn^{3+} and lower absolute amounts of manganese may thus have been necessary.

Little is known about the sites and the organisation of secondary production of mosaic tesserae: where the glass for the tesserae was coloured and whether intermediate so-called glass cakes from which the tesserae were ultimately cut were formed in the same workshops. In the context of tesserae from Damascus and Khirbat al-Minya it was observed that different colours with an Egyptian 1A and Egypt 1Ax base glass may have been produced in the same secondary workshop, and that this workshop is more likely to have been located in Egypt, since the Levantine and Egypt 1A compositional glass groups remain well separated (Adlington *et al.* 2020). Even though it has been shown that Levantine and Egyptian primary production groups were occasionally processed in the same secondary workshop to make vessels without being extensively mixed (Freestone *et al.* 2015b), it is unlikely that the two glass types were used simultaneously in the same tesserae workshop. Given the selective use of Levantine glass for certain colours (mostly cobalt blue and gold leaf tesserae, but also red), workshops specialising in tesserae-making must have existed in the Levant also, but some re-use of older Levantine tesserae is likely as well. Levantine glass as a base material for mosaic tesserae has been identified in mosaics from various late Roman (e.g. Schibille *et al.* 2018b) and Byzantine contexts (Freestone *et al.* 1990; Neri *et al.* 2017; Schibille and McKenzie 2014), occasionally indicating colour preferences. However, as Ian Freestone observed (2020), outside the Levant Egyptian base glasses such as Foy 2.1 were generally more common than Apollonia-type Levantine I glass as early as the sixth and seventh centuries. This observation can be confirmed using an extensive data set from the sixth-century church of Hagia Sophia in Constantinople. Of over 300 mosaic tesserae analysed, including red, blue and gold leaf tesserae, only about 5% correspond to a Levantine base glass, while the overwhelming majority are of a Foy 2.1 composition (unpublished data). Hence, it is unclear at present whether mosaic workshops were still active in the Levant in the late seventh or early eighth century CE and what the extent of the output of Levantine mosaic workshops was in general. What can be said is that Egyptian mosaic workshops were in full swing throughout the late antique and into the early Islamic periods. Vast material resources were required for the various ambitious Umayyad building projects and decorative programmes of the early eighth century, surpassing anything seen elsewhere in the Mediterranean at the time (James 2017, p. 261). Early Islamic monuments such as the Great Mosque

in Damascus are the visual representation of a new world order, a materialisation and visualisation of Umayyad power and Muslim triumph (James 2017, p. 263; Flood 2001, pp. 214-216). The large expanse of wall mosaics was part of this visual rhetoric to assert the political and economic power of the Umayyad caliphate. The mosaics are, above all, an expression of the ability of the Umayyad dynasty to mobilise the necessary economic and material resources from all corners of the caliphate (see the discussion in George, 2021, particularly chapter 6).

The last hurrah of natron-type glass in the Levant

The procurement of mosaic assemblages in Damascus and Khirbat al-Minya mirrors common trends in the supply and consumption patterns of glass in the early eighth century in Syria-Palestine. The compositional characteristics of numerous domestic assemblages in Syria-Palestine revealed a general diversification and fundamental transformation in the supply of glass during this period (Phelps *et al.* 2016). Specifically, the presence of Apollonia-type Levantine I glass declined significantly; Bet Eli‘ezer-type Levantine II glass occurred for the first time; and relatively large quantities of Egyptian glasses were imported in the form of Egypt 2 (Phelps *et al.* 2016). There is some uncertainty in the early dating of these Egypt 2 finds from Syria-Palestine. According to our investigations of precisely dated early Islamic glass weights, the production of Egypt 2 glass began no earlier than the last quarter of the eighth century CE, and other studies have confirmed that the Egypt 2 base glass type is typically associated with Abbasid glass assemblages, meaning the second half of the eighth century at the earliest (Schibille *et al.* 2019). Despite the uncertainty surrounding the dating of the Syro-Palestinian glass finds (Phelps *et al.* 2016), the overall chronological developments proposed by Phelps and colleagues are corroborated by our findings from the mosaic assemblages of Damascus and Khirbat al-Minya. The Great Mosque of Damascus in particular provides an exact point in time for the changing trade patterns between Egypt and the Levant. The import of considerable quantities of Egyptian glass to Syria-Palestine accordingly began as early as the first decades of the eighth century, when Levantine glass of the Apollonia type receded. It must be kept in mind, however, that mosaic tesserae represent specialised products and that the manufacture of and trade in vessel glass could follow a different temporal trajectory. This is suggested by two independent pieces of evidence: we have established that Egyptian glass has been used more frequently for the manufacture of tesserae since the sixth century and, secondly, as far as I am aware there are only a very few examples of vessels made from either Egypt 1A or Egypt 1B outside Egypt. The Damascus mosaics may therefore reflect the situation of tesserae-glass production rather than

the manufacture of and trade in glass more generally. A more systematic synthesis of the base glass of different types of artefacts and optical properties may not only shed light on the extent of the markets for Egyptian and Levantine glasses and their transformation, but may also provide some indication of secondary working practices.

No plant ash glasses are linked unequivocally to the original early eighth-century architectural materials from the Great Mosque in Damascus. A small number of plant ash tesserae that we identified probably stem from later restorations that are known to have been carried out by the Abbasids in the ninth and/or tenth centuries, by Seljuk, Ayyubid and Zengid rulers in the eleventh and twelfth centuries, and again during the Mamluk period in the thirteenth century (Leal 2020). Window glass fragments from Khirbat al-Minya with a plant ash signature are very probably of Mesopotamian origin (Adlington *et al.* 2020). Phelps and colleagues have tentatively dated six plant ash glass vessels from various Palestinian sites to the middle of the eighth century (Phelps *et al.* 2016). If correct, this would mean that these findings are the earliest Islamic plant ash glasses ever found in the Levant. Upon closer inspection, however, the dates attributed to these six objects cover a much wider range from the mid-eighth to the early ninth and up to the tenth centuries (supplementary table in Phelps *et al.* 2016). If the earliest occurrence of plant ash glass is to be argued for, then clearly the latest possible date of the time span needs to be applied, not the earliest. Taking a more cautious approach, the earliest securely dated Islamic plant ash glasses in the Syro-Palestinian tradition can then be attributed to al-Raqqa in Syria (Henderson 1995; Henderson 1999; Henderson *et al.* 2004).

The twin cities of al-Raqqa and al-Rafiqqa on the banks of the Euphrates in northern Syria were relatively minor towns during the Umayyad period, but rapidly developed into a sprawling urban complex, including industrial and commercial areas, during the early Abbasid caliphate (Heidemann 2006). The site was chosen as the new caliphal residence and seat of government by the Abbasid caliph Hārūn al-Rašīd (796-808 CE) at the end of the eighth century. Excavations conducted in 1992 and 1993 yielded evidence of several glass furnaces for primary production as well as the secondary working of glass at Tell Zujaj that, according to the archaeologists, supplied both the caliphal residence and the urban population during the late eighth and early ninth centuries CE (Heidemann 2006; Henderson 1995; Henderson 1999; Henderson *et al.* 2004; Henderson *et al.* 2005a; Henderson *et al.* 2005b). In 2010 another ninth-century tank furnace for the primary production of glass was discovered nearby, at the site of Tell Abu Ali, together with a circular glass furnace with an unknown purpose (Khalil and Henderson 2011). Four different compositional glass groups have been defined

that are associated with the glass processing installations at Tell Zujaj, one being a natron glass, while the other groups exhibit the characteristics of early Islamic plant ash glasses (Henderson *et al.* 2004). Unfortunately, none of the remains from Tell Abu Ali have yet been analysed or published.

There is no analytical or archaeological evidence for the primary production of natron-type glass at al-Raqqa (Henderson *et al.* 2005b). Rather, the natron glass from al-Raqqa appears to be closely related to Levantine glasses from Apollonia and Bet Eli'ezer in terms both of their chemical composition and isotopic signature, even though the Raqqa glass does not exactly match the material from either primary production site in the Levant (Fig. 33). The al-Raqqa glasses tend to have somewhat higher lime and lower soda levels than the glass from the primary furnaces at Apollonia. The lime lining of glass furnaces can occasionally contaminate the glass batch and thereby augment the lime concentrations (Chen *et al.* 2021), while prolonged or repeated heating can result in the loss of sodium (Freestone 2015). It is likely that cullet was the main raw material for further processing at al-Raqqa, and we can assume that glass cullet and raw glass derived from more than one primary production site (Henderson *et al.* 2005b). This explains the compositional variability of the natron-type glass group recovered from al-Raqqa.

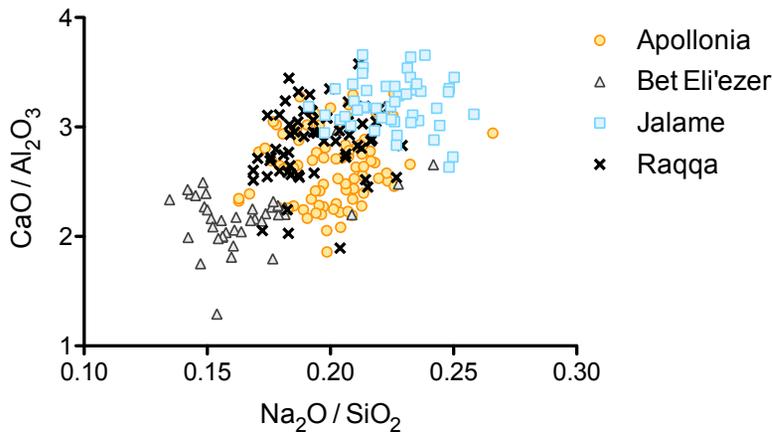


Fig. 33:

CaO/Al₂O₃ and Na₂O/SiO₂ confirm the compositional similarities between the natron glass from al-Raqqa and Apollonia-type Levantine I. Data sources: (Brill 1999) for Jalame; (Brems *et al.* 2018; Freestone *et al.* 2008b) for Apollonia; (Brems *et al.* 2018; Freestone *et al.* 2000; Freestone *et al.* 2015b; Phelps *et al.* 2016) for Bet Eli'ezer; (Henderson *et al.* 2004; Henderson *et al.* 2009b) for al-Raqqa.

The earliest plant ash glasses from the Bilâd al-Shâm

Raqqa group 1 & Raqqa group 4

The situation is very different where the plant ash glasses from al-Raqqa are concerned. There are clear indications of the local primary production of different plant ash glass types in the ninth, eleventh and twelfth centuries CE (Henderson *et al.* 2004; Henderson *et al.* 2005a; Henderson *et al.* 2020). Three different plant ash glass groups were defined, of which one (Raqqa 4) has a very large compositional spread in terms of both the silica-related elements as well as the plant ash component. This group was interpreted by Julian Henderson and colleagues as evidence of experimentation (Henderson *et al.* 2004; Henderson *et al.* 2005a). Independently of the exact nature and extent of primary glass production at al-Raqqa, there is strong evidence that some plant ash glasses were produced at Tell Zujaj and/or Tell Abu Ali in the early ninth century CE. This makes Raqqa one of the earliest attested Islamic plant ash glass production sites in Greater Syria. The failed attempt to produce glass from a mixture of Levantine coastal sand and plant ash that may underlie the great glass slab at Bet She‘arim in Israel dates from about the same time (Freestone and Gorin-Rosen 1999; Freestone *et al.* 2000). These findings lend support to the idea of experimentation with raw materials and glass recipes in the early phases of Islamic plant ash glassmaking. This also shows that the manufacture of plant ash glasses may have commenced in Greater Syria as early as in the last decade of the eighth or beginning of the ninth century, thus about a century or more before its start in Egypt.

Two different plant ash glass types (Raqqa 1 and Raqqa 4) were supposedly produced in ninth-century al-Raqqa, but they display very different compositional characteristics. One fragment of frit-like material from Tell Zujaj was analysed and corresponds to Raqqa 4 at the high end of the magnesium and the low end of the potassium oxide contents (Fig. 34a). Regardless of whether the fragment in question is indeed glass frit or merely unreacted batch material (Brill 2005a; Henderson 1999; Henderson *et al.* 2004; Phelps 2017), its presence implies that this type of glass was indeed manufactured at al-Raqqa. Almost 55% of the analysed glasses from the ninth-century contexts at Tell Zujaj correspond to the highly variable Raqqa 4 type, and about 30% correspond to Raqqa 1. While the latter is consistent with what is commonly associated with an eastern Mediterranean (Syro-Palestinian) Islamic soda-rich plant ash glass, Raqqa 4 exhibits features typical of Mesopotamian glasses with high magnesium and lower calcium and phosphorus levels (Fig. 34). In fact, glass from the Persian Empire dating to the Parthian and Sasanian periods tends to have very similar compositions, characterised by high

magnesium concentrations and on average lower lime and phosphorus contents, and a wide range of alumina concentrations. The high magnesium levels of these Mesopotamian glasses may derive from the use of specific plants as raw material and the influence of the magnesia-rich alluvial deposits of the Euphrates and Tigris rivers (Freestone 1991; Freestone 2006). The use of plant ash from the quaternary fluvial system of the Euphrates valley is supported by the strontium isotopic signature of most of the Raqqa plant ash glasses (Henderson *et al.* 2020).

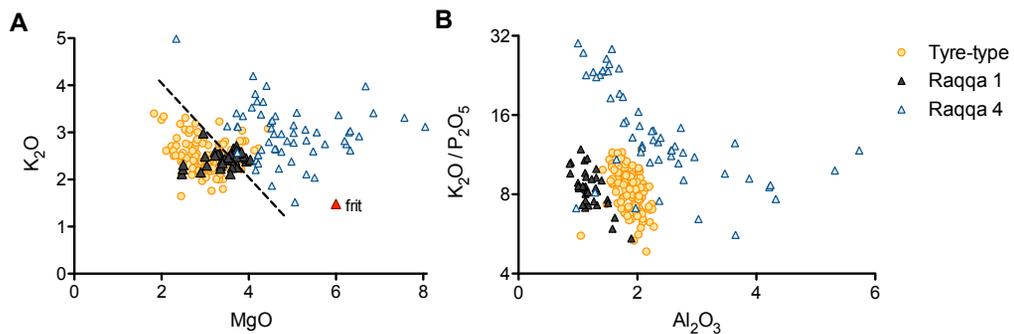


Fig. 34:

Compositional characteristics of the ninth-century plant ash glasses from al-Raqqa in comparison with Levantine material of Tyre-type plant ash glass. (a) Potassium and magnesium oxides typically separate Syro-Palestinian from Mesopotamian plant ash glass; the dashed line shows the proposed division between the two regional production areas; (b) ratios of potash to phosphorus reflect differences in the plant ash component, while the alumina levels showcase the relatively pure silica source underlying Raqqa Type 1 compared to glass from Tyre and Raqqa Type 4. Data sources: (Henderson *et al.* 2004; Henderson *et al.* 2009a) for al-Raqqa; (Freestone *et al.* 2000; Freestone 2002; Phelps 2017) for Tyre-type glass.

The similarities with Parthian and Sasanian glasses strongly suggest a transfer of skills and Mesopotamian glassmaking traditions to early Islamic al-Raqqa rather than an independent development. It is perfectly possible that Hārūn al-Rašīd brought glass workers experienced in Mesopotamian plant ash glass production to al-Raqqa to take charge of the development of the local glass industry that served the newly established caliphal residence. Textual sources indicate that this may well have been common practice. The ninth-century polymath, al-Ya‘qūbī, for instance remarked that the caliph al-Mu‘tasim had ordered skilled artisans, including ‘people who make glass’ to come from every town in the empire to his newly founded city of Samarra in 836 CE (Northedge 2014, p. 50). The construction of a new caliphal residence required the supply of considerable material resources within a relatively short period of time, and the Raqqa 4 glass type may reflect exactly this process. Glass workers familiar with Mesopotamian

recipes and raw materials may have gathered and established primary glassmaking at al-Raqqa. Raqqa 4 may thus not be considered proof of the emergence of a new soda-rich plant ash recipe as such, but rather a continuation (and refinement) of Mesopotamian practices and traditions. It is noteworthy that al-Muqaddasī does not mention glass in connection with al-Raqqa in his tenth-century geography of the world of Islam (Miguel 1993), stating that ‘It [al-Raqqa] abounds in Nature’s blessings, and yields the best soap and olives in plenty’ (Ranking and Azoo 1897, p. 230). By contrast, al-Muqaddasī does not fail to point out that ‘From Tyre come sugar, glass beads and glass vessels both cut and blown’ (Ranking and Azoo 1897, p. 296). So, at least in the tenth century, al-Raqqa was not renowned for its glass production, which may imply that it was not a major producer of raw glass or glass objects destined for a wider market.

The Raqqa 1 glass group on the other hand tells a different story, and may very well represent one of the earliest examples of a new Syro-Palestinian soda-rich plant ash glassmaking tradition that makes use of different raw materials, recipes and possibly even technologies. It is a relatively homogeneous group. According to my calculations, Raqqa 1 contains magnesium and potassium oxides between 2% and 4%, an average soda content of 13.8%, lime at 8.25%, and relatively low titanium oxide at 0.07% (Table 5). It is thus remarkably similar to the glass produced in tenth- and eleventh-century Tyre (Freestone 2002) and Levantine plant ash glasses from Israel (Phelps 2018) in terms of the plant ash component. Raqqa 1 and the glass from Tyre also share a common strontium isotope signature (Fig. 35; Freestone *et al.* 2009a; Henderson *et al.* 2009a; Henderson *et al.* 2020). This suggests that soda-rich plant ash may have been prepared following a similar formula, probably starting from related alkaline plants that grew in geologically comparable environments (Barkoudah and Henderson 2006; Ganio *et al.* 2013). In a recent study of the isotopic characteristics of early Islamic plant ash glasses, Julian Henderson and colleagues (Henderson *et al.* 2020) discovered that the majority of ninth- to fourteenth-century plant ash glasses from various sites in Greater Syria, including al-Raqqa, Tyre, Damascus and Beirut, have matching $^{87}\text{Sr}/^{86}\text{Sr}$ signatures compatible with the use of plants from Syrian semi-desert areas (Fig. 35).

	Na ₂ O	MgO	Al ₂ O ₃	SiO ₂	P ₂ O ₅	K ₂ O	CaO	TiO ₂	Fe ₂ O ₃
Tyre (n=9)	12.7	3.52	1.84	65.2	0.34	2.25	11.0	0.09	0.54*
stdev	1.2	0.33	0.3	1.5	0.05	0.19	2	0.01	0.05
Raqqa 1 (n=35)	13.8	3.43	1.21	67.5	0.29	2.44	8.25	0.07	0.53
stdev	1.2	0.4	0.22	1.5	0.05	0.17	1.3	0.01	0.22
Banias (n=13)	12.6	2.68	1.03	70.5	0.27	1.85	8.57	0.14	0.39
stdev	0.4	0.09	0.17	1.1	0.04	0.18	0.90	0.03	0.09

*excluding the dark blue samples BM7230-12

Table 5:

Average compositions and standard deviations of the glass samples from Tyre (Phelps 2017), ninth-century Raqqa 1 (Henderson *et al.* 2004), and Banias (Freestone *et al.* 2000).

Raqqa 1 differs from more or less contemporary glass assemblages from the Levant in the elements related to the silica source, such as aluminium and titanium as well as the neodymium isotope ratios (Fig. 35) that are much lower in the glass from al-Raqqa than in that from both Tyre and Banias (Freestone *et al.* 2009a; Henderson *et al.* 2009a; Leslie *et al.* 2006). New isotopic data from sand sources collected from various beaches on the Lebanese coast (Beirut, Sidon, Ghazieh, Tyre) as well as inland sites including the Euphrates river suggest that quartz-rich Syrian desert sand was used for the production of the al-Raqqa glass instead of a more local silica source from the Euphrates (Henderson *et al.* 2020). The Syrian geographer, Yâqût al-Hamawî (1179 – 1229 CE), mentioned in his *Kitab Mu‘Jam al-buldan* (Dictionary of Countries) that the ‘fine white sands’ from around Jebel Bishri, located between al-Raqqa and Palmyra (see Fig. 2), were collected and used for the production of glass in Aleppo (cited in Heidemann 2006, p. 40). The isotopic data confirm that sands like these could have been used for the production of early Islamic glass, including that of al-Raqqa (Henderson *et al.* 2020). The careful selection of silica sources that were rich in quartz and depleted in accessory minerals and feldspars for the primary production of glass has been observed in the context of early Abbasid Samarra (Schibille *et al.* 2018a).

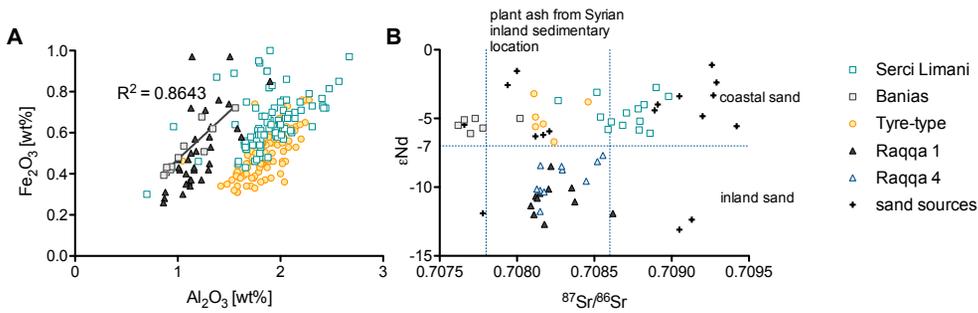


Fig. 35:

Levantine-type plant ash glasses from al-Raqqa (Raqqa 1), the primary workshop at Tyre, the secondary workshop at Banias and the Serçe Limani shipwreck. (a) Iron and aluminium oxide show a strong positive correlation in the Banias glasses and underpin the close relationship between Tyre-type glass from Israel and the finds from the Serçe Limani shipwreck, while confirming the singular nature of Raqqa 1; (b) strontium and neodymium isotope signatures separate the glass from Banias and the Serçe Limani from both Tyre and al-Raqqa glass in terms of the plant ash component, while confirming the use of a coastal silica source; Tyre and al-Raqqa share common strontium isotopes, but differ considerably with respect to their neodymium isotope signatures. Data sources: (Henderson *et al.* 2004; Henderson *et al.* 2009a) for al-Raqqa; (Degryse *et al.* 2010a; Freestone *et al.* 2000; Freestone 2002; Phelps 2017) for Tyre-type glass and Banias; (Brill and Stapleton 2012; Henderson *et al.* 2020) for Serçe Limani; please note that for Brill's data nominal neodymium values have been assumed between -3.1 and -5.8 in steps of 0.3 to compensate for the lack of Nd isotopes. (Degryse 2014; Henderson *et al.* 2020) for sand sources.

If the dating and interpretation of Tell Zujaj as a primary production location of Raqqa 1 glass in the ninth century are correct, then Raqqa 1 indeed represents the beginnings of a specifically Islamic soda-rich plant ash glassmaking technology that was to become typical of the Syro-Palestinian region. It also proved to be long-lasting. Over 70% of the glass analysed from the eleventh-century glassmaking complex at Tell Fukhkhari matches Raqqa 1, and only about 14% of the later glasses have Raqqa 4 compositions (Henderson *et al.* 2004). A possible scenario, then, is that the transformations in glass production at al-Raqqa, and particularly the choice of the raw materials, were inspired by Mesopotamian glassmakers, who may have initially produced Raqqa 4 glasses. These developments eventually led to the establishment of the Raqqa 1 recipe. The evidence for this is that Raqqa 1 is a relatively tightly clustered glass group that was apparently manufactured for several centuries to come. It is more probably the end-result of an established and well controlled glassmaking process and recipe rather than an early stage of experimental development. How the raw materials were selected and when or why they changed remain elusive, but the overlap between Raqqa 1 and Raqqa 4 in terms of their strontium and neodymium isotopic signatures implies that the

raw materials must all have been derived from the same geographical region with few exceptions. Some of the Raqqa 4 samples are closer to the Sasanian groups, indicating that not all of these glasses were produced locally (chapter 3).

Glass from the primary production site of Tyre

Reconstructing the evidence of early Islamic plant ash glass production in Syria-Palestine proves challenging as only limited analytical data on well contextualised and precisely dated vitreous material are available. This task is further complicated by the fact that glass assemblages from consumer sites are often made up of a variety of compositional groups that often originate from different geographical regions. An example of the complexities arising from the multifaceted provenance of samples is illustrated, for instance, in the highly diverse collection of glasses retrieved from al-Hadir in northern Syria. As judged from the archaeological evidence, the site dates to between the second half of the seventh and the thirteenth centuries CE, and importantly, no residual material from the pre-Islamic period has been found (Foy 2012b). The glasses that were analysed are more narrowly dated to the seventh to ninth centuries. The glass finds from al-Hadir thus provide a relatively precise window into early Islamic consumption patterns of vitreous materials not disturbed by earlier or later occupations at precisely the time when the transition to a plant ash recipe might be expected. No clear distinction could be made between the Umayyad and Abbasid phases on typological grounds, as Umayyad vessel types emerged from all levels of occupation (Foy 2012b). Of the 44 fragments that were analysed by Bernard Gratuze, 24 were of a natron-type base glass, sub-divided into three main compositional groups which included Egypt 1A and 1B, Bet Eli'ezer-type Levantine II and a heterogeneous group of mostly mixed and recycled glasses (Gratuze and Foy 2012). The remaining 20 samples were soda-rich plant ash glasses with a relatively wide compositional range. Bernard Gratuze and Danièle Foy separated the plant ash glasses into two groups based on their alumina and lime concentrations (groups 4 and 5 in Gratuze and Foy 2012). At the time of publication, the authors tentatively proposed an Egyptian provenance for the glasses of al-Hadir group 4 based on their heavy element signatures (Y, Ce, Zr), and mixed origins for group 5 (Gratuze and Foy 2012). With more analytical data on contemporary plant ash glasses now available, it has since transpired that all the plant ash glasses from al-Hadir are consistent with Mesopotamian glassmaking recipes, indicated above all by their elevated chromium to lanthanum ratios. Hence, there are no indications of the presence of plant ash glasses with Syro-Palestinian characteristics among the archaeological record of al-Hadir up to and including the ninth century CE. In fact, no soda-rich plant ash glass with a Syro-Palestinian

signature that can be safely attributed to before the turn of the ninth century CE has been found anywhere. Based on all the currently available analytical data taken together, there is no conclusive evidence for Levantine plant ash glass production prior to the ninth century CE, and it can be inferred that the beginning of Islamic plant ash glassmaking in Greater Syria belongs firmly to the ninth century CE.

The only known primary production sites for plant ash glasses in the Levant dating to the early Islamic period are four large furnaces at Tyre, Lebanon (Aldsworth *et al.* 2002; Freestone 2002), and possibly the large slab of glass found *in situ* at Bet She‘arim, Israel (Freestone and Gorin-Rosen 1999). The glass slab from Bet She‘arim will not be considered further as it represents a failed attempt at glassmaking and the available analytical data are limited. The glassmaking activities at Tyre are generally dated to the tenth and eleventh centuries based on associated finds, but a somewhat broader life-span extending into earlier and/or later periods cannot be entirely ruled out (Aldsworth *et al.* 2002, p. 65). The capacity estimate of Tyre Furnace 1, which is the largest furnace and the only one with obvious evidence of glassmaking, is 37 tons, whereas the smallest, Furnace 3, would have produced an estimated 13 tons of raw glass (Aldsworth *et al.* 2002). All four furnaces appear to have been used several times. There can be no doubt that raw glass was manufactured here on an industrial scale and destined for an export market. As early as the tenth and certainly by the eleventh century, Tyre had become famous for its glass, which was exported to various countries, including Egypt. This is reflected in written sources such as al-Muqaddasī’s geography (Ranking and Azoo 1897, p. 296) and the Cairo Geniza (Gil 1997, p. 238), and has been confirmed by our recent analytical evidence of tenth- and eleventh-century Islamic glass weights from Egypt (Schibille *et al.* 2019).

The Tyre plant ash glasses share some features with Levantine natron-type glasses with respect to the silica-related elements, namely their relatively low titanium and iron oxide contents (Tables 4 and 5). Neodymium isotopes furnish further proof that the Tyre plant ash glasses, like Levantine natron glass, were made from Levantine coastal sands, despite the relative heterogeneity of their isotopic composition (Degryse *et al.* 2010a). The authors attributed these variations to stratigraphic differences in the sediments that had formed over time at the isthmus of Tyre and that are assumed to vary according to climatic changes (Degryse *et al.* 2010a). The ϵ_{Nd} values range from -7 to -3 and are perfectly consistent with the isotopic signatures of Levantine coastal sands, and in this respect clearly differ from the plant ash glasses from al-Raqqa (Fig. 35b; Henderson *et al.* 2020). As regards the elements associated predominantly with the plant ash, the glasses from Tyre contain moderate alkali and alkaline earth elements, phosphorus (Fig. 34) and relatively high lime concentrations (Table 5). The strontium isotopic

signature of the Tyre samples, indicative mainly of the plant ash, is remarkably similar to that of Raqqa 1 and Raqqa 4, matching the $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of halophytic plants sampled from inland areas of Syria and the Lebanon (Fig. 35; Freestone *et al.* 2009a; Henderson *et al.* 2009a; Henderson *et al.* 2020; Leslie *et al.* 2006). It appears, then, that Tyre glass, like Levantine natron glasses, was made from coastal sand and a plant ash comparable to the majority of the plant ash glass from al-Raqqa. We can therefore assume that the plant ash used for the production of the Tyre and al-Raqqa glass derived from a shared geographical region dominated by a common geology (Henderson *et al.* 2009a; Henderson *et al.* 2020). The trade in plant ash is a feasible explanation for these common characteristics (Ashtor and Cevdalli 1983; Freestone *et al.* 2009a; Leslie *et al.* 2006). The trade in Syrian plant ash is well documented for later periods (Ashtor and Cevdalli 1983) and, as suggested previously by Ian Freestone and colleagues (Freestone *et al.* 2009a), the similarities between Raqqa and Tyre glass indicate that plant ash may have been traded already during the ninth and tenth centuries. As a result, the same plant ash could have been combined with very different silica sources, which adds another layer of complexity to the identification and definition of production groups. The use of the same plant ash in combination with two distinct silica sources was observed, for example, in the context of the Sasanian glass assemblage from Veh Ardašîr (Mirti *et al.* 2008; Mirti *et al.* 2009), supporting the hypothesis that plant ash may have been a commodity early on (see chapter 3 for a more detailed discussion on the isotopic characteristics of early Islamic plant ash glass assemblages).

Glass from the Serçe Limani shipwreck and the secondary workshop at Banias

The glass recovered from the shipwreck of the Serçe Limani which had sunk off the coast of Bodrum in southwest Turkey in the first half of the eleventh century (Bass *et al.* 2009) has long been linked to the primary production installations at Tyre (Brill 2009). New neodymium and strontium isotopic data on samples from the Serçe Limani have now revealed that the glass was indeed most likely produced from Levantine coastal sands (Henderson *et al.* 2020). The neodymium isotopes of the samples ($-6 < \epsilon\text{Nd} < -2.75$) match those of the glass produced at Tyre and Levantine sand sources more generally (Fig. 35b). As Julian Henderson and colleagues have pointed out, the use of a coastal beach sand may not be surprising since the glass was destined for export, but other sources cannot be excluded entirely (Henderson *et al.* 2020). Interestingly, the Serçe Limani glass differs from the output of the Tyre glass factory as well as the al-Raqqa glasses in terms of its higher $^{87}\text{Sr}/^{86}\text{Sr}$ ratios, with the exception of a large plate (#3545)

(Fig. 35b). The distinct strontium isotopic signature of the Serçe Limani glass rules out the use of plant ash from halophytic plants from Syrian semi-desert areas dominated by sedimentary geology. Based on these findings, it is unlikely that the Serçe Limani glass was manufactured in Tyre (Henderson *et al.* 2020). This implies the existence of a hitherto unknown primary glass production site elsewhere along the Levantine coast which must have been active in the early eleventh century CE, and which used silica sources collected from Levantine beach deposits in combination with a different type of plant ash, possibly from plants grown in the coastal region as well (Henderson *et al.* 2020). The isotopic similarities between the Serçe Limani glass and the first-century glass from Dibba in the United Arab Emirates (Van Ham-Meert *et al.* 2019) are interesting in this respect because they demonstrate that plants for the production of alkali-rich ashes had long been harvested from geologically different soils, and that the isotopic fingerprint of the Serçe Limani glass is not an isolated case.

Similarly, the distinct $^{87}\text{Sr}/^{86}\text{Sr}$ values of the glasses from the secondary production site of Baniyas (Israel), dated between the tenth/eleventh and thirteenth centuries CE, reflect the use of yet another type of plant ash (Fig. 35b). According to Julian Henderson and colleagues (Henderson *et al.* 2009a; Henderson *et al.* 2020), the unusually low $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of the Baniyas glass points to the use of plants from a basaltic environment such as the one south of Damascus for instance. The $\delta^{18}\text{O}$ and ϵNd data on a small number of samples from Baniyas suggested the use of a Mediterranean coastal sand similar to that used in the Tyre furnaces (Degryse *et al.* 2010b; Freestone *et al.* 2009a; Leslie *et al.* 2006). However, the compositional data suggest otherwise. Chunks of raw glass found in Baniyas have consistently lower aluminium (positively correlated with iron; Fig. 35a), higher titanium and zirconium levels, reflected in very different Th/Zr and La/TiO₂ ratios compared to Tyre-type plant ash glass (Fig. 36). Whereas the Tyre samples are at the higher end of both ratios, consistent with Levantine natron glasses, the Baniyas glass chunks exhibit much lower La/TiO₂ and Th/Zr ratios akin but not identical to Egyptian primary production groups represented by the natron groups Egypt 1A and Egypt 1B. As already noted, the $^{87}\text{Sr}/^{86}\text{Sr}$ signature furthermore indicates that the plant ash that was used for the Baniyas glasses must have derived from different areas. Baniyas glass is distinct from the Tyre glass also in the absolute magnesium and potassium oxide contents (Table 5). Taken together, it appears that the Baniyas glass is the result of very different raw materials. Baniyas was a secondary glass workshop and raw glass was most certainly imported from somewhere else (Freestone *et al.* 2003a). A local supply as suggested by Henderson *et al.* (2020) is doubtful, given the distinct isotopic and compositional features of the Baniyas glass which do not match any known primary production group and/or silica source, or

those of other assemblages from consumer sites. The primary production location of this type of plant ash glass is yet to be determined. The compositional and isotopic map of early Islamic plant ash glasses is certain to evolve as more data on well contextualised and dated assemblages are added, but it underlines the complexities of early Islamic plant ash glass production and working in Greater Syria by the tenth/eleventh century CE.

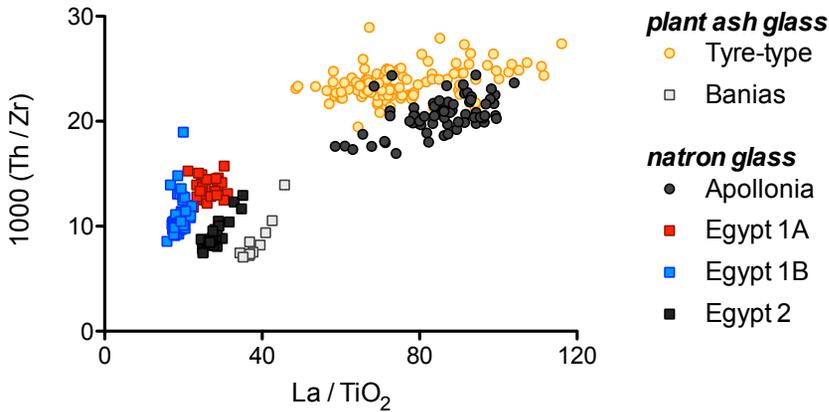


Fig. 36:

Comparison of Tyre-type and Banias plant ash glass with Egyptian and Levantine natron glass reference groups. Th/Zr and La/TiO₂ ratios suggest similarities between plant ash glass from Tyre and Levantine natron glasses, while the plant ash glasses from Banias have no clear parallels but bear some resemblance to the natron-type groups Egypt 1A, Egypt 1B and Egypt 2 in terms of their high zirconium levels. Data sources: (Brems *et al.* 2018) for Apollonia; (Phelps 2017) for Tyre and Banias; (Schibille *et al.* 2019) for Egyptian groups.

The elemental composition in combination with the isotopic fingerprints of early Islamic plant ash glasses allows about four to five production centres in Syria-Palestine to be distinguished (Henderson *et al.* 2020). Early Islamic plant ash glass of the Levantine tradition is primarily characterised by relatively high levels of sodium, moderate potassium, magnesium and phosphorus oxides, high contents of lime and low silica-related elements such as aluminium, titanium, iron, zirconium and REE (Fig. 37). The plant ash component as well as the silica sources can potentially vary, and can be distinguished on the basis of their neodymium and strontium isotopes. On the one hand, there is evidence for the continuous use of sand from the Levantine coastal area (Tyre, Serçe Limani, perhaps Banias), reflected in the relatively high neodymium isotope signatures. The silica source exploited for the primary production of Raqqa 1 as well as Raqqa 4 certainly did not derive from the same littoral region as they have considerably lower neodymium values, but perhaps came from the area around Jebel Bishri, southeast of al-Raqqa, famous

for its white sands (Henderson *et al.* 2020). The strontium isotope ratios further suggest the use of at least three different types of plant ash. The most common type, used for the glass production at Tyre and al-Raqqa, corresponds to plants growing in regions with Cretaceous, Eocene and Neogene sedimentary geologies of inland Syria (Henderson *et al.* 2020). The data from the Serçe Limani shipwreck and the secondary glass workshop at Baniyas reflect the use of plant ash from different areas. In the case of the Serçe Limani plants from saline coastal soils may have been used, while the chemical and isotopic composition of the Baniyas glass does not allow for a clear attribution. By the early eleventh century several primary glass productions were evidently active in Syria-Palestine, producing glasses with a characteristic compositional and isotopic range.

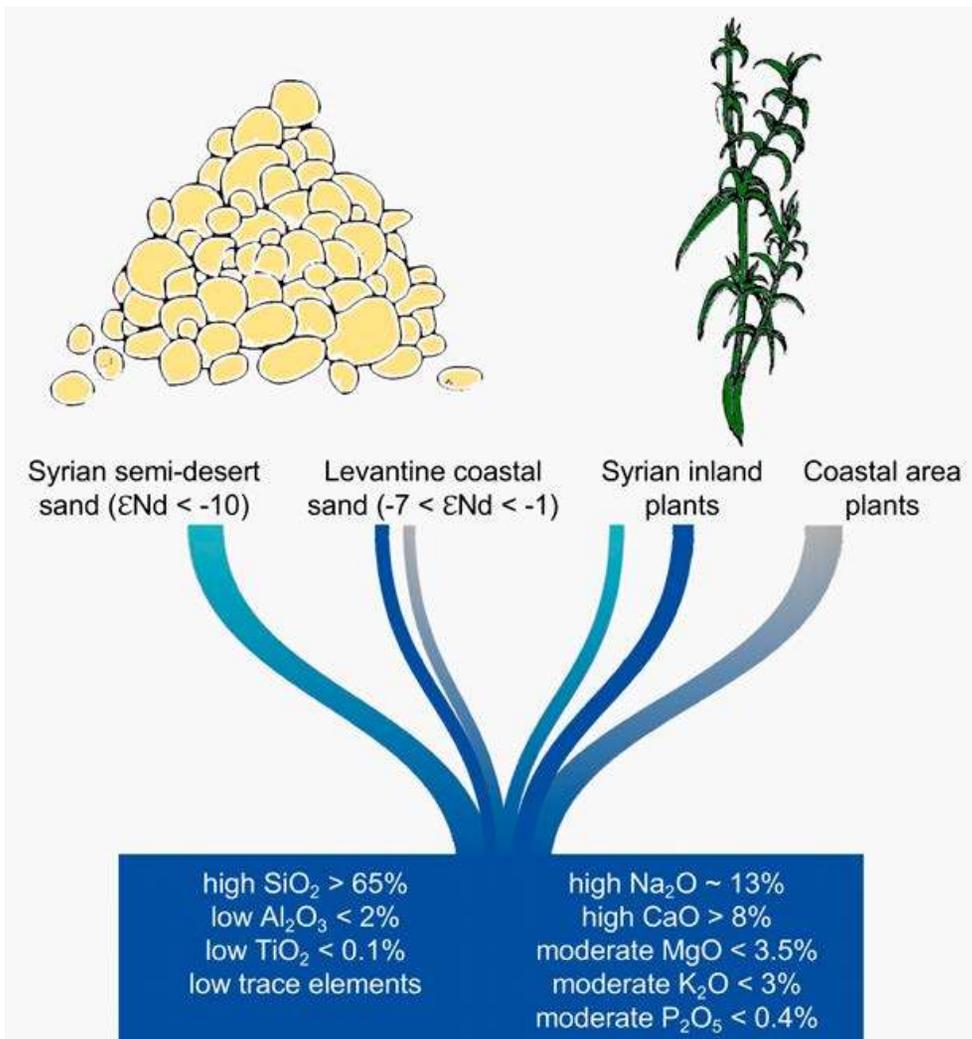


Fig. 37: Schematic representation of the compositional and isotopic characteristics of Levantine plant ash glasses (9th – 11th centuries CE)

Ruptures and shifts in the production of glass in the Levant

A comparative approach and increasing number of compositional and isotopic data allow us gradually to build a more complete picture of the changes in the glassmaking industry in the Bilād al-Shām during the early Islamic period. This model is certain to be refined as more data and better chronologies are included. The relationship between centres of production and the sources of the raw materials is much more complex than is often assumed. By the eighth century, significant ruptures and shifts in the supplies of raw glass can be gleaned from glass assemblages from consumer sites (Phelps *et al.* 2016) as well as the monumental mosaic decorations in Damascus and Khirbat al-Minya (Adlington *et al.*, 2020). The small proportion of Levantine glasses among the mosaic tesserae from the Great Mosque in Damascus suggests that production of natron glass may have already been severely restricted in the coastal regions of Syria-Palestine. Some Levantine glasses are still present in the form of Apollonia-type Levantine I, which may represent reused and/or recycled material, as well as isolated occurrences of the eighth-century Beth Eli'ezer-type Levantine II. The major source of raw glass supply in the eighth century, however, was Egypt, first in the form of Egypt 1A and the sub-category Egypt 1Ax, then, starting presumably in the second half of the eighth century, in the form of Egypt 2 (Phelps *et al.* 2016). The import of a large consignment of Egyptian glass is striking, considering that until this point, Syria-Palestine appears to have been effectively self-sufficient and a net exporter of raw glass. Roman antimony-decoloured glasses are almost completely absent from the archaeological record of the Levant, and late antique glass groups from Egypt such as HIMT, Foy 3.2 and Foy 2.1 are likewise relatively rare. In turn, Beth Eli'ezer Levantine II glass does not seem to have been exported to the western Mediterranean, which a century earlier had received large quantities of fresh glass supplies from the Levantine coast, as judged by our recent findings about the vitreous materials from the Iberian Peninsula. Perhaps these changing patterns have to be seen in the context of the wider commercial trends at the time. At Beirut, for example, the Umayyad ceramic deposits (700-750 CE) show a substantial shift in the origins of amphorae and fine wares when compared to the late Byzantine period (Reynolds 2003; Reynolds 2018). Absent are many of the regional products that were quite common during the sixth and seventh centuries, while the number of Egyptian finds increased dramatically (Reynolds 2003). These parallels between the ceramic deposits and glass finds during the Umayyad period imply a strong commercial link with Egypt and possibly the decline of the local industries more generally.

Written sources paint a picture of Syria-Palestine around the time of the Arab conquest as a place of agricultural communities, and not of thriving commercial centres (Kennedy 1985, p. 148). Intriguingly, the ninth-century historian Baladhuri explicitly commented on the absence of any industry along the Syrian coast, by which he possibly meant the shipbuilding industry which, according to Baladhuri, was confined to Egypt (Khuri Hitti 1916, p. 180; Kennedy 1985, p. 148). An economic decline and drastic decrease in population, however, appear to have been set in motion long before the arrival of the Arabs, around the middle of the sixth century, as a result of a devastating bubonic plague, earthquakes and the war between the Byzantine and Persian Empires (Kennedy 1985). An economic revival and growth are noticeable towards the end of the seventh and particularly in the first half of the eighth centuries CE (Walmsley 2000). Intensification of commercial activities in the region could be expected, given the shift in Mediterranean power structures. By the late seventh century the Bilâd al-Shâm had become the geo-political centre of a vast Umayyad caliphate with Damascus as its capital (Fig. 1). From the reign of the Caliph ‘Abd al-Malik (685-705 CE) to the Abbasid rebellion of 748-750 CE, the Bilâd al-Shâm once again enjoyed economic and cultural prosperity. With the Abbasid ascent and the foundation of the new imperial capital at Baghdad came a geographical re-orientation towards Iraq (Kennedy 2007, p. 97; Walmsley 2000). It is around this time that natron glass production in Syria-Palestine ceased.

The adoption of a new plant ash recipe is not attested to before the turn of the ninth century CE. As far as the available archaeological and archaeometric evidence goes, al-Raqqā appears to be the earliest known Islamic plant ash glassmaking site with the compositional characteristics of Syro-Palestinian glass (Raqqā 1) as opposed to Mesopotamian productions (Raqqā 4). The sequence of glassmaking activities at al-Raqqā is not entirely conclusive, but it seems likely that the plant ash glassmaking technology may have been introduced to or at least been inspired by Mesopotamian glassworkers who were brought to al-Raqqā when the caliphal residence was established there in 796 CE. That artisans and craftsmen from different regions were called upon for caliphal building campaigns is well documented in textual sources, in the context both of the monumental mosques at Damascus, Medina and Mecca, as well as the foundation of the caliphal city of Samarra in Iraq. This is not to say that glassworkers in the Levant were not familiar with the plant ash glassmaking tradition, but the re-introduction of plant ash as the main fluxing agent in glassmaking after the eastward shift of the Abbasid caliphate is unlikely to be a coincidence. By the ninth century, plant ash glasses of different compositions (Mesopotamian and Levantine) were in circulation (Phelps 2017); however, Levantine plant ash glasses remain rare. In al-Hadir none of the analysed

fragments can be confidently attributed to a Levantine plant ash glass production, and among 27 glasses from Ramla that were assigned to the ninth century, only 12 were attributed to a Tyre-like Levantine plant ash glass. Moreover, samples that are dated to the ninth to eleventh centuries were also included in this selection (Phelps 2018). Hence, the available data on glass assemblages from consumer sites in Israel do not provide the necessary temporal resolution to draw more accurate conclusions than that different types of Levantine plant ash glasses appeared on the scene no earlier than the ninth century CE.

Distribution patterns and the glass market

While the available evidence is still sketchy, it indicates that the early Islamic glass industry and the trade in vitreous materials in the Levant followed different developments from those observed in Egypt, even though there are also some similarities. By the eighth century, Islamic natron glass variants (Levantine II, Egypt 1A) had replaced the late antique glass groups in both Syria-Palestine and Egypt. The scale of production was considerable to begin with, as reflected in the size and capacity of the tank furnaces at Beth Eli‘ezer and the relative importance of Egypt 1A and Egypt 1Ax base glasses among the mosaic tesserae from Damascus and Khirbat al-Minya. In the case of Beth Eli‘ezer, however, the material does not appear to have been traded outside Syria-Palestine. Even though the glass trade out of Egypt had contracted as well, the glass manufacturers in Egypt still produced a surplus to meet the demands of several monumental construction and decoration campaigns in Syria and Palestine, and perhaps even of the Great Mosques in Medina and/or Mecca. According to al-Muqaddasī, the latter were signed by Syrian as well as Egyptian mosaicists (Ritter 2017, p. 208). Natron glass production came to an end in the Levant presumably sometime in the late eighth century. In Egypt, by contrast, production of Egypt 2 lasted until the middle or second half of the ninth century CE. The reasons for the abandonment of natron as the fluxing agent are still not obvious. As regards the situation in Greater Syria, it has been suggested that the availability of mineral soda was limited (Phelps *et al.* 2016) and that this had a knock-on effect on what type of glass and how much of it was produced. It seems unlikely that a shortage of natron at its source triggered a reduction in natron glass production in the eighth century as such, for Egyptian glasses, especially the mosaic tesserae from Damascus, continued to have very high soda contents, higher even than in some of the late antique glass groups from Egypt. This observation may in fact provide part of the explanation.

Within a very short period of time the Umayyad caliphs undertook numerous monumental building projects, which triggered a huge demand for architectural

glass and thereby increased the burden on the glass industry. Large quantities of material resources had to be mobilised for the mosaics of the Dome of the Rock in Jerusalem (begun in 691 CE), the al-Aqsa mosque, also begun during the reign of ‘Abd al-Malik but completed by his son al-Walīd perhaps as late as 715 CE, and the courtyard and interior walls of the Great Mosque of Damascus (705/706 – 715 CE), in addition to the mosques in Mecca and Medina which are all reported to have been decorated with mosaics. The main supplier of glass tesserae for the Great Mosque in Damascus was Egypt, presumably because the local glass industry in Syria-Palestine was unable to meet the sudden surge in demand and/or secondary mosaic workshops were no longer active there. In other words, glass tesserae were probably supplied by Egypt upon a special caliphal request. Special commissions to meet the demands of monumental edifices have been observed in the context of gothic stained glass windows, for instance the mid-thirteenth-century stained glass windows of the Sainte-Chapelle in Paris (Lagabrielle and Velde 2015). A similar scenario for large building campaigns of imperial patronage, which required enormous material resources in the early Islamic world, is conceivable. The result was a previously unidentified compositional group (Egypt 1Ax) with unexpectedly high soda levels, but which is otherwise intimately related to Egypt 1A. The production of large quantities of glass with high soda contents may have put an unusual strain on the soda sources in Egypt, a fact which is likely to have limited, if not led to the complete cessation of, soda exports. The final products (i.e. the mosaic tesserae) or the intermediate coloured glass cakes were in turn shipped to the Levant, indicating that the trading system and regional trade networks were still intact. The surge in glass production in Egypt may have been the final nail in the coffin for the Levantine natron-type glass industry.

The flow of material resources changed its direction again sometime between the second half of the ninth and the late tenth century CE. The primary manufacture of natron-type glass appears to abate in Egypt during the ninth century, whereas in Greater Syria an upswing is noticeable, this time in the form of a new soda-rich plant ash recipe. Several compositional plant ash groups were in circulation from the ninth century, but the scale and range remained restricted. Some Syro-Palestinian plant ash glasses were identified among the ninth-century glass assemblages at Samarra in Iraq (Schibille *et al.* 2018a) and the Sinai Peninsula (Kato *et al.* 2009; Kato *et al.* 2010), and numerous consumer sites in Israel (Phelps 2018). Starting in the late tenth century, large shipments of Levantine plant ash glasses from Tyre made their way to Egypt (Schibille *et al.* 2019), and soon, it seems, also northwards along the coast of Asia Minor, with the Byzantine Empire as a possible destination. The main cargo of the Serçe Limani which sank off the coast of Bodrum in southwest Turkey (Bass *et al.* 2009) included large quantities

of plant ash glass that is consistent with a Syro-Palestinian provenance. Individual objects of soda-rich plant ash glass with Levantine characteristics have been found in ninth- to tenth-century Italy, at Grado and Vicenza (Silvestri *et al.* 2005), and around the same time in the Venetian area (Verità 2013), perhaps somewhat later in southern Italy at Bari (Neri *et al.* 2019), and in greater quantities in tenth- to eleventh-century Sicily (Schibille and Colangeli 2021). The mosaic tesserae from eleventh-century Torcello also bear witness to the presence of soda-rich plant ash glass of probably Levantine origin in the Venetian lagoon (Andreescu-Treadgold and Henderson 2006). Some eastern Mediterranean plant ash glasses have been documented in ninth-century Spain at Córdoba (De Juan Ares *et al.* 2021; Duckworth *et al.* 2015), and a generation or two later in Ciudad de Vascos (De Juan Ares and Schibille 2017b). It almost appears as if Levantine glass production and trade started where it had left off about two centuries earlier. However, it never again reached the same dominance as natron-type glasses, either in terms of quantity or as regards its geographical distribution. The primary glass industry in Egypt does not seem to have recovered quite to the same extent or at the same rate. Whereas Levantine and Mesopotamian soda ash glass turned up in the western medieval world, in Spain and Italy, Egyptian plant ash glass is extremely rare. For example, out of more than 200 analysed samples from Madīnat al-Zahrā' in Córdoba dating to the tenth century, only a single fragment appears to be an Egyptian import (unpublished). Similarly, only two objects out of more than 200 glass fragments from ninth- to sixteenth-century Sicily show compositional characteristics that correspond to an Egyptian provenance (Colangeli 2022). If the presence or absence of glass groups at consumer sites in the western Mediterranean is indicative of the scale of primary production, then it is reasonable to conclude that the Egyptian plant ash glass industry developed later and on a smaller scale than that on the Levantine coast. Egypt, however, became famous for luxury high-end products. The development of the silver stained glass technique, for instance, is attributed to Coptic craftsmen prior to the advent of Islam, and was eventually transmitted to Syria and possibly Mesopotamia in the eighth and ninth centuries CE (Carboni and Whitehouse 2001). A particularly exceptional epigraphic silver-stained vessel with an Egyptian natron glass composition was found in eighth- to ninth-century Córdoba and ranks among the earliest such finds in the entire Islamic world (De Juan Ares *et al.* 2020).

Glass production in Mesopotamia: preservation of plant ash recipes

The previous two chapters have shown that the extensive research over the last decade, particularly on glass from the Bilâd al-Shâm, has revealed a clearer picture of the evolution of the Mediterranean glass industry from the late antique to the early Islamic periods. The technological changes from natron glassmaking to a soda ash recipe at the turn of the ninth century in Syria was preceded by the importation of considerable quantities of Egyptian glass in the eighth century (Adlington *et al.* 2020; Freestone *et al.* 2015b; Gratuze and Foy 2012; Phelps *et al.* 2016). In Egypt natron glass production continued well into the ninth century, and the appearance of an Egyptian plant ash glass towards the latter part of the tenth century was accompanied by the arrival of large shipments of Levantine soda ash glass, possibly from Tyre or related location (Gratuze 1988; Kato *et al.* 2010; Schibille *et al.* 2019). The situation east of the Euphrates river, in Mesopotamia and Central Asia, was fundamentally different. Both regions have long been recognised as important glass production zones (Brill 2001; Schibille *et al.* 2018a; Wypyski 2015). Mesopotamia was most likely the birthplace of glassmaking during the Late Bronze Age from where it was subsequently transferred to Egypt (Angelini *et al.* 2019; Kemp *et al.* 2020). While Roman and late antique glasses in Egypt and Greater Syria were typically of a natron-type composition, in Mesopotamia soda-rich plant ash was used as the main fluxing agent throughout the Persian, Parthian and Sasanian Empires (Brill 1999; Freestone 2006; Ganio *et al.* 2013; Shortland *et al.* 2018; Van Ham-Meert *et al.* 2019). In recent years a growing body of glass assemblages from various Mesopotamian and Iranian sites have been analysed, notably those from Samarra (Schibille *et al.* 2018a), Nishapur (Wypyski 2015) and Siraf (Swan *et al.* 2017) as well as some individual samples from numerous sites which are now stored at the Iran National Museum (Salehvand *et al.* 2020). To this we can now add a sizeable collection of glass samples from Merv (Turkmenistan, Meek *et al.* in preparation).

Even though the volume of compositional data has increased, it is still insufficient really to define the modifications of the glass industry during the

early Islamic period, especially since pre-Islamic glasses from Mesopotamia and Central Asia have so far not been subject to intensive investigation. The only relatively large corpus (n=88) of well contextualised and dated glass finds that has been analysed is that from the Sasanian site of Veh Ardašīr (Fig. 1), one of several cities and suburbs that sprawled along both banks of the Tigris river and made up the metropolis of Ctesiphon during the Sasanian period (Ganio *et al.* 2013; Kröger 1993; Mirti *et al.* 2008; Mirti *et al.* 2009). The relative lack of analytical data presents a severe problem in tracing any potential technological changes from the Sasanian through to the early Islamic periods, not least because Sasanian and early Islamic glass assemblages have on occasion proved difficult to distinguish on typological or archaeological grounds (Kröger 1995; Simpson 2014b).

In the absence of any archaeological evidence for glassmaking in Mesopotamia prior to the Islamic period and the glassmaking installations at al-Raqqā, we rely exclusively on analytical data and the prevalence of distinct compositional groups across different regions. The data from Veh Ardašīr provide the greatest detail yet of any Sasanian glass assemblage, including a range of trace elements as well as strontium and neodymium isotope signatures, and therefore form the basis for the following discussion of the Sasanian glassmaking tradition. This is complemented, where possible, by data from Brill (Brill 1999) and a recent study of first-century glasses from Dibba, United Arab Emirates (Van Ham-Meert *et al.* 2019), which proved to be relevant comparative material. In addition, I included some unpublished data from Sasanian Ctesiphon, even though the chronological attribution of some of the samples is not beyond doubt. There is good reason to believe, however, that some of the glass finds are in fact Sasanian as opposed to Islamic. The ongoing Sasanian projects at the British Museum led by St John Simpson will in the near future most certainly shed further light on the chemical and typological features of Sasanian glass. What follows should therefore be considered a preliminary survey of our current understanding of Mesopotamian and Central Asian glass. Future analytical studies will tell whether the conclusions can stand up to scrutiny.

Sasanian glassmaking tradition - Veh Ardašīr *et al.*

The broad category of Mesopotamian plant ash glasses has in the past been distinguished from Egyptian, Levantine and the rare Roman plant ash glasses based on their higher magnesium and potassium (e.g. Fig. 34) and on average lower calcium and phosphorus contents. This has usually been interpreted as the result of using different plants to prepare the soda-rich ashes (Mirti *et al.* 2009; Phelps 2018; Schibille *et al.* 2018a; Swan *et al.* 2017). A further subdivision of plant ash glasses

into three regional primary production groups (Mediterranean, Mesopotamian Type 1 & Type 2) has recently been proposed, using a combination of magnesia to lime ratios and alumina levels (Phelps 2018). This is indeed a fairly good initial assessment of the various plant ash glass groups, but the model is not invariably applicable. Using these criteria, some of the high alumina plant ash glasses from Egypt and Spain, for instance, would be consistent with Mesopotamian Type 1, and samples from Siraf (Iran) that were shown to be probably the output of a local or regional glass production would seem to correspond to the Levantine and Egyptian plant ash groups (Swan *et al.* 2017). Additional distinguishing criteria are therefore needed to consolidate the classification into specific production zones. A comparison of the fluctuations in the refractory and non-volatile elements of Late Bronze Age glasses and alluvial deposits of the Nile on the one hand and the Tigris and Euphrates on the other has identified chromium to lanthanum ratios as a promising indicator for the discrimination of glass finds from the two geographical regions (Shortland *et al.* 2007). In accordance with the higher Cr/La ratios of Mesopotamian clay deposits compared to the Nile silts, glass finds of supposedly Mesopotamian provenance tend to have higher Cr/La ratios than Egyptian and Levantine glasses. However, even the chromium to lanthanum ratios are not infallible and, as will be shown, multiple criteria have to be used in combination to define Mesopotamian plant ash glass. Similarly, the observation made by Julian Henderson and colleagues (Henderson *et al.* 2016) that the Cr/La and Li/K ratios increase from the Mediterranean coast towards Iran can only partially be upheld.

Glass group	Date	Na ₂ O	MgO	Al ₂ O ₃	SiO ₂	P ₂ O ₅	K ₂ O	CaO	TiO ₂	MnO	Fe ₂ O ₃	Cr	Sr	Zr	Ce
Sasanian 1a (n=29)	3 rd – 7 th stdev	15.9 1.5	4.06 0.41	2.27 0.56	60.4 2.7	0.32 0.06	3.33 0.43	6.68 0.89	0.19 0.04	0.15 0.41	1.11 0.32	84.1 25.7	392 73	173 54	15.4 1.6
Sasanian 1b (n=17)	4 th – 7 th stdev	15.8 1.3	4.01 0.50	2.33 0.35	60.3 2	0.27 0.06	3.36 0.36	6.71 0.97	0.13 0.03	0.09 0.20	0.97 0.18	91.6 34.0	425 104	41.2 16.9	10.2 1.6
Sasanian 2 (n=12)	4 th – 7 th stdev	17.6 0.7	7.39 0.77	1.61 0.41	58.2 2.6	0.14 0.02	2.89 0.29	5.89 1.01	0.09 0.02	0.20 0.23	0.56 0.14	58.3 27	510 95	45.3 23.7	7.75 1.41

Table 6:

Average compositions and standard deviations of Sasanian glasses from Veh Ardašir. Metal oxides are given as [wt %], Cr, Sr, Zr and Ce are given as [ppm]. Data sources: (Mirti *et al.* 2008; Mirti *et al.* 2009).

Piero Mirti and colleagues (2008 & 2009) originally distinguished two compositional groups of plant ash glasses among the assemblage from the third- to seventh-century Sasanian city of Veh Ardašīr, of which one was further subdivided into Sasanian 1a and Sasanian 1b. While the partitioning into Sasanian 1 and Sasanian 2 is based on elements associated with the plant ash component such as magnesium, potassium and phosphorus oxides (Fig. 38a), the difference between Sasanian 1a and 1b lies in the silica source reflected in, for instance, zirconium, cerium (Fig. 38b) and rare earth elements (Mirti *et al.* 2008; Mirti *et al.* 2009). To be more precise, Sasanian 2 glasses have exceptionally high magnesia concentrations ($MgO > 6\%$) and low phosphorus levels ($P_2O_5 < 0.2\%$), while Sasanian 1a and Sasanian 1b share features related to the plant ash component, having lower magnesia but higher potash and phosphorus levels (Table 6; Fig.

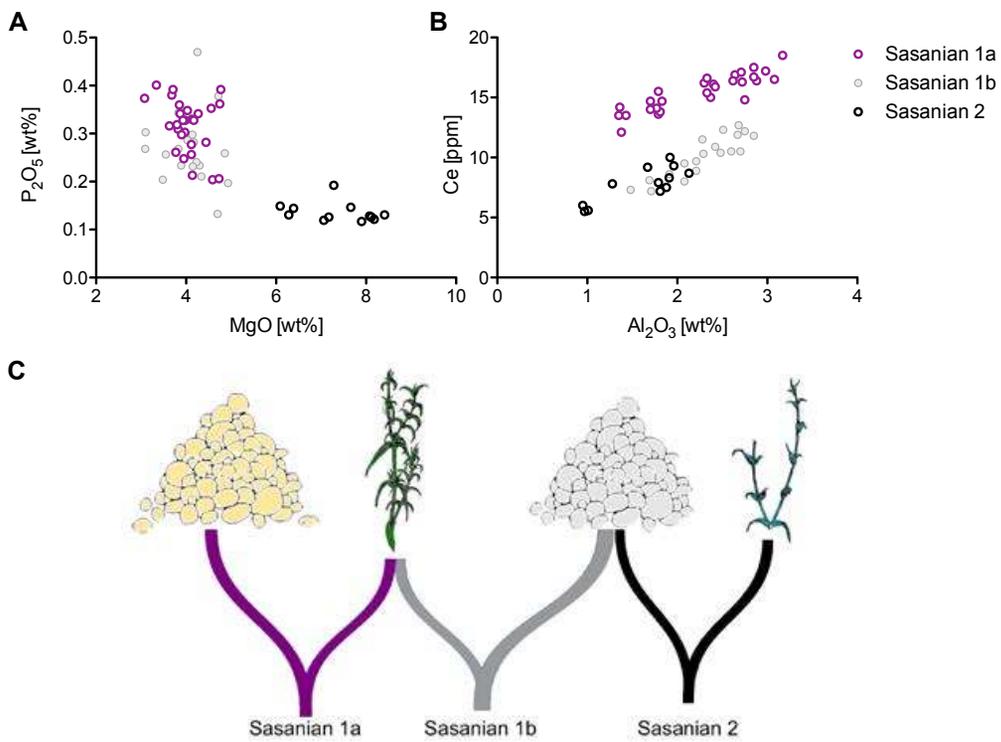


Fig. 38: Compositional characteristics and group affiliations of the Sasanian glasses from Veh Ardašīr. (a) Phosphorus and magnesia levels distinguish two different plant ash components of Sasanian 1 and Sasanian 2; (b) cerium and alumina concentrations and their ratios separate Sasanian 1a from Sasanian 1b and Sasanian 2 glasses; please note that minor groups (intermediate, outliers) were not included in these graphs; (c) different combinations of plant ash and silica sources of the three Sasanian groups from Veh Ardašīr. Data sources: (Mirti *et al.* 2008; Mirti *et al.* 2009).

38a). In contrast, Sasanian 1a differs from Sasanian 1b in terms of the silica source by having elevated trace elements such as cerium ($\text{Ce} > 13 \text{ ppm}$), high zirconium ($\text{Zr} > 100 \text{ ppm}$) and overall higher REEs (Mirti *et al.* 2009). Sasanian 2 has the lowest levels of silica-related impurities, while it partially overlaps with Sasanian 1b. The glass assemblage from Veh Ardašīr thus represents three different configurations of glass raw materials, where the same plant ash was combined with different silica sources (Sasanian 1a & 1b) or vice versa, i.e. different types of plant ash were mixed with the same silica source (Sasanian 1b & Sasanian 2; Fig. 38c). In relation to comparative material Sasanian 2 appears to be the exception, and the majority of samples published by Brill (1999) as well as the glasses from Ctesiphon (Schibille, unpublished data) and Dibba (Van Ham-Meert *et al.* 2019) match Sasanian 1, and more precisely Sasanian 1b as judged on the basis of the available cerium concentrations.

The results of strontium isotope analyses (Ganio *et al.* 2013) offer an even more complex picture, suggesting a sub-division into two distinct populations that do not correspond to the elemental group affiliations (Fig. 39). The bulk of the Veh Ardašīr glass is tightly clustered in terms of its strontium isotopic ratios consistent with raw furnace glass from al-Raqqa (Raqqa 1 & 4) and Tyre, and by extension consistent with the use of halophytic plants growing on Syrian inland sediments (Henderson *et al.* 2020). Four samples (two of Sasanian 1b and Sasanian 2 each) have higher $^{87}\text{Sr}/^{86}\text{Sr}$ isotope signatures and in this respect resemble the glass from the Serçe Limani shipwreck, for which a plant ash ultimately deriving from a coastal stretch is thought to have been used (Henderson *et al.* 2020). This discrepancy between the elemental composition and strontium isotopes has far-reaching implications for the interpretation of the compositional data associated with the plant ash component. This means that the variations in the potassium, magnesium and phosphorus concentrations of the different Sasanian groups cannot be attributed to different geological and geographical origins. Similar observations have been made in relation to the Raqqa 1 and Raqqa 4 plant ash glass categories (Henderson *et al.* 2009a; Henderson *et al.* 2009b). Instead, the differences in the absolute concentrations of the alkali and alkaline earths are likely to reflect the use of different plants, different plant parts and/or different treatments and processes involved in the preparation of the plant ash (Ganio *et al.* 2013). What the combined isotopic and elemental data therefore seem to show is that the type and/or preparation of the plant ashes differed between glassmaking traditions, and that there is by and large a systematic difference between Mesopotamian and Mediterranean glasses (Ganio *et al.* 2013). This may simply involve different ashing and/or purification processes that the plant ash underwent. To my knowledge, there is no evidence for the purification of plant ash in Sasanian

glassmaking. If the ashes were washed, it is safe to assume that the procedure was much simpler than the complex processes involved in the production of Venetian *crystallo* glass. The multi-stage purification processes necessary to obtain Venetian *crystallo* commonly eliminate almost entirely some of the ash compounds such as magnesium, calcium, phosphorus, as well as iron (Cagno *et al.* 2012; McCray 1998; Verità and Zecchin 2009), which is not evident from the Sasanian glass data. This does not rule out a simpler form of washing before the ashes were employed in glassmaking. However, the immense chemical variability of plant ash (Barkoudah and Henderson 2006) makes it difficult to estimate what impact different purification techniques might have had on the already existing variability of plant ash glass compositions.

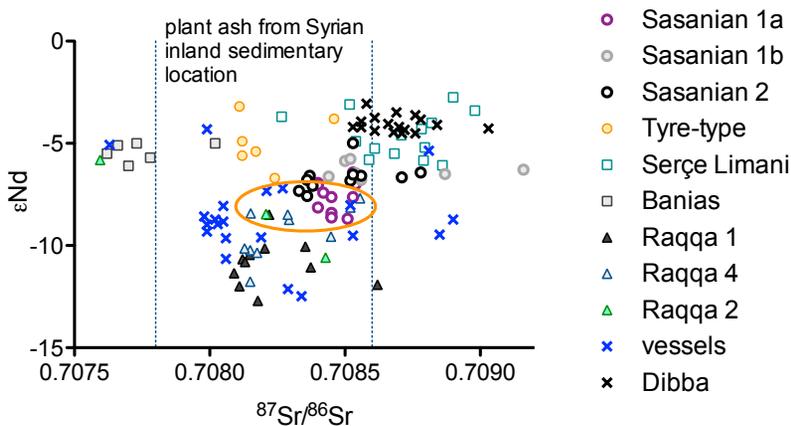


Fig. 39:

Strontium and neodymium isotopic signatures of Sasanian plant ash glasses in comparison with data from Tyre, Serçe Limani, Banias, al-Raqqa, Dibba and vessel glass from Beirut and Damascus. Orange ellipse surrounds the coloured glass from al-Raqqa that are assumed to have been imported. Data sources: (Degryse *et al.* 2010a) for Banias and Tyre; (Ganio *et al.* 2013) for Veh Ardašīr; (Henderson *et al.* 2020) for al-Raqqa, Beirut and Damascus; (Brill and Stapleton 2012; Henderson *et al.* 2020) for Serçe Limani; please note that for Brill's data nominal neodymium values have been assumed between -3.1 and -5.8 in steps of 0.3 to compensate for the lack of Nd isotopes; (Van Ham-Meert *et al.* 2019) for Dibba.

To distinguish regional production and supply patterns, trace elements derived from the silica source (Ti, Cr, Zr, La) and neodymium isotopes offer more reliable discriminants. Monica Ganio and colleagues (2013) identified possibly four different silica sources based on the neodymium isotope signatures of the samples from Veh Ardašīr. However, the neodymium isotope groupings do not strictly adhere to the compositional groups either, and there is substantial overlap

between the groups as defined on the basis of their elemental signatures. The average neodymium ratios of the samples ($-8 < \epsilon\text{Nd} < -6$) are somewhat lower than the typical Levantine coastal data represented by the glass from Tyre and higher than the continental silica source of the al-Raqqa furnace glass (Fig. 39). A considerable number of vessel glasses from al-Raqqa and twelfth- to fourteenth-century Damascus and Beirut have the same neodymium isotope range. Five samples from the Sasanian 1a group have somewhat lower ϵNd values ($\epsilon\text{Nd} < -8$), while two samples of the Sasanian 1b and one from the Sasanian 2 group show the highest ϵNd values ($\epsilon\text{Nd} > -6$). The isotopic spread of the Sasanian glass from Veh Ardašīr is not particularly wide considering, for example, the variability of the neodymium isotopes of the samples from the tank furnaces at Tyre ($-5.6 < \epsilon\text{Nd} < -3.2$; Degryse *et al.* 2010a). Thus, the range of neodymium isotopes of the Sasanian samples is well within the limits of glass produced at a single site from a single silica source. Recycling and mixing of glass made from coastal and inland sand is a possibility for the intermediate neodymium isotope values (Henderson *et al.* 2020). However, the more likely explanation for the neodymium isotope signature of the Sasanian glass from Veh Ardašīr is the existence of a yet unidentified primary glass production site. For example, we might reasonably assume that raw glass was manufactured in or near the Sasanian capital Ctesiphon.

Despite the relative homogeneity of the ϵNd data, the zirconium to titanium and chromium to lanthanum ratios vary significantly (Fig. 40). Sasanian 1a shows overall relatively constant Cr/La but highly variable Zr/Ti ratios, and it is significantly richer in zirconium than the other groups (Table 6). No linear correlation between zirconium and any of the usual suspects of silica-related elements such as titanium, vanadium or iron is apparent. Zirconium usually comes from the very stable zircon found in sediments, and it is often associated with quartz (Shortland *et al.* 2007). However, if zirconium is not linked with any of the silica-related elements, then a significant and highly variable amount of zirconium must have been introduced to the Sasanian 1a glasses through a different source, although from exactly where is unclear at this point. A possible explanation for the presence of varying amounts of zirconium in the Sasanian 1a glasses is that it is an accidental contamination through the crucible or some kind of grinding tool. In contrast, chromium is highly correlated with aluminium, iron and titanium oxide (Fig. 40), indicating that the chromium in Sasanian glasses derived primarily from the silica source.

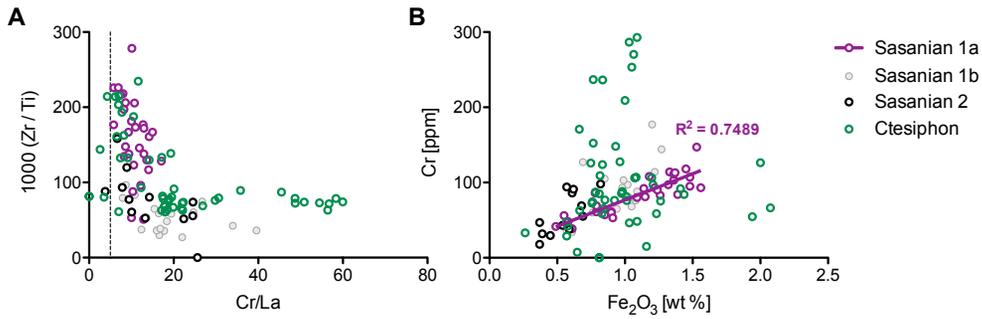


Fig. 40:

Elemental characteristics of the silica sources of Sasanian plant ash glasses. (a) Comparison of Zr/Ti and Cr/La ratios demonstrates the great variability of the zirconium to titanium ratios in the Sasanian 1a group; (b) chromium shows a strong correlation with iron oxide in the Sasanian 1a group. Data sources: (Mirti *et al.* 2008; Mirti *et al.* 2009) for Sasanian glass; unpublished data on Ctesiphon (Schibille).

Additional data on Sasanian glass samples published by Brill (1999 & 2012) and some unpublished data from Ctesiphon as well as the first-century glasses from Dibba (Van Ham-Meert *et al.* 2019) reinforce the observations made in relation to the assemblage from Veh Ardašīr. Virtually all Sasanian glasses for which trace element data are available have elevated chromium to lanthanum ratios ($\text{Cr/La} > 5$; Fig. 41a), which can therefore be considered a reliable compositional marker for identifying Mesopotamian glasses. This is not to say that glass of Mesopotamian origin cannot have low Cr/La ratios, as will be discussed later, but if plant ash glasses have elevated Cr/La ratios the chances are that they have been produced from a Mesopotamian silica source. Some of the glass finds from Ctesiphon have exceptionally high chromium to lanthanum ratios, while the first-century glasses from Dibba may represent an exception to the rule, due to their surprisingly high lanthanum levels, with an average lanthanum content of almost 40 ppm (Fig. 41a; Van Ham-Meert *et al.* 2019). Dibba, located on the Gulf of Oman (Fig. 1), was an important port city in antiquity with trade links connecting the Roman Empire with Mesopotamia as well as India (Van Ham-Meert *et al.* 2019). The provenance of these glasses is therefore problematic as no compositional or isotopic equivalent is known, and it remains to be seen whether they are indeed Mesopotamian, produced locally, or imported from another still unknown primary production centre (Van Ham-Meert *et al.* 2019).

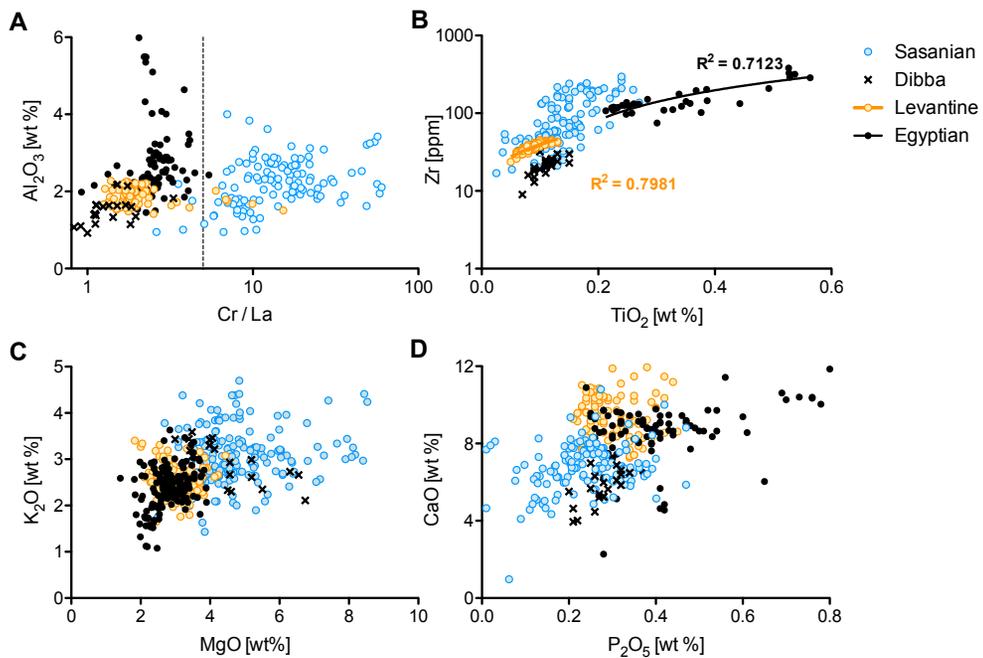


Fig. 41:

Compositional characteristics of Sasanian plant ash glasses in comparison with Islamic plant ash glasses from Egypt, the Levant and first-century Dibba (U.A.E.). (a) Sasanian glasses have typically higher Cr/La ratios ($\text{Cr/La} > 5$, indicated by a dotted line) compared to Egyptian and Levantine plant ash glasses with few exceptions; (b) Sasanian glass displays considerable variations in the zirconium content and in their ratios of Zr/Ti in contrast to Levantine and Egyptian glass where titanium and zirconium are typically strongly correlated; (c) potassium and magnesium oxide concentrations tend to be higher in Sasanian plant ash glass than in Islamic plant ash glasses from the Levant and Egypt, reflecting differences in the ash component; (d) Sasanian glasses have on average lower lime and phosphorus levels than plant ash glasses of Mediterranean origin, confirming the use of different plant ashes, ashing procedures and/or ash treatments. Data sources: (Brill 1999; Mirti *et al.* 2008; Mirti *et al.* 2009) for Sasanian glasses, including unpublished data on Ctesiphon (Schibille); (Schibille *et al.* 2019) for Egyptian plant ash glass; (Phelps 2017) for Levantine plant ash glass P1; (Van Hammeert *et al.* 2019) for Dibba. Please note that some of the Levantine plant ash glasses (Phelps 2017) may need to be re-attributed to a Mesopotamian origin according to their elevated Cr/La ratios.

From the above it transpires that chromium may indeed be a robust discriminant for Mesopotamian glass, especially in relation to lanthanum contents, whereas zirconium concentrations can be somewhat erratic and do not always appear to be diagnostic of the silica source. This is somewhat surprising, given that zirconium is commonly used to distinguish between different populations of vitreous materials. However, similar observations have been made in the context of Iron Age glass, where highly variable and exceptionally high zirconium contents may be related to

processes involved in the crushing of quartz pebbles used as the main silica source for the production of these glasses (Bernard Gratuze, personal communication). The elevated and variable zirconium concentrations appear to affect only a subset of Sasanian samples (Sasanian 1a, Fig. 40). The glass from Ctesiphon displays a similar pattern, in that the zirconium concentrations in some samples with Sasanian 1a characteristics are inconsistent. This phenomenon certainly needs to be kept in mind when evaluating the compositional data of Mesopotamian glasses. If the zirconium contents in these glasses are indeed unrelated to any of the other elements associated with the silica source, this may, when fully understood, provide valuable insights into the techniques involved in the processing of the raw materials.

Other distinguishing features that all Sasanian glasses seem to have in common are their relatively high and fluctuating magnesium oxide (and probably lithium) concentrations, as well as lime and phosphorus levels that are typically lower than those of Egyptian and Levantine plant ash glasses (Fig. 41c-d). The simplest explanation is that the plant ash used for the production of the Mesopotamian glasses derived from plants growing in areas dominated by the alluvium of the Euphrates and the Tigris that has been shown to be high in magnesium (Freestone 2006). This magnesium-rich environment would give rise to plant ash rich in magnesium and, by extension, to glasses with high magnesium concentrations. The lower lime and phosphorus concentrations may in turn be the result of washing (Cagno *et al.* 2012; McCray 1998; Verità and Zecchin 2009). The strontium isotopic signatures are also consistent with the origin of the plants being the Euphrates valley (Henderson *et al.* 2020). As we have seen, however, the strontium isotopes of these Mesopotamian glasses do not differ from those of glass produced on the Levantine coast, suggesting that the plants must have been harvested from geologically related environments. The significant discrepancies in the elemental composition could be the result of different types of plants or plant parts being used and/or different ways of preparing the plant ash. Bio-available elements are accumulated differently in plants depending on species and plant part, whereas isotopic signatures remain unchanged (Barkoudah and Henderson 2006; Wedepohl and Simon 2010). The careful comparison of isotopic data and trace element characteristics of all extant data may reveal more systematic patterns and regional variations, while experimental work could potentially provide some indication about the processing of plants and the ashing techniques.

Sasanian glass is generally very variable in composition, presumably due to poorly controlled raw materials and a smaller scale of production compared to natron-type glass or early Islamic plant ash glass manufactured on the Mediterranean coast. The Sasanian glass types nonetheless share some characteristics that

distinguish them from other glassmaking traditions, such as high magnesia (and $\text{Li} > 10$ ppm), low phosphorus and high chromium to lanthanum ratios. The attribution of an archaeological glass sample to a Mesopotamian provenance presupposes that ideally all these criteria are met.

The transition to Islamic glassmaking in Mesopotamia

Mesopotamian group Raqqa 4

Most of the compositional characteristics of Sasanian glasses established above (high Mg, elevated Cr/La, low P_2O_5) are also found in early Islamic plant ash glasses produced in the region. As mentioned in the previous chapter, al-Raqqa is the earliest known primary production centre of Islamic plant ash glass and the only archaeologically attested site in Mesopotamia. While Raqqa 1 is compositionally close to Islamic plant ash glass from Syria-Palestine, Raqqa 4 exhibits all the features that are typical of Mesopotamian glasses. Raqqa 4 has high magnesia ($\text{MgO} > 3.5\%$) and on average lower calcium concentrations, resulting in relatively high but variable magnesium to calcium ratios, covering the entire compositional range of the Sasanian glasses from Veh Ardašīr, including Sasanian 1 and Sasanian 2 (Fig. 42a). Unfortunately, only a minority of analyses of Sasanian and al-Raqqa material include trace element data (Henderson *et al.* 2016). The available data nonetheless exhibit another feature of Mesopotamian glass production. Glasses of Mesopotamian origin generally contain lower phosphorus and higher lithium relative to soda concentrations than both Levantine and Egyptian plant ash glass (Fig. 42b). Intriguingly, this also includes Raqqa 1 glass which, apart from the elevated lithium levels, shows all the characteristics of glass produced according to a Syro-Palestinian recipe (see chapter 2). Lithium contents are highly susceptible to volatilisation during the melting process, which may be reflected in its negative relationship with phosphorus that tends to be enriched by prolonged heat treatment (Paynter 2008). The systematic differences in lithium contents between Mediterranean (Levantine, Egyptian) and Mesopotamian plant ash glasses thus reflect diverging regional glassmaking and processing of the raw ingredients.

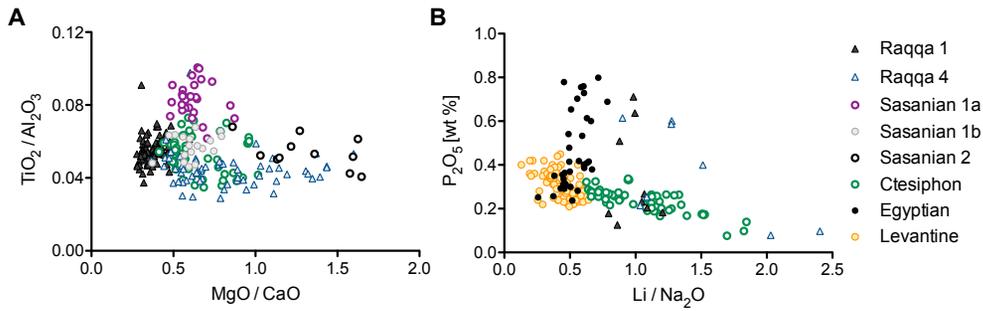


Fig. 42:

Raqqa 1 and Raqqa 4 glasses in comparison with the Sasanian, Levantine and Egyptian glass groups. (a) $\text{TiO}_2/\text{Al}_2\text{O}_3$ versus MgO/CaO ratios highlight the similarities between Raqqa 4 and Sasanian 1 in terms of the plant ash component, while the silica sources mostly differ (some Raqqa 4 glasses are close to Sasanian 2); (b) phosphorus compared to lithium to soda ratios underscore the regional differences in Mediterranean and Mesopotamian glassmaking practices. Data sources: (Henderson *et al.* 2004; Henderson *et al.* 2016) for al-Raqqa; (Mirti *et al.* 2008; Mirti *et al.* 2009) for Sasanian glass; unpublished data on Ctesiphon (Schibille); (Schibille *et al.* 2019) for Egyptian plant ash glass; (Phelps 2017) for Levantine plant ash glass P1.

As far as the silica source is concerned, the Raqqa 4 samples bear some resemblance to Sasanian 1b and Sasanian 2. They exhibit a broad spectrum of aluminium, titanium and iron oxide concentrations, and they have somewhat lower and more consistent $\text{TiO}_2/\text{Al}_2\text{O}_3$ ratios than the Sasanian glasses (Fig. 42a). The few chromium and lanthanum data that are available show that Raqqa 1 has generally low chromium to lanthanum ratios ($\text{Cr}/\text{La} < 5$), while some of the Raqqa 4 samples have elevated values (Henderson *et al.* 2016). Thus, the data are not entirely conclusive. The strontium and neodymium isotopes have furthermore demonstrated the distinct nature and provenance of the bulk of the al-Raqqa raw furnace glass belonging to both the Raqqa 1 and Raqqa 4 groups (Henderson *et al.* 2020). Their very low neodymium isotope ratios ($\epsilon\text{Nd} < -10$) set the Raqqa glasses apart from vitreous material produced from a Levantine coastal silica source as well as from the Sasanian glass from Veh Ardašīr (Fig. 39). Syrian semi-desert sand was proposed as the likely source of silica (Henderson *et al.* 2020), again for both Raqqa 1 and Raqqa 4 glasses. The strontium isotope ratios are overall uniform and broadly consistent with the range of local Syrian plant ashes as well as the glasses from Tyre (Fig. 39). One raw glass chunk from al-Raqqa (sample Raqqa 40) matches the strontium as well as the neodymium isotopic composition of the glasses from Banias. This sample belongs to the Raqqa 2 group and has been interpreted as having been imported to al-Raqqa (Henderson *et al.* 2009a; Henderson *et al.* 2020). Another group of mostly strongly coloured bangles,

window glass fragments and flasks is distinct from the bulk of the al-Raqqa glasses due to its higher neodymium isotope ratios similar to those of the Sasanian glass, especially Sasanian 1a (singled out by an orange ellipse in Fig. 39). These mostly coloured glasses were apparently produced elsewhere (Henderson *et al.* 2009a; Henderson *et al.* 2020).

The general similarities between the early Islamic glasses from al-Raqqa and Sasanian glasses from Veh Ardašīr reflect their common geographical origin, shared glassmaking traditions and exploitation of similar raw materials. The data strengthen the hypothesis that at least some of the Raqqa 4 glasses were produced according to a Mesopotamian glassmaking recipe, possibly introduced by artisans who gathered in al-Raqqa when it became the caliphal residence. It is near impossible to prove the precise origins of the primary glasses or a technological link between the Sasanian and early Islamic traditions, not least due to a chronological gap of about 150 years between the glasses from Veh Ardašīr and the glass production activities at al-Raqqa. Even so, it is at least possible to identify and eliminate those glasses that have not been produced locally. The chemical and isotopic composition of the glass finds from al-Raqqa exhibits a degree of variability that indicates that some of the manufactured objects such as facet-cut vessels, bangles and strongly coloured window glasses were produced from different silica sources and were thus most certainly imported. Some compositional heterogeneity among early Islamic glass assemblages of a single site is not uncommon. Separate production centres for specific decorative forms and object types have already been described in other contexts, for instance in relation to painted and stained glass objects, faceted artefacts or architectural decorations (Carboni and Whitehouse 2001; Schibille *et al.* 2018a). It can therefore be misleading to define a heterogeneous group such as Raqqa 4, as it evidently conflates glasses of different origins. Instead, it would be preferable to separate the Raqqa 4 glasses according to their isotopic signatures and trace elements. Isotope data have in recent years been increasingly and successfully employed to determine the geological provenance of glass raw materials. It needs to be stressed, however, that trace element profiles should be considered alongside the isotope data. It has been shown that the strontium and neodymium isotopes do not always match the elemental composition of the glass which often reflects greater variability as a result of several primary production events. What is more, silica sources of the same geological age are bound to be isotopically related and therefore do not always allow for a clear geographical attribution. Sand collected from the Euphrates near al-Raqqa is a case in point. Its neodymium isotope ratios are the same as those of Levantine coastal sands (Henderson *et al.* 2020). In a nutshell, to define production zones and regional technological processes of Islamic plant ash glass a combination of compositional

and isotopic data is required. The success of this approach ultimately depends on comprehensive and systematic sampling of well contextualised and well dated glass finds.

Two early Islamic glass groups from Mesopotamia: Samarra 1 and Samarra 2

A quarter of a century ago, Robert Brill (1995) identified a special type of colourless glass among the finds from ninth- to tenth-century Nishapur in north eastern Iran (Fig. 1), for which he found parallels at Fustat (Egypt) and Qasr al-Hayr (Syria). Mark Wypyski has since recognised the same type of clean, colourless glass (Type A) in Samarra (Iraq) and Raya al-Tur in the Sinai Peninsula, also noting similarities with Sasanian type 2 from Veh Ardašīr (Wypyski 2015). Judging from the geographical and chronological distribution and relative abundance, he hypothesised that this glass might have been imported to Nishapur from Mesopotamia, possibly from the region of Samarra (Wypyski 2015, p. 136). Based on an extensive analytical study of the glass finds from Samarra we have been able to demonstrate that this ‘Nishapur colourless’ glass and a closely related subtype of weakly coloured glass were indeed the principal glass groups employed in Samarra in the ninth century (defined as Samarra 1 and Samarra 2; Schibille *et al.* 2018a).

An important centre of Abbasid artistic production (Leal 2020), the palace-city of Samarra (Iraq) was founded a generation after al-Raqqā in 836 CE by the caliph al-Mu‘tasim on the banks of the Tigris river about 125 km north of Baghdad (Fig. 1 & 2). Excavations in 1911 and 1912-13 yielded a considerable number of glass finds ranging from more ordinary utilitarian objects to elaborately decorated vessels and different forms of architectural glass such as mosaic tesserae, glass inlays and monochrome deep purple and aqua-coloured glass tiles, as well as intricate millefiori tiles (Lamm 1928; Schibille *et al.* 2018a). With the exception of some traditional mosaic tesserae that are of an older and imported natron-type base glass, all the architectural glass was made with Samarra 1 and Samarra 2 plant ash raw glass. Over 75% of all the analysed samples from Samarra correspond to these two glass groups. They have high magnesia and lithium contents, combined with low lime and phosphorus concentrations typical of Mesopotamian plant ash glasses (Fig. 43). Judging from the relative ubiquity of these two primary glass groups, they were most likely produced locally (Schibille *et al.* 2018a).

Like the Sasanian glass from Veh Ardašīr, the Samarra glass can be separated into two distinct groups based on the aluminium and cerium concentrations (Fig. 43). A few of the Sasanian 2 samples at the lower end of mineral impurities are similar in many respects to the colourless Samarra 1 group, while Samarra 2

is closer to Sasanian 1a with higher Ce and rare earth elements. Samarra 1 has exceptionally low levels of accessory elements such as alumina ($\text{Al}_2\text{O}_3 < 1\%$; Fig. 43c), iron oxide ($\text{Fe}_2\text{O}_3 \leq 0.4\%$), titanium oxide ($\text{TiO}_2 < 0.05\%$) and all other trace and rare earth elements (Table 7). Chromium is highly correlated with aluminium, iron and titanium, suggesting that the silica source was a very clean quartz-rich and chromite-bearing sand with or without an admixture of quartz pebbles possibly derived from the region of the Tigris. Due to the extraordinarily clean nature of its raw materials, Samarra 1 does not have the distinct elevated chromium to lanthanum ratios that would otherwise be expected from a Mesopotamian glass (Fig. 43d), but they are still higher than those of Levantine and Egyptian plant ash glasses. The compositionally closely related Samarra 2 glass type makes up the

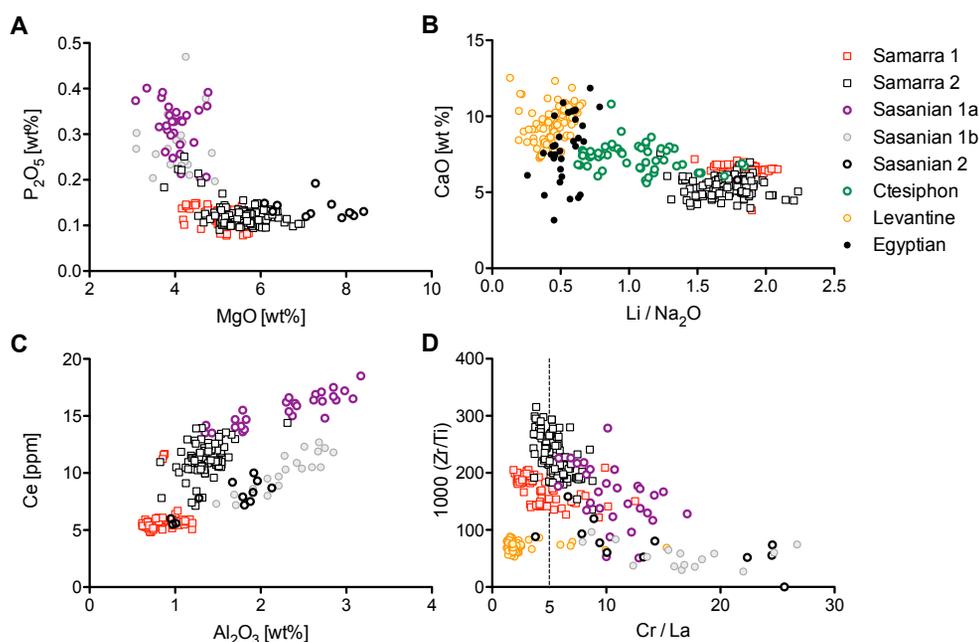


Fig. 43:

Main distinguishing features of Samarra 1 and Samarra 2. (a) Phosphorus and magnesium oxides of the Samarra glass in comparison with Sasanian glass from Veh Ardašir reveal the similarities with Sasanian 2 in terms of high magnesia and very low phosphorus concentrations; (b) lime and lithium to soda ratios separate the Samarra glass from the Sasanian glass from Ctesiphon as well as Levantine and Egyptian reference groups; (c) cerium and alumina levels distinguish Samarra 1 and Samarra 2 in parallel to Sasanian 1 and Sasanian 2, underpinning the similarities between some Sasanian 2 and Samarra 1; (d) the glass from Samarra has relatively constant Cr/La ratios around the proposed threshold of $\text{Cr}/\text{La} = 5$ indicated by a dotted line, while it varies in terms of Zr/Ti ratios. Data source: (Schibille *et al.* 2018a) for Samarra, (Mirti *et al.* 2008; Mirti *et al.* 2009) for Sasanian glass; unpublished data on Ctesiphon (Schibille); (Schibille *et al.* 2019) for Egyptian plant ash glasses; some unpublished data on Egyptian plant ash glass (Schibille); (Phelps 2017) for Levantine plant ash glass P1.

bulk of the glass assemblage from Samarra, made from a silica source that was less pure, a fact which is reflected in higher trace and rare earth element concentrations. The two groups from Samarra have different optical properties depending on the impurity levels associated with the silica source. Samarra 1 is a high quality, quasi-colourless glass which was used for wall inlays and finely decorated vessels (Fig. 51a), while Samarra 2 has either an aqua tinge (Fig. 51b) or has been coloured by additives such as manganese, iron, cobalt, copper or lead stannate (Schibille *et al.* 2018a). The incorporation of substantial amounts of additives in some of the Samarra 2 samples (e.g. millefiori glass tiles Fig. 51d) also explains the subtle compositional variations within this group.

A difference in the expressed colour of the glass has been observed in relation to the Sasanian groups from Veh Ardašīr (Mirti *et al.* 2008; Mirti *et al.* 2009). Whereas Sasanian 2 tends to be nearly colourless, the earlier Sasanian 1a is usually green to yellowish green. Since there is a chronological dimension in that Sasanian 1a-type glass was first recorded in third-century contexts and Sasanian 2 dates to the fourth to sixth centuries CE, this temporal change in colour was interpreted as a shift towards new aesthetic sensibilities in relation to the optical properties of vitreous materials (Mirti *et al.* 2009). At Samarra, by contrast, there is no chronological distinction between the colourless Samarra 1 and the weakly coloured Samarra 2 base glasses. An obvious alternative explanation would be cost. Based on the compositional and visual characteristics, we hypothesised that Samarra 2 may have been a less expensive variant of Samarra 1, used to make coloured and/or less prestigious objects (Schibille *et al.* 2018a). If both glass types were equally accessible, had the same value, and were equally cost-effective to produce, then it is hard to explain why Samarra 1 was not used exclusively. The colourless Samarra 1 type is clearly somewhat exceptional in that raw materials free of mineral impurities were carefully selected to obtain a colourless glass. It is possible that this included the use of crushed quartz pebbles. Samarra 1 glass was a highly specialised primary production, deliberately chosen for luxury glassware and architectural inlays to be set in stucco with an inherent aesthetic value, and it was at the same time destined for far-flung export. As such, Samarra 1 seems to have its roots in an ancient Sasanian tradition of the production of near-colourless high quality glasses.

Colourless glass from Nishapur

As mentioned above, a colourless glass similar to Samarra 1 was originally singled out among the glass finds from Nishapur (Brill 1995; Wypyski 2015). Between the ninth and thirteenth centuries CE Nishapur was one of the most important cities

and mercantile centres in the Khurasan province of what is now north-eastern Iran (Fig. 1). It is strategically located on one of the major branches of the Silk Road network connecting the Mediterranean Sea in the west with India and China in the east, crossing Mesopotamia and Transoxiana along the way (Wilkinson 1973). Nishapur played an important role in the Abbasid uprising in 748 CE, after which it became the seat of Abbasid governors. The province of Khurasan gained autonomy and Nishapur became the capital under the Tahirids in the ninth century (821 - 873 CE), when it developed into an important commercial and intellectual centre (Kröger 1995). Famous for its textile industry (silk, cotton, wool), mineral deposits, particularly turquoise, and ‘the earth of Nishapur’ that was believed to have pharmaceutical properties, Nishapur’s prosperity derived from a combination of trade and the exploitation of local resources (Holakooei *et al.* 2018). A number of different sites at Nishapur were excavated by the Persian (later Iranian) expedition of the Metropolitan Museum of Art during several campaigns from 1935 to 1940. These excavations unearthed vast numbers of materials from architectural decorations (stucco panels, frescos, tiles) to ceramics, metalwork and glass, much of which ended up in the Metropolitan Museum in New York (Hauser and Wilkinson 1942). The field archaeologist, and subsequently Jens Kröger, who published an extensive catalogue of the Nishapur glass in 1995, concluded that glass must have been made at Nishapur, even though no archaeological evidence of glassmaking was found (Hauser and Wilkinson 1942; Kröger 1995).

This assumption has since been called into question on the basis of the analytical data on some of the glass finds that are now stored in the Metropolitan Museum in New York (Brill 1995; Wypyski 2015). Some unpublished LA-ICP-MS data (courtesy of Bernad Gratuze, James Lankton & Mark Wypyski) in comparison with the Samarra glass lend support to the interpretation that at least some of the glass was imported to Nishapur from Mesopotamia. Brill originally divided the assemblage into colourless (water-white) and coloured glasses that also included naturally coloured samples (Brill 1995), while Mark Wypyski distinguished three main groups based on variations in the potassium, magnesium, phosphorus and aluminium oxide contents (Wypyski 2015). A thorough evaluation of the LA-ICP-MS data confirms Wypyski’s grouping on the whole, but refines the categories further by reassigning individual samples to best match the corresponding group. Nearly half of the evaluated glasses, referred to as Nishapur 1 (similar to Wypyski Type A), form part of a relatively homogeneous group that has high magnesia ($\text{MgO} > 4\%$), moderate potash (average $\text{K}_2\text{O} \sim 2.5\%$), very low phosphorus oxide ($\text{P}_2\text{O}_5 < 0.15\%$) and low alumina levels (average $\text{Al}_2\text{O}_3 \sim 1\%$; Table 7; Fig. 44). Nishapur 1 can be sub-divided into 1a and 1b. Nishapur 1b differs from Nishapur 1a in higher magnesia to lime ratios as well as elevated silica-related

impurities, especially titanium, zirconium and cerium, but only slightly higher alumina concentrations. Both sub-groups include mostly colourless glasses, with the exception of some greenish-blue fragments among Nishapur 1a and two cobalt blue samples among Nishapur 1b. All of the faceted vessels and most of the wheel-cut decorated artefacts belong to Nishapur 1a, as do some more ordinary jars, miniature bottles and molar flasks.

Glass group	Date	Na ₂ O	MgO	Al ₂ O ₃	SiO ₂	P ₂ O ₅	Cl	K ₂ O	CaO	TiO ₂	Fe ₂ O ₃	Li	Cr	Sr	Zr	Ce
		stdev	stdev	stdev	stdev	stdev	stdev	stdev	stdev	stdev	stdev	stdev	stdev	stdev	stdev	stdev
Samarra 1 (n=72)	9 th	13.1	5.08	0.81	69.9	0.12	0.64	3.22	6.38	0.03	0.23	24.0	12.7	397	31.0	5.91
	stdev	0.7	0.40	0.14	1.0	0.02	0.08	0.48	0.45	0.01	0.08	2.0	6.4	31	9.4	1.40
Samarra 2 (n=121)	9 th	15.1	5.54	1.36	66.5	0.12	0.61	2.66	5.40	0.08	0.60	26.1	34.6	434	104	11.1
	stdev	1.3	0.52	0.16	2.0	0.02	0.06	0.27	0.59	0.01	0.24	3.0	7.8	44	22	1.4
Co flasks (n=23)	9 th	14.2	2.80	2.08	67.0	0.19	0.70	2.24	6.60	0.12	2.54	28.5	67.9	329	94.9	17.8
	stdev	0.5	0.37	0.26	1.3	0.03	0.10	0.25	0.71	0.01	0.50	3.1	11.4	24	20.3	4.2
Nishapur 1a (n=52, *18)	9 th	12.5	4.90	1.01	70.9	0.11	0.75	2.53	6.35	0.05	0.30	21.0*	19.4	458	43.7	8.2
	stdev	0.9	0.47	0.14	1.5	0.06	0.10	0.42	0.50	0.01	0.26	4.3	6.2	73	14.3	1.5
Nishapur 1b (n=12)	9 th	15.0	5.74	1.21	68.5	0.11	0.74	2.63	4.48	0.09	0.47		30.1	585	171	17.3
	stdev	1.1	0.47	0.17	1.7	0.03	0.07	0.35	0.43	0.02	0.31		8.8	87	85	2.3
Nishapur high Cr (n=14)	9 th	16.7	4.66	2.46	63.0	0.30	0.91	3.10	6.25	0.13	1.01		86.4	662	111	17.0
	stdev	1.9	0.77	0.42	2.5	0.06	0.13	0.55	0.89	0.02	0.28		38.9	111	40	3.6
Nishapur low Cr (n=28)	9 th	16.4	4.34	2.93	62.3	0.36	0.87	3.44	7.18	0.13	0.92		27.3	699	98.4	20.7
	stdev	1.8	0.39	0.71	2.6	0.11	0.26	0.79	1.35	0.04	0.27		16.1	140	41.0	4.2
Merv low Cr (n=60)	9 th	14.4	3.79	2.95	64.7	0.39	0.56	3.87	7.54	0.11	0.71	15.7	15.8	455	64.3	12.9
	stdev	1.6	0.68	0.71	1.9	0.06	0.13	0.46	1.30	0.04	0.19	3.2	6.1	133	32.0	3.0
Merv high Al (n=52)	9 th	15.0	4.12	5.99	59.4	0.44	0.50	4.63	7.96	0.22	1.26	23.9	27.0	403	95.6	20.2
	stdev	0.8	0.64	0.71	2.4	0.05	0.13	0.39	1.31	0.04	0.30	2.5	4.5	67	14.3	3.6

Table 7:

Average compositions and standard deviations of Mesopotamian (Samarra, Co flasks, Nishapur 1 & high Cr) and putative Central Asian (Nishapur low Cr, Merv) glass. Metal oxides and chlorine are given as [wt %], Li, Cr, Sr, Zr and Ce are given as [ppm]. Data sources: (Schibille *et al.* 2018a) for Samarra and cobalt flasks; (Meek *et al.* in preparation) for Merv; data on glass from Nishapur (courtesy of B. Gratuze, J. Lankton & M. Wypyski).

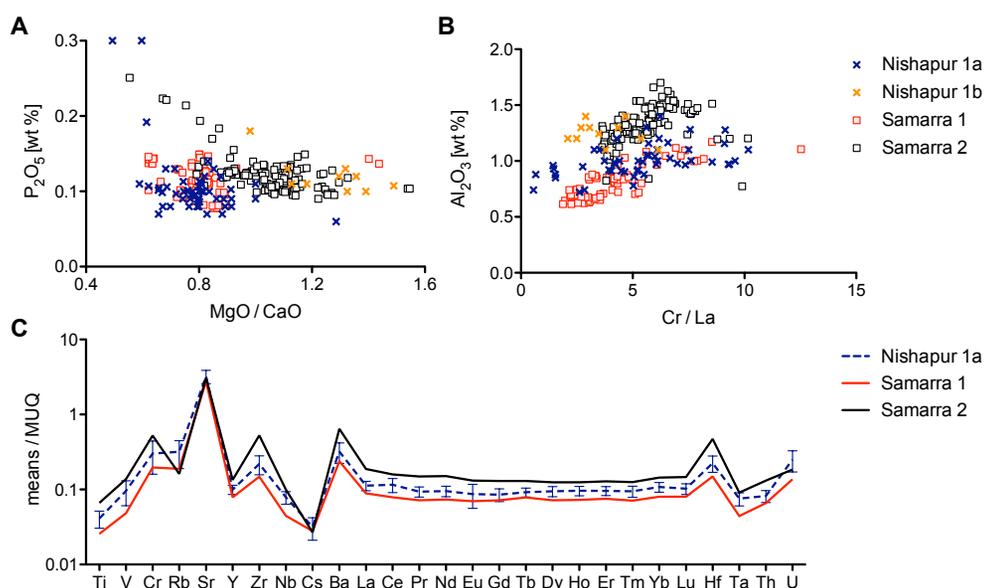


Fig. 44:

Nishapur colourless glass (Nishapur 1) compared to Samarra 1 and Samarra 2. (a) All three groups have exceptionally low phosphorus levels and highly variable magnesia to lime ratios; (b) chromium to lanthanum ratios versus alumina concentrations confirm similarities between Nishapur Type 1a and Samarra groups 1 and 2; (c) trace element patterns of Nishapur 1a compared to Samarra 1 and Samarra 2. Mean concentrations were normalised to the abundance of the earth's upper continental crust (Kamber *et al.* 2005). Data sources: (Schibille *et al.* 2018a) for Samarra; data on glass from Nishapur (courtesy of B. Gratuze, J. Lankton & M. Wypyski).

As already remarked by Robert Brill (1995) and Mark Wypyski (2015), the colourless (and some weakly coloured) samples from Nishapur (Type 1a) form a very tight cluster due to the use of a very clean, quartz-rich silica source, with low levels of all silica-related elements. In this respect, Nishapur 1a has a strong resemblance to Samarra 1. It has similar absolute alumina concentrations and comparable chromium to lanthanum ratios that tend to be elevated, suggesting a Mesopotamian origin (Fig. 44b). Nishapur 1a has on average somewhat higher trace and rare earth elements than Samarra 1. It literally lies between the two Samarra groups and follows the same trace element profile (Fig. 44c). Even though there seems to be a shift in the Nishapur 1a glass composition compared to Samarra 1 in terms of its absolute concentrations, the ratios between many of the silica-related elements are relatively constant. The similarities between Samarra 1 and Nishapur 1a are illustrated, for example, in the cumulative frequency curves of titanium to aluminium and zirconium to neodymium ratios, whereas the cumulative frequency curve of chromium to lanthanum ratios of Nishapur 1a leans more towards

Samarra 2 (Fig. 45). As has repeatedly been emphasised, absolute quantities of elements such as aluminium, titanium, lanthanum and zirconium on their own do not necessarily imply different raw materials, but potentially only different relative amounts of ingredients from the same source and ratios may be more reliable (Shortland *et al.* 2007). In short, while it is not possible to demonstrate the identity of the colourless glass from Nishapur and either of the two compositional groups from Samarra, the fact that they are compositionally at the intersection of Samarra 1 and Samarra 2 strongly suggests a common Mesopotamian provenance. To all intents and purposes, the Nishapur 1a glass may have been imported from Samarra or a related primary production site located in the Tigris valley.

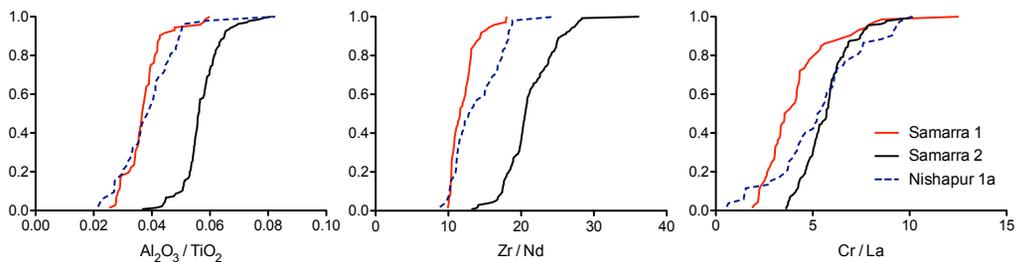


Fig. 45:

Cumulative frequency distribution of Nishapur 1a compared to Samarra 1 and Samarra 2. Cumulative curves of $\text{Al}_2\text{O}_3/\text{TiO}_2$ and Zr/Nd show a good match between Nishapur 1a and Samarra 1, while the Cr/La curve of Nishapur 1a intersects with both Samarra 1 and Samarra 2. Data sources: (Schibille *et al.* 2018a) for Samarra; data on glass from Nishapur (courtesy of B. Gratuze, J. Lankton & M. Wypyski).

Millefiori tiles from Samarra and the 'missing link'

Islamic historians like al-Ya'qubi (d. 897 CE) recount how the caliph al-Mu'tasim gathered various groups of craftspeople, including glassworkers, from Basra and sent them to his new capital city of Samarra (Northedge 2007, p. 271). If this was indeed the case, it could explain the sophistication and selective nature of the glass finds from Samarra. The glass assemblage from Samarra reflects a high degree of glassmaking and glass-working skills, while revealing critical information about the provenance and technological variability of vitreous materials found at a single ninth-century Mesopotamian site. The correlation between compositional groups and object types and the systematic differences between Samarra 1 and Samarra 2 imply selective production strategies and the careful and deliberate selection of raw materials (Schibille *et al.* 2018a). The purity of a sub-category of architectural glasses and some luxury ware suggests a willingness to invest

considerable time and effort to produce near-colourless glass, and to achieve a desired aesthetic effect that underlies the creation of the Abbasid 'glass palaces' resonant with the legendary palace of King Solomon described in the Quran (Q. 27:44). The Mesopotamian nature of these glasses is reminiscent of the Sasanian glasses from Veh Ardašīr (including some colourless glasses) and Ctesiphon, and confirms the continuity of a plant ash glass production using locally sourced raw materials. Intriguingly, this appears to have included also intensely coloured and opaque glasses such as the famous millefiori tiles (Fig. 51d) that are believed to have adorned the audience hall of the Dar al-Khilafa (Saba 2015), as well as all the cobalt blue vessel fragments with scratch decorations (Lamm 1928). This is in contrast to al-Raqqā, where no evidence for the production of strongly coloured glass was found (Henderson *et al.* 2009a; Henderson *et al.* 2009b).

Of particular interest in this context are the compositional characteristics of the millefiori tiles belonging to the Samarra 2 group in comparison with Sasanian glass from Ctesiphon, as well as a set of Merovingian glass beads from Bossut Gottechain (Belgium) that likewise represent strongly coloured Sasanian glasses (Mathis *et al.* forthcoming). The glass finds from Ctesiphon include glass cakes and mosaic tesserae of many different colours and opacities. They are of the general Mesopotamian type with relatively high magnesia ($\text{MgO} > 3.5\%$), low phosphorus ($\text{P}_2\text{O}_5 < 0.3\%$) and elevated chromium to lanthanum ratios ($\text{Cr/La} > 5$; Fig. 46). The Ctesiphon glasses appear to fit well with the Sasanian glass from Veh Ardašīr, and particularly with Sasanian 1 (1a & 1b) as far as the plant ash component is concerned, and with Sasanian 1b with respect to the silica-related elements. The Merovingian plant ash beads are also consistent with this pattern ($\text{MgO} > 3.5\%$, $\text{P}_2\text{O}_5 < 0.4\%$, $\text{Cr/La} > 5$). A sub-population of the beads has lower phosphorus (and potassium) levels than the samples from Ctesiphon (Fig. 46a). The glasses from Ctesiphon, the Merovingian beads as well as Sasanian 1 are clearly distinct from the millefiori tiles from Samarra. The tiles have similar plant ash features to Sasanian 2, with high magnesia and low phosphorus and calcium oxide concentrations. Both plant ash types may very well derive from the same geographical zone, as discussed earlier in connection with the isotopic evidence. The Samarra millefiori glass has higher zirconium relative to titanium contents than the Sasanian groups from Ctesiphon and the Merovingian beads which both contain significantly higher chromium concentrations (Fig. 46b). So while all three populations can be attributed to a common Mesopotamian glassmaking tradition, they have widely different base glass characteristics, suggesting the exploitation of different, locally sourced raw materials. It needs to be emphasised, however, that we do not know the origins of the Ctesiphon glasses, since no primary production location dating to the Sasanian period has been archaeologically documented.

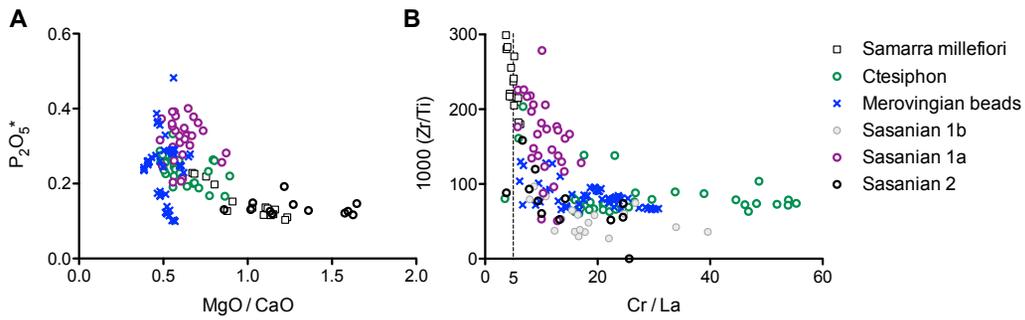


Fig. 46:

Millefiori tiles from Samarra in comparison with glass cakes and mosaic tesserae from Ctesiphon and some Merovingian glass beads from Belgium. (a) MgO/CaO ratios and phosphorus contents highlight similarities between the glasses from Ctesiphon, Merovingian beads and Sasanian 1, while the millefiori tiles from Samarra are closer to Sasanian 2; (b) the cakes and tesserae from Ctesiphon and the Merovingian beads have higher and variable Cr/La ratios, while the Samarra millefiori tiles lie on the proposed threshold of $Cr/La = 5$ marked by a dotted line. The asterisks indicate reduced and normalised data. Data sources: (Schibille *et al.* 2018a) for Samarra; (Mirti *et al.* 2008; Mirti *et al.* 2009) for Sasanian glass; unpublished data on Ctesiphon (Schibille); (Mathis *et al.* forthcoming) for Merovingian beads.

The colouring technologies and additives evident from the compositional data separate the Sasanian material further from Samarra, and they reveal a chronological change, particularly as regards the cobalt colourant. The cobalt compound used in the samples from Ctesiphon and the Merovingian beads is associated with elevated nickel concentrations (Fig. 47a) which are consistent with late antique fourth- to seventh-century cobalt sources (Gratuze *et al.* 2018). The cobalt in the Samarra millefiori tiles, in contrast, has low nickel but elevated zinc contents (Fig. 47b). The copper concentrations do not differ much and can thus be excluded as the source of the elevated zinc levels (Fig. 47c). Cobalt sources with elevated zinc concentrations were first introduced during the early Islamic period, no earlier than in the second half of the eighth century CE (Gratuze *et al.* 2018). This means that the cobalt colourant used in Ctesiphon and for the Merovingian glass beads is of a late antique high nickel type, while the cobalt employed by the glassworkers at Samarra is an Islamic high zinc variant. Thanks to the specificity of the cobalt colourant, the glass cakes from Ctesiphon and the Merovingian beads can therefore be attributed to the Sasanian period, whereas the millefiori tiles from Samarra are unequivocally of a later, Islamic date.

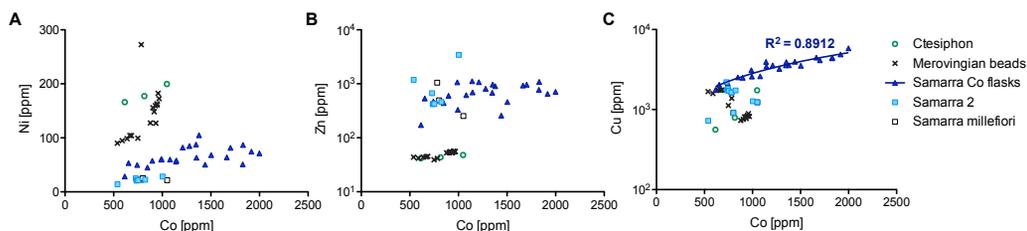


Fig. 47:

Characteristics of the cobalt colourant in glass from Samarra, Ctesiphon and Merovingian glass beads. (a) Cobalt versus nickel distinguish between late antique and Islamic cobalt sources; (b) elevated zinc levels are clearly associated with Islamic cobalt sources; while (c) copper levels remain constant. Data sources: (Schibille *et al.* 2018a) for Samarra; unpublished data on Ctesiphon (Schibille); (Mathis *et al.* forthcoming) for Merovingian beads.

If we assume that all the glass cakes recovered from Ctesiphon are more or less contemporary it follows that they all represent Sasanian colouring and opacifying techniques. The green, yellow, turquoise and white cakes and tesserae are opacified by tin compounds, either lead stannate or tin oxides (cassiterite), respectively. They thus constitute the earliest examples of tin-opacified plant ash glasses since antiquity. Most notable is the presence of tin oxide white which tends to be much less common in late antique and Byzantine glass productions (Bonnerot *et al.* 2016; Freestone *et al.* 1990; Matin 2019; Neri *et al.* 2017; Tite *et al.* 2008). Judging from the elevated tin concentrations (1% - 6% SnO₂) and the low levels of lead oxide (1% - 5% PbO), the white and turquoise glasses are presumably opacified with tin oxide particles (Fig. 48a), which is consistent with the observations made by Moujan Matin (2019) that white and blue glasses from the fourth to tenth centuries typically have low Pb/Sn ratios (Pb/Sn < 3.5). Additional analyses will be necessary to confirm this. Admittedly, the data on opaque glasses are not particularly abundant from either Sasanian or Islamic collections, but the available data suggest that there is not much difference between the tin oxide (cassiterite) opacified white and blue glasses from the Sasanian and Abbasid periods. The same seems to be true for the lead-tin pigment contained in the yellow samples, with on average approximately 10% PbO and 1-1.5% SnO₂ (Fig. 48b). The green samples from Ctesiphon tend to have lower lead oxide (average PbO ~5.5%) and tin oxide levels (SnO₂ ~1%) than the yellow samples, while the Merovingian beads appear to be translucent rather than opaque. Their low tin oxide contents (SnO₂ < 0.5%) are linked to copper (Fig. 48b). The similarities between lead stannate and tin oxide opacified glass from the Sasanian (Merovingian beads, Ctesiphon)

and Abbasid (Samarra, Nishapur) periods confirm a certain continuity in glass colouring and opacifying techniques. This may also provide part of the explanation for the development of the low lead cobalt blue on tin oxide white glazed pottery in ninth-century Iraq (Matin *et al.* 2018; Tite *et al.* 2015).

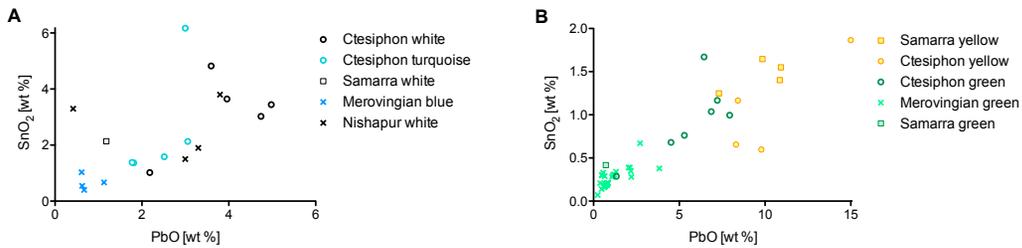


Fig. 48:

Tin opacified samples from Samarra, Nishapur, Ctesiphon and some Merovingian beads. (a) Tin and lead oxide contents in white, blue and turquoise samples; (b) tin and lead oxide concentrations in yellow and green samples. Data sources: (Schibille *et al.* 2018a) for Samarra; unpublished data on Ctesiphon (Schibille); (Mathis *et al.* forthcoming) for Merovingian beads; (Wypyski 2015) for Nishapur white.

By contrast, the red samples exhibit two distinct colouring techniques. Unfortunately, no red samples were among the Merovingian beads. In order to boost the number of comparative data, I included some early Islamic eighth- and early ninth-century millefiori beads from Ribe (Denmark). The red cakes and tesserae from Ctesiphon have moderate copper ($\text{CuO} = 3\% - 4\%$), some lead oxide ($\text{PbO} = 0.25\% - 1\%$) and low iron oxide ($\text{Fe}_2\text{O}_3 < 1\%$), while the red segments in the millefiori tiles from Samarra have even lower copper ($\text{CuO} < 2\%$), only traces of lead ($\text{PbO} = 0.1\% - 0.2\%$), but relatively high iron contents (average $\text{Fe}_2\text{O}_3 \sim 2\%$; Fig. 49). The Islamic glass beads from Ribe are similar to the Samarra millefiori glass, even though some of the beads have higher lead contents. Both the Sasanian and Islamic types of copper red belong to the low copper and low lead category (Barber *et al.* 2009; Freestone 1987; Freestone *et al.* 2003b). The main colourant in these glasses is thought to be nanoparticles of metallic copper that have formed from copper oxide dissolved in the glass melt under reducing conditions (Barber *et al.* 2009). The elevated levels of iron in the Samarra millefiori tiles and the glass beads from Ribe may have served as an additional reducing agent, aiding the precipitation of metallic copper droplets (Barber *et al.* 2009; Freestone 1987; Freestone, Stapleton and Rigby 2003b).

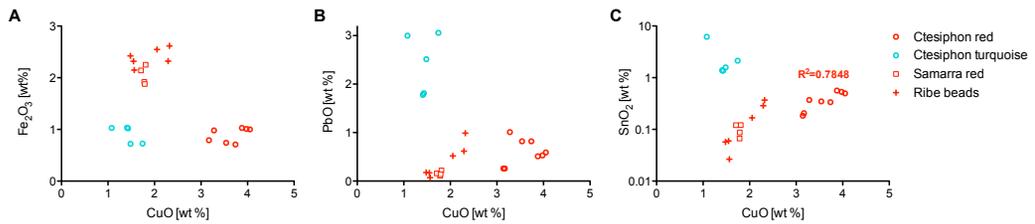


Fig. 49:

Copper red and turquoise samples from Samarra, Ctesiphon and some Viking beads from Ribe. (a) Iron and copper; (b) lead and copper; and (c) tin and copper contents showcase the differences between Sasanian (Ctesiphon) and early Islamic copper red glass. Data sources: (Schibille *et al.* 2018a) for Samarra; unpublished data on Ctesiphon (Schibille); (Sode and Gratuze forthcoming) for Viking millefiori beads from Ribe.

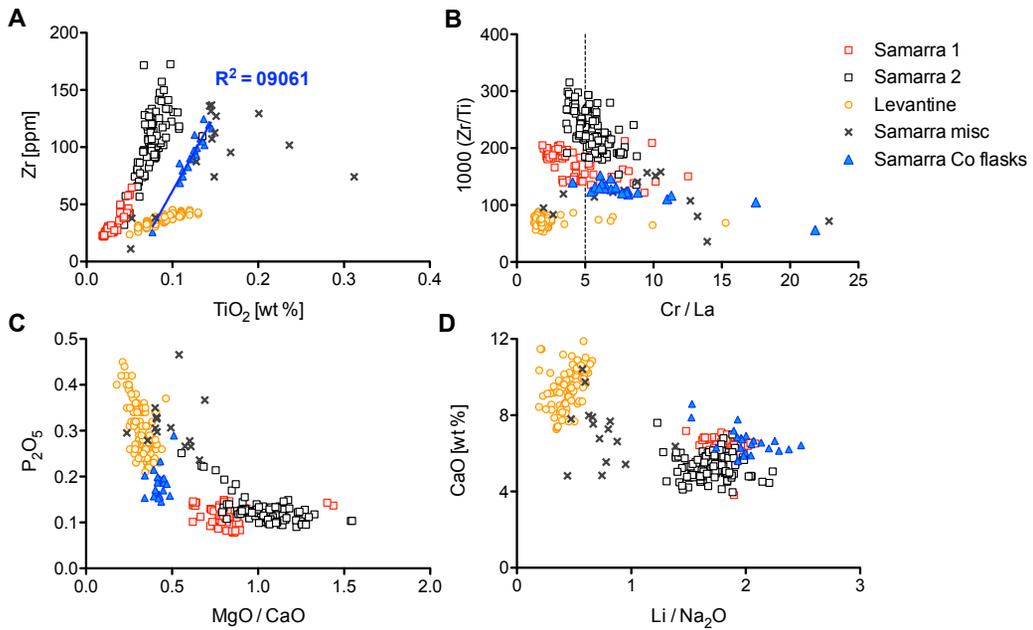
The copper to tin correlation of the Ctesiphon red samples suggest the use of a bronze as the source of copper (Fig. 49c), which might be indicative of Mesopotamian colouring techniques as described in some ancient cuneiform clay tablets that give instructions for the preparation of red opaque glass (Freestone 1987; Oppenheim *et al.* 1970). The texts contain detailed descriptions of the production of red opaque glass for which ‘fast bronze’ was used, while for turquoise ‘slow copper’ was the source of the colourant instead (Oppenheim *et al.* 1970, pp. 35, 39, 44–45). In fact, the tin to copper ratios of the turquoise samples from Ctesiphon exceed the typical ratios of tin bronzes, highlighting the role of tin as an opacifier which must have been added independently of the copper. Perhaps the glassworkers responsible for the glass cakes from Ctesiphon indeed used ‘slow copper’ for the turquoise samples, while a ‘fast bronze’ may have been used for the red opaque glass as described in the cuneiform tablets. In an experimental work using a 7:2:1 copper-lead-tin bronze alloy, Brill was able to replicate the formation of ‘bright red opaque cuprous oxide crystals’ in the glass (Oppenheim *et al.* 1970, p. 123). Without further analysis of the samples, however, it is not clear whether the lead and copper concentrations in the Ctesiphon glasses are sufficient to produce cuprite (Cu_2O) or whether the main colourant is predominantly sub-micron metallic copper as well. For red metallic copper glass, the presence of lead does not seem to be functional and can thus be highly variable, not related to any specific chronological developments but rather to workshop traditions and recipes (Gratuze in press).

Taken together, the glass production and colouring techniques in early Islamic Mesopotamia hark back to Sasanian glassmaking traditions and recipes. The glass cakes and tesserae from Ctesiphon together with plant ash based Merovingian

beads may provide the missing link of the use of tin oxide opacified white and blue/turquoise plant ash glasses as well as the possible persistence of ancient Mesopotamian colouring techniques of copper red glasses into the Sasanian period. The change in the cobalt source between the late antique and early Islamic periods that has been observed with respect to Mediterranean glass production (Gratuze *et al.* 2018) appears to have taken place in Mesopotamian glassmaking as well. The compositional data on the Islamic glass beads from Ribe confirm these chronological transformations (Sode and Gratuze forthcoming), in terms of both the cobalt source and the copper red samples. The currently available data certainly indicate that the colouring technologies and raw materials employed for the production of cobalt blue and copper red glasses in Mesopotamia changed sometime between the Sasanian and early Islamic periods. No substantial differences were observed in the tin-opacified glasses. However, only a very limited set of data on strongly coloured and opacified glasses dating to the Sasanian and early Islamic periods are at present available, and a thorough investigation of strongly coloured vitreous materials, not only in terms of their base glass composition but above all with attention to the light-scattering particles, is necessary to reveal systematic differences in secondary production technologies and recipes.

Message in a bottle

We also analysed 23 elongated cobalt blue bottles from Samarra, which seem to belong to yet another primary production group (Schibille *et al.* 2018a). These cylindrical bottles are of a very thin delicate fabric with rounded bases and crudely cut-off necks (Fig. 51f). As noted by Danièle Foy (2020), these bottles must have been kept lying down and their contents must have been very popular and widely used, because they are among some of the most common glassware from the tenth century found throughout the entire Islamic world. Examples have been recovered in very large numbers from Fustat (Egypt), several sites in Palestine, Nishapur as well as Arabia and at Şabra al-Manşūriya near Kairouan in Tunisia (Foy 2020, and references therein). The finds from Samarra rank among the earliest of these peculiar delicate bottles. The silica source used for the production of the cobalt blue flasks found in Samarra differs considerably from that for Samarra 1 and Samarra 2, having much higher trace and rare earth element levels (Schibille *et al.* 2018a). Zirconium and titanium are generally correlated, but their ratio in the cobalt blue flasks is very different from that in the main groups in Samarra as well as from Levantine plant ash glasses, reflecting a geologically distinct silica source (Fig. 50a, b). The blue flasks were therefore probably imports from a different primary glassmaking location yet to be identified.

**Fig. 50:**

Compositional characteristics of the cobalt blue flasks from Samarra in comparison with Samarra 1 & 2, Samarra miscellaneous and Levantine reference groups. (a) Zirconium and titanium oxide values separate the Co blue flasks clearly from the Samarra as well as Levantine reference glasses; (b) Samarra Co flasks and Samarra miscellaneous tend to have chromium to lanthanum ratios in excess of the cut-off $\text{Cr}/\text{La} > 5$, suggesting a Mesopotamian origin; (c) phosphorus and magnesia to lime ratios seem to affiliate the cobalt blue flasks more with Levantine productions than with Samarra 1 and 2; (d) lime and lithium to soda ratios clearly distinguish the blue flasks from the Levantine reference group. Data sources: (Schibille *et al.* 2018a) for Samarra; (Phelps 2017) for Levantine plant ash glass P1.

In view of the geographical patterns of soda-rich plant ash components and the moderate magnesia and potash concentrations of the cobalt blue flasks (Fig. 50c), I originally attributed the cobalt blue flasks to a Mediterranean production zone, either Syria-Palestine or Egypt (Schibille *et al.* 2018a). However, in light of new data and the potential discrepancy between the compositional characteristics of the plant ash component and the glass provenance, this attribution has to be revised. According to our current understanding the production of plant ash glass had not yet resumed in Egypt in the middle of the ninth century, and Egypt, which was presumed to be one of the realistic options as a production centre, can therefore be excluded as a likely source (Foy 2020). As mentioned above, the zirconium and titanium concentrations separate the cobalt blue flasks also from the Levantine reference group (Fig. 50a). Phelps has previously attributed similar objects to a Mesopotamian origin (Phelps 2018), and their elevated chromium to lanthanum ratios ($\text{Cr}/\text{La} > 5$; Fig. 50b) as well as their elevated lithium levels (Fig. 50d)

confirm this attribution. Hence, the composition of the cobalt blue flasks again reflects a combination of Levantine plant ash characteristics (moderate MgO & K₂O) with a Mesopotamian silica source (elevated Cr/La), as observed in al-Raqa (Raqa 1) as well as ninth- to eleventh-century Siraf in Iran (Swan *et al.* 2017), and Mesopotamian working practices that cause an augmentation of the lithium levels.

The blue bottles differ also from the other cobalt blue glasses from Samarra in terms of their cobalt colourant. Consistent with an early Islamic cobalt source, the cobalt is associated with elevated zinc contents, but it also is strongly correlated with copper (Fig. 47). None of the Samarra 2 glasses coloured by cobalt show a correlation between cobalt and copper and the copper concentrations are considerably lower (i.e. 1500 ppm compared to 3500 ppm Cu). These mass-produced bottles evidently represent their own primary production (base glass) as well as secondary working practices (cobalt colourant). Based on the chrome to lanthanum ratios and lithium values, it is not unreasonable to assume that the place of manufacture was somewhere in Mesopotamia, the geological environment and glassmaking tradition of which gave rise to this peculiar pattern of trace elements. What is more, cobalt blue glass seems to have come predominantly (if not exclusively) from Mesopotamia during the early Islamic period. All the cobalt blue glasses that I have analysed so far from tenth-century al-Andalus, for instance, have a Mesopotamian base glass signature, except for some mosaic tesserae with Byzantine base glass characteristics (Gomez-Morón *et al.* 2021). The elevated lithium and chromium levels of the cobalt blue flasks also favour a Mesopotamian provenance, and the low absolute potash and magnesia values may simply point to the use of a different plant ash or a different ashing protocol. To date, no other early Islamic glass group from the Near East or Mesopotamia with similar overall compositional characteristics has been identified.

The samples from Samarra provisionally grouped as ‘miscellaneous’ display varying compositional features (Fig. 50). They have lower magnesia and MgO/CaO ratios, and higher phosphorus concentrations compared to Samarra 1 and Samarra 2. Nonetheless, Mesopotamian traits still prevail, in that many of the miscellaneous samples have elevated chromium to lanthanum ratios. This implies that individual objects arrived at Samarra, in some cases presumably as personal possessions (e.g. ink bottles). Among these samples are three stained glass fragments of bowls made from aqua bluish glass with a geometric and fish-scale pattern painted in yellow and blue on the outside and silver staining on the inside (Fig. 51c; Lamm 1928, pp. 93-98). Carboni has interpreted these fragments as a Mesopotamian attempt to imitate a quintessentially Egyptian technique by artisans working in the newly established caliphal capital at the time (Carboni and Whitehouse 2001, p. 201).

From the compositional data it is now clear that at least the base glass was not local to Samarra, and the three stained objects are compositionally so close that it is reasonable to conclude that they came from a single primary production location (Fig. 50). Other examples of stained glass objects include two fragments from Cairo, signed in the name of ‘al-Basri’ (the man from Basra), suggesting that the making of stained glass was in some ways linked to Basra. The city of Basra was famous for its glass makers and potters who, as mentioned earlier, were allegedly brought to Samarra at the request of the caliph al-Mu‘tasim (Ettinghausen 1942; Northedge 2007, p. 271). Two almost complete beakers with yellow silver stain, one in the Corning Museum of Glass, the other in the National Museum of Damascus, that were found in palace B at al-Raqqa are emblazoned with Arabic inscriptions stating that they were ‘made in Damascus’ (Al-Moadin 2019; Carboni and Whitehouse 2001, p. 208-209). Historical sources appear to confirm that glass workshops in Basra, Kufa, Samarra, Damascus and Fustat were renowned for making stained glass decorations (Al-Hassan 2009, pp. 126-126 and 148-154). Whether these sites were also the location of primary production, however, is at present unclear. Earlier eighth- to ninth-century examples of Islamic stained glasses recovered from Egypt (Fustat, Tebtunis, Raya) and Córdoba (Spain) are all of Egyptian natron glass (Foy *et al.* 2003a; Kato *et al.* 2009; Kato *et al.* 2010). The stained glass from Samarra ranks among the earliest plant ash glasses decorated with silver staining thus far recorded. All three fragments are compositionally and stylistically intimately related, which pleads for a common origin, in terms of both the raw glass and the secondary glass-working techniques.

The newly built caliphal city of Samarra was a major consumer of vitreous materials in the ninth century, displaying an impressive array of objects and optical properties (colours and opacity). There is no doubt that the presence of the caliphal court was a decisive factor in the pattern of patronage and consumption. The court was certainly the most dynamic market for large-scale architectural decorations that may have been commissioned by the caliph himself. Drawing from earlier sources, Ibn al-Jawzi (d. 1201) describes that the *maqsura* of al-Mutawakkil’s mosque was decorated with 2,400 tiles (*tawabiq*) of glass (Northedge 2007, pp. 122-123), and al-Harawi (d. 1215) specifies that the glass revetment ‘resembles a mirror’ (Northedge 2007, pp. 329). These descriptions seem to refer to the deep purple and dark blue glass tiles found in Samarra (Fig. 51e; Lamm 1928; Northedge 2007). The demand for glass supplies must accordingly have been high and the bulk of these architectural decorations were of the Samarra 1 and Samarra 2 glass types. The flourishing local or regional glass industry in the ninth century was probably driven by these caliphal commissions to supply new foundations and elaborate architectural displays. All the luxury ware recovered from Samarra

was likewise of either Samarra 1 when colourless, or Samarra 2 when coloured, whereas some vessels (e.g. cobalt blue flasks, stained glass vessels) were clearly imported from other sites. Given the compositional heterogeneity of the glass assemblage from Samarra as a whole, there must have been numerous primary glassmaking centres that were active in the ninth century in different regions of Mesopotamia. Even though there is no archaeological evidence yet to support this interpretation, the chemical data provide clear evidence for a diverse and prolific Mesopotamian plant ash glass production during the Abbasid period.



Fig. 51:

Selection of glass finds from Samarra housed in the Museum für Islamische Kunst in Berlin. (a) Figurative relief-cut bowl of colourless Samarra 1 base glass (Ident. Nr. Sam 606.2. Lamm 243); (b) fragment of relief-cut vessel of greenish aqua coloured Samarra 2 base glass (Ident. Nr. SamKat Lamm 246a); (c) painted and lustre painted fragment of a Mesopotamian base glass (Ident.Nr. SamKat 274); (d) fragment of millefiori tile of Samarra 2 base glass (Ident. Nr. Sam 772.6); (e) purple glass tile of Samarra 2 base glass (Ident.Nr. SamKat Lamm 887.1); (f) cobalt blue bottle (Ident.Nr. Sam I.21); © Photo: Museum für Islamische Kunst der Staatlichen Museen zu Berlin – Preußischer Kulturbesitz, photographer: Johannes Kramer (<http://www.smb-digital.de>).

The port city of Siraf – a trading hub

Another possible primary production site was the medieval port city of Siraf on the Iranian coast of the Persian Gulf (Fig. 1). The city's wealth and prosperity were firmly rooted in its function as an important commercial hub within a vast maritime trading network (Whitehouse 1970). The archaeological record of Siraf therefore consists largely of imports from other regions of the Islamic world, including glass from Egypt and Persia (Whitehouse 1970). LA-ICP-MS data on 101 glass finds from Siraf obtained at IRAMAT-CEB (Orléans) and recently published (Swan *et al.* 2017) add substantially to this picture. The glass finds from Siraf can be divided into two groups: the main group with high zirconium levels constituting two thirds of the assemblage, and another group with inconspicuous zirconium concentrations called low Zr group (Fig. 52a; Swan *et al.* 2017). The main group displays some seemingly contradictory compositional features, in that it has magnesium and potassium oxide levels that resemble plant ash glasses from Syria-Palestine or Egypt, coupled with high chromium to lanthanum ratios in line with Mesopotamian glasses (Fig. 52b, c). The authors concluded that the main group was produced from a local silica source enriched with chromium and zirconium and a plant ash imported from the Levant (Swan *et al.* 2017). However, the lithium levels of both Siraf glass types are elevated and correspond to other Mesopotamian and Iranian glass compositional groups (Fig. 52d). As discussed earlier in the context of the isotopic data, differences in the absolute concentrations of potassium and magnesium oxides do not necessarily indicate geographically different origins and/or different production locations. While the trade in plant ash is certainly a possibility, an alternative explanation is the use of a different plant species and/or different processing of the plant ash on site. The elemental differences in coastal plants compared to inland plants should also be studied in this context.

The low zirconium group is, according to the authors, compositionally affiliated with contemporary glass finds from Iraq and Iran (Swan *et al.* 2017). Five samples with low alumina levels are indeed related to Samarra 1, while the rest shows some similarity with Sasanian glasses from Veh Ardašīr (Fig. 52). Specifically, the plant ash component of the Siraf low Zr samples is similar to that of Sasanian 1 (1a & 1b) which has slightly higher phosphorus and lower magnesia to lime ratios than the glass from Samarra, and there are parallels with all three Sasanian groups in terms of the silica-related elements such as zirconium and titanium. The glasses from Veh Ardašīr appear to provide a good match, even if they are not identical. An origin in a common geographical production zone is therefore likely. Since some samples from al-Raqqā display similar features, we may assume that the Siraf low Zr glasses were produced in Mesopotamia somewhere in the Euphrates

or Tigris valley between al-Raqqā in the northwest and the Persian Gulf in the southeast. Despite Siraf's strategic location with direct maritime links to the Indian Ocean trading network and the Red Sea, the early Islamic glass finds from Siraf are clearly tied to the glass productions in Iraq and western Iran. The presence of these glasses in an important trading port reflects the relative importance of Mesopotamian glass production during the ninth and tenth centuries CE.

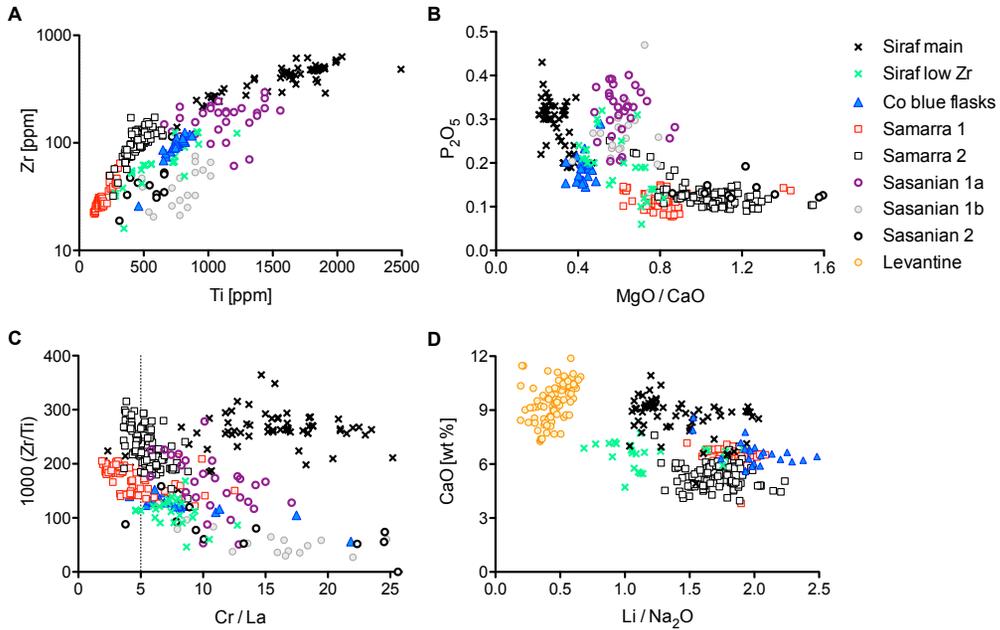


Fig. 52:

Plant ash glasses from Siraf in comparison with glass from Samarra and Veh Ardašīr. (a) Zirconium to titanium ratios of Siraf low Zr resemble those of the Sasanian glass from Veh Ardašīr; (b) the main group from Siraf has significantly higher phosphorus and lower magnesia to lime ratios than the glass from Samarra and is closer to plant ash glasses from Syria-Palestine in terms of the plant ash component; (c) zirconium to titanium and chromium to lanthanum ratios clearly separate the two glass groups from Siraf, while their elevated chromium to lanthanum ratios ($\text{Cr/La} > 5$) suggest a Mesopotamian provenance for both groups; (d) lithium to soda ratios are elevated in both groups from Siraf relative to the Levantine glass reference group and are in this respect similar to Mesopotamian glass productions. Data sources: (Mirti *et al.* 2008; Mirti *et al.* 2009) for Sasanian glass; (Schibille *et al.* 2018a) for Samarra; (Swan *et al.* 2017) for Siraf; (Phelps 2017) for Levantine plant ash glass P1.

Notwithstanding the chronological gap of about 150 odd years between the end of the Sasanian Empire and the earliest evidence of Islamic glass production provided by the glassmaking installations at al-Raqqā, the general compositional similarities between Sasanian and early Islamic glass assemblages suggest a degree of continuity in the production of plant ash glass in Mesopotamia. Given the internal variability of individual glass assemblages and between sites, it is

likely that glassmaking in late antique and early Islamic Mesopotamia occurred on a smaller scale compared to that in the Mediterranean region. Primary glass production appears to have been concentrated in urban centres associated with an imperial residence (al-Raqqa, Samarra, possibly Veh Ardašīr/Ctesiphon) or wealthy commercial centres such as Siraf. Julian Henderson proposed a model whereby artisans, including glassmakers and workers, moved with the caliphal court (Henderson 2003), and there is good evidence that this may apply to Mesopotamia during the early Abbasid period. The foundation of Veh Ardašīr in the early third century CE is said to have been associated with the establishment of glass workshops, suggesting that artisans, including glassworkers, were mobile and moved as needed already at the beginning of the Sasanian period (Simpson 2014b). At the same time it is clear that glass was extensively and widely traded throughout the Sasanian Empire and the Islamic Caliphates. Despite the importance of local production, certainly at al-Raqqa but probably also at Veh Ardašīr, Samarra and Siraf, finished glass objects were imported from other sites, and there is some evidence for the import of raw glass to al-Raqqa (Phelps 2017, p. 360). This suggests a certain degree of specialisation (e.g. Co blue flasks, stained glass, colourless high silica glass) that opens up a further dimension of the organisation of the glass industry at the time. Glassmaking in Mesopotamia seems to have differed from that in Egypt and the Levant in this respect, possibly due to structural differences in the local administration as well as different production technologies and strategies.

Glass from Iran and Central Asia – multiple origins of the glass at Nishapur and Merv

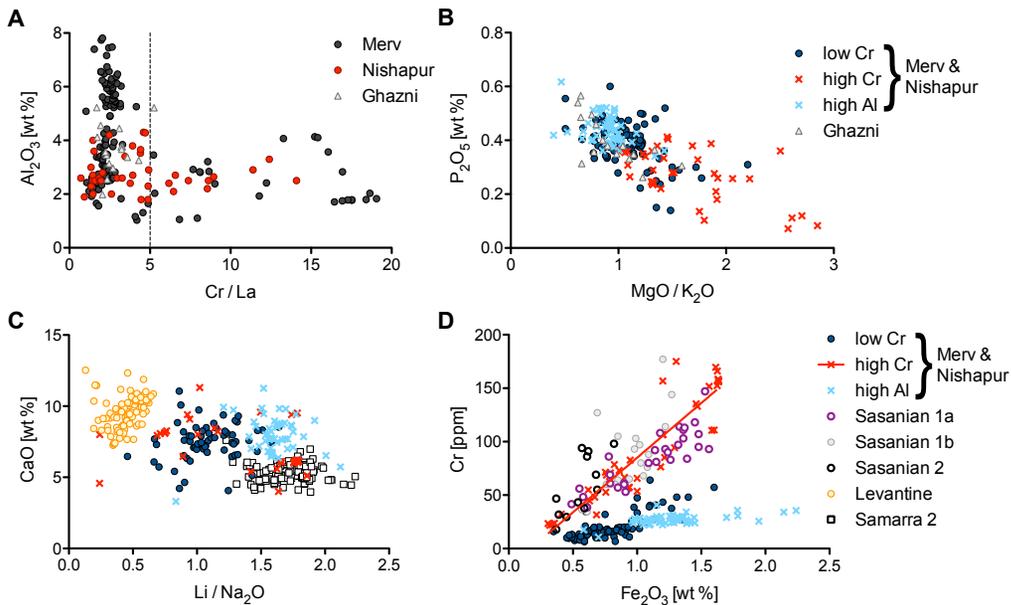
Heading east along the Silk Road to Nishapur and Merv (Fig. 1), I will attempt to address the issue of Iranian and Central Asian plant ash glass production. From earlier studies by Robert Brill and Mark Wypyski (Brill 1995; Wypyski 2015) it is clear that the quality and diversity of archaeological glass finds at Nishapur were shaped by the city's position as a mercantile centre in the trading network of the Silk Roads. Cargoes arrived at Nishapur from Mesopotamia in the west and Central Asia further to the east, while the city may also have exported materials in either direction (Kröger 1995). The colourless Nishapur 1a glass has been discussed in detail in relation to Samarra 1 and Samarra 2 (see above). Here, I concentrate on the remaining finds that have been analysed and that suggest a local eastern Iranian or Central Asian origin based on comparative material from Merv.

The ancient city of Merv is located in a fertile oasis in southwest Central Asia, present-day Turkmenistan, at a crossing point of the Silk Road leading north to Bukhara and on to Samarkand, one branch leading southeast to Bactra and yet another heading southwest to Nishapur and further on to Mesopotamia (Fig. 1; Herrmann 1997a; Herrmann 1997b). The site of the murder of the last Sasanian ruler, Yazdgerd III (r. 633-651 CE), Merv was soon integrated into the Umayyad Empire. In the eighth century a new suburb was established, eventually developing into one of the largest and most splendid cities of the Abbasid and Seljuk periods. Merv was largely destroyed by a Mongol invasion in 1221 CE (Herrmann 1997a; Herrmann 1997b). Glass finds are seemingly rare in Middle Sasanian levels at Merv, but increase in frequency in the later Sasanian and early Islamic periods, although no archaeological evidence for glassmaking has been discovered (Herrmann 1997b; Simpson 2014a). In collaboration with the British Museum, we recently analysed 148 glass samples mostly from the early Islamic period (ninth century), and the data serve as an interesting comparison for the Nishapur assemblage. The analysed finds were recovered within the scope of the International Ancient Merv project, an archaeological collaboration between the National Institute for the History of Turkmenistan of the Cabinet of Ministers, University College London and the British Museum. I have excluded some outliers and the cobalt blue samples (Co > 200 ppm) from the following discussion for reasons of simplicity and clarity.

Except for three scratch-decorated vessels that are natron-type glasses, all vitreous material recovered from Nishapur and Merv has been produced using soda-rich plant ash with at times very high magnesia levels. The compositional characteristics have clearly affiliated the colourless glass Nishapur 1a (Wypyski's Type A) with Samarra 1 and Samarra 2. As far as Nishapur Type 1b is concerned, these glasses have a significantly different silica source make-up, both in absolute concentrations and in varying or absent correlations between elements. For example, there is no clear correlation between chromium and titanium or between zirconium and neodymium. The compositional characteristics and low chromium to lanthanum ratios ($Cr/La < 5$) are therefore ambiguous, but the low lime and phosphorus contents and relatively high MgO/CaO ratios point to a Mesopotamian provenance for these glasses as well (Fig. 44b). The coloured samples from Nishapur (Wypyski's Type B and C) are highly variable, precluding an easy classification and/or geographical attribution. However, by comparing the Nishapur data with the analyses of ninth-century glass from Merv further east along the Silk Road, we can detect and quantify compositional shifts across space.

In order to convert the heterogeneous data set from Nishapur and Merv into meaningful glass groups and to establish systematic geographical patterns, the first step is to apply some of the discriminants of Mesopotamian glass such as chromium to lanthanum, magnesia to lime and magnesia to potash ratios in combination with alumina and phosphorus concentrations (Fig. 53). In so doing, it becomes possible to distinguish the glass that is most likely imported from Mesopotamia from that with a putative Central Asian origin. The chosen thresholds are provisional and ultimately depend on the overall silica-related impurity levels of the glass as reflected in the clean Samarra groups, where the chromium to lanthanum ratios are clustered on either side of the proposed cut-off ($\text{Cr/La} = 5$). Comparing the alumina concentrations of the Nishapur and Merv assemblages there is an obvious alumina cut-off at about 4.5% (Fig. 53a). None of the Nishapur samples have alumina levels higher than 4.5% and none of the Merv high alumina group have elevated chromium to lanthanum ratios. This high alumina group from Merv has on average higher potash ($\text{K}_2\text{O} > 4\%$) and somewhat higher phosphorus ($\text{P}_2\text{O}_5 \sim 0.44\%$) concentrations. Compared to Levantine plant ash glass, Merv high Al has higher lithium to soda ratios and is similar in this respect to the Mesopotamian glass from Samarra (Fig. 53c). The silica source underlying this high alumina group from Merv is rich in feldspars as well as in heavy minerals such as zirconium, titanium and thorium. The combination of these features suggest a Central Asian provenance and confirms Robert Brill's initial observation that plant ash glass of the Islamic period in Central Asia often has greater potassium levels than contemporary glasses from Syria-Palestine and/or Mesopotamia (Brill 2001).

Allocating the other glass samples from Nishapur and Merv to clearly defined compositional groups is more challenging, as they exhibit some conflicting evidence regarding the plant ash and silica sources. Alumina concentrations range from about 1% to 4.5% and the chromium to lanthanum ratios are highly variable (Fig. 53a). Many of the samples with elevated chromium to lanthanum ratios ($\text{Cr/La} > 5$) also tend to have on average higher magnesia to potash ratios as well as lower phosphorus concentrations (Fig. 53b). These features recall Mesopotamian plant ash glass groups. The low Cr/La group, in contrast, resembles the Merv high alumina type that is assumed to be of Central Asian provenance. It is worth noting that a handful of samples from Merv with especially low alumina and high magnesia contents is compositionally close to Nishapur 1a and, by extension, to Samarra 1 and Samarra 2. The majority of the glass finds from Merv, however, belong either to the high alumina variant or to the low Cr/La group with on average higher potassium, calcium and phosphorus contents than typical Mesopotamian glass.

**Fig. 53:**

Comparison of the coloured glass from Nishapur with assemblages from Merv and Ghazni. (a) Alumina concentrations versus chromium to lanthanum ratios establish a cut-off between a Merv high Al glass ($\text{Al}_2\text{O}_3 > 4.5\%$), as well as a low and a high chromium group; (b) Merv high Al are similar to the low Cr group with respect to the phosphorus concentrations and the magnesia to potash ratios; (c) all three compositional groups from Merv and Nishapur show elevated lithium to soda levels compared to Levantine reference glasses; (d) chrome is strongly correlated with iron in the high Cr sub-type similar to the Sasanian glass from Veh Ardašir. Data sources: (Meek *et al.* in preparation) for Merv; (Mirti *et al.* 2008; Mirti *et al.* 2009) for Sasanian glass; (Phelps 2017) for Levantine glass; (Schibille *et al.* 2018a) for Samarra (Fiorentino *et al.* 2019b) for Ghazni.

Compositionally, the assemblage from Merv as a whole shows similar group structures and distributions to that from Nishapur, but with a different weighting of the groups. To visualise the differences between the two glass assemblages the relative proportions of the glass groups at each site may be considered. If we express the number of samples in each glass group as a percentage of the total number of objects analysed (Fig. 54), we can quantify the internal variability and interregional differences and start drawing up supply patterns. For example, the assemblage from Merv contains 37% of high alumina glass, which is entirely absent from Nishapur. In contrast, about 55% of the Nishapur samples are consistent with Mesopotamian glass similar to Samarra 1 and Samarra 2, while only some isolated fragments (4%) of this high purity glass type were identified among the Merv finds. A similar percentage of samples with elevated chromium to lanthanum ratios ($\text{Cr/La} > 5$) was found in Nishapur and Merv, but there is a

clear trend towards more low chromium glass in Merv. Since the chronology of the two assemblages is approximately the same, these differences are necessarily of a geographical nature, reflecting access to different glass supplies, on the assumption that the sampling is representative.

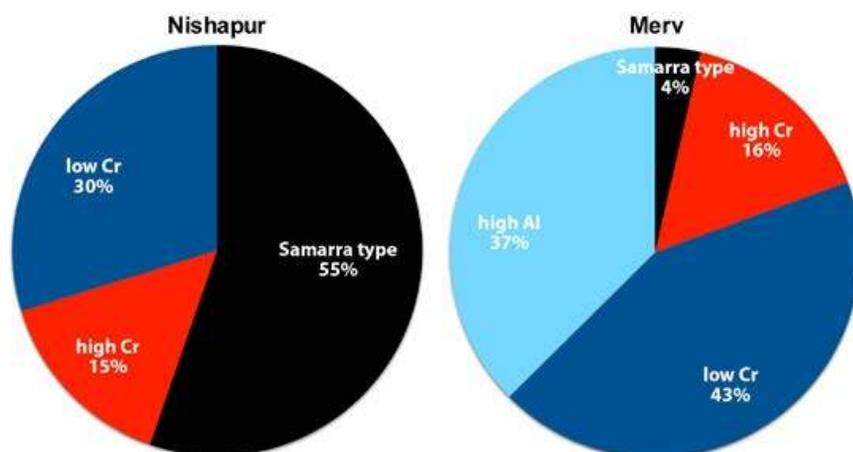


Fig. 54:

Camemberts of ubiquity distribution of the different Mesopotamian, Iranian and Central Asian glass groups represented at Nishapur (left) and Merv (right).

Taken together, almost three quarters of the glass from Nishapur is compositionally linked to Mesopotamian glassmaking practices (high Cr, high MgO/CaO and MgO/K₂O, low P₂O₅). The group of coloured samples with elevated chromium to lanthanum ratios seems to be roughly equivalent to Wypyski's Type B that he suggested may have been produced locally (Wypyski 2015). However, the use of chromite-bearing sands appears to be characteristic of Mesopotamian glass productions in view of the overwhelming evidence from Samarra, Veh Ardašīr, Ctesiphon and Siraf. The glass with elevated chromium to lanthanum ratios from both Nishapur and Merv exhibits clear similarities with the Sasanian glass from Veh Ardašīr in terms of its strong positive correlation between iron and chrome (Fig. 53d). Thus, in the absence of archaeological evidence of glass production at Nishapur and in light of the fact that the majority of the samples analysed are compositionally linked to the vitreous material from Samarra (Nishapur 1) and Veh Ardašīr (high Cr/La), the importation of these high Cr/La glasses from the Mesopotamian region seems likely. These glasses also tend to have higher magnesia relative to both potash and lime, which can be explained by the magnesia-rich soil deposits from the Tigris and Euphrates that have had an important impact on the composition of the plant ash used in Mesopotamian glassmaking.

The picture changes considerably when it comes to the glass with low chromium to lanthanum ratios. Moving eastwards from Nishapur, this type of glass seems to increase in number and diversify dramatically. The samples attributed to this group have typically somewhat higher phosphorus, potassium and calcium oxide concentrations, and they therefore lack the distinguishing features of Mesopotamian glassmaking. The glass assemblage from Merv consists of about 80% of low Cr/La and high alumina type glass that has highly variable compositions in terms of the elements related to the silica source and otherwise exhibits few conspicuous characteristics. No firm conclusions about the provenance of these glasses can be drawn because of the lack of comparative data. The relative ubiquity of the low Cr/La and high Al groups among the finds from Nishapur and Merv suggests the increasing importance of these compositional groups along the Silk Road from west (Nishapur) to east (Merv). This interpretation is further backed by the analytical data on glass from Ghazni, another trading centre along the Silk Road further east in Afghanistan on the route to Kandahar (Fig. 1). The bulk of a small set of glass finds from the Ghaznavid Palace of Ghazni, dated to between the second half of the eleventh and the end of the twelfth centuries CE (Fiorentino *et al.* 2019b) conforms broadly to the low Cr/La group from Nishapur and Merv, even though it is overall more variable and has somewhat lower magnesia contents (Fig. 53). From this we may reasonably conclude by way of exclusion that the low Cr/La group that is largely absent from glass assemblages further west but that is present at Nishapur, Merv and Ghazni can be attributed to an eastern Iranian or Central Asian glass production.

The cobalt blue glass samples provide independent evidence that the high and low chromium glass groups from Nishapur and Merv originated from separate primary as well as secondary glassmaking and glass-working events and, by extension, centres. The cobalt colourants used at the two sites are strikingly different. The one used for the Merv samples of the low Cr/La group is a cobalt with substantially higher concentrations of zinc than any of the Mesopotamian cobalt blue fragments from Samarra and Nishapur (Fig. 55b). The cobalt used in the Nishapur high Cr/La glass has instead surprisingly high nickel concentrations strongly correlated with cobalt, and which is reminiscent of late antique nickel rich cobalt sources such as the one exploited for Merovingian beads (Fig. 55a). Their zinc content is at the same time similar to that of the cobalt blue samples from Samarra, both of the Samarra 2 sub-type as well as the cobalt blue flasks. Different origins can therefore be assumed for the cobalt colourant, which lends further support to a geographical distinction between the chromium-rich and chromium-poor plant ash glasses in Mesopotamia and Central Asia.

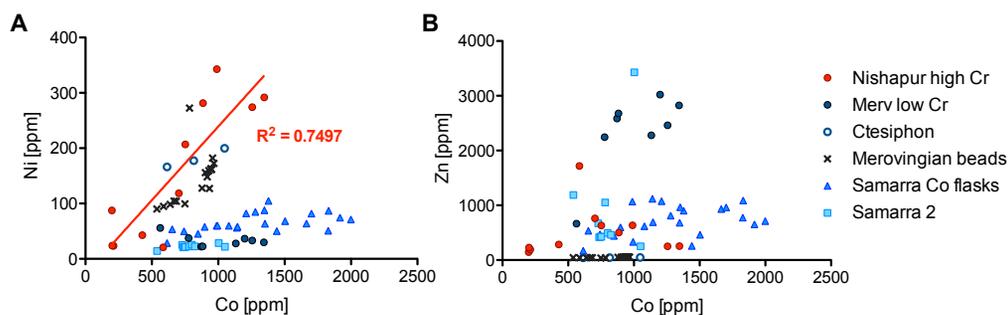


Fig. 55:

Cobalt colourant in blue samples of Nishapur high Cr and Merv low Cr compared to data from Ctesiphon, some Merovingian glass beads and Samarra. (a) Cobalt and nickel are strongly correlated in the Nishapur high Cr/La glass as in late antique Sasanian glass represented by the Merovingian beads and the finds from Ctesiphon; (b) Merv low Cr samples have very high zinc concentrations, while Nishapur high Cr shows similarities with cobalt blue glass from Samarra. Data sources: (Schibille *et al.* 2018a) for Samarra; unpublished data on Ctesiphon (Schibille); (Mathis *et al.* forthcoming) for Merovingian beads; (Meek *et al.* in preparation) for Merv; data on Nishapur glass (courtesy of B. Gratuze, J. Lankton & M. Wypyski).

Mesopotamian versus Central Asian glass productions

The similarities between Nishapur, Merv and Ghazni do not disclose where exactly these glasses were made or in which direction they travelled along the Silk Road, but they certainly indicate the use of different raw materials and glassmaking techniques that distinguish these glasses from Mesopotamian assemblages and that identify them as northeastern Iranian or Central Asian glasses. Nothing is known about the origins of Central Asian glassmaking. It may have its roots in Sasanian traditions developed in Mesopotamia during the third and fourth centuries CE, even though no evidence of primary production or secondary working of glass has yet been found on the Iranian plateau or Central Asia prior to the ninth century CE. Simpson (2014b) points out that the Islamic conquest and Umayyad expansion led to the mobility of craftsmen and accelerated the development of local industries, and that Islamic glassmaking inherited numerous technological practices from its Sasanian predecessors, including the choice of materials and some aesthetic preferences. Although the evidence is still sketchy, there is a growing body of analytical data that illustrates the continuous use of soda-rich plant ash as the main fluxing agent in Mesopotamian glassmaking, certainly since the first century CE (e.g. Dibba) and perhaps even without interruption since the beginnings of glassmaking in the Late Bronze Age. The wide internal heterogeneity of individual

assemblages supports a model whereby glass was produced on a moderate scale, and several primary production centres were active at the same time, which is already evident in Sasanian glassmaking. Small-scale production implies greater variability due to variations in the raw materials, but also due to a higher probability of contamination through the furnace environment, crucibles and glassmaking tools. This variability complicates group affiliations and hampers a clear classification of many of the plant ash glasses. Future chemical characterisation of sand deposits that could have been used for glass production particularly in Mesopotamia, the Iranian plateau and in Egypt, alongside the analysis of substantial well-dated glass assemblages, will be necessary to establish discrete production zones and ultimately reveal the temporal dissemination of compositional groups.

Comparison of the more tightly defined clusters representative of Mesopotamian and Central Asian raw materials already allows us to establish a set of discriminants to distinguish vitreous materials from the two regions. Samarra 1 and Samarra 2 originated with a high degree of certainty in Mesopotamia in the vicinity of Samarra itself, and they constitute relatively homogenous groups (Schibille *et al.* 2018a). Merv low Cr/La and high Al likewise form a relatively uniform groups and, as discussed above, are most likely of Central Asian provenance. The Samarra glasses have significantly higher magnesia to lime ratios and much lower phosphorus oxide concentrations that represent differences in the plant ash component (Fig. 56a). The plant ash used for the Central Asian glass from Merv contains notably higher potassium oxide as well as rubidium, caesium and possibly barium concentrations, all linked to the higher potash levels (Fig. 56b). Strontium is indirectly reflective of the plant ash as well in that it is intimately related to calcium, and its abundance varies according to the geology of the environment in which the plants grow, but also to how and where it accumulates within the plant (Barkoudah and Henderson 2006). In relation to wood ash, for example, it was shown that strontium together with calcium was especially enriched in the bark of beech trees and, by extension, in twigs more than in trunks due to the larger surface ratios compared to the wood core (Wedepohl and Simon 2010). Differences in lime and strontium concentrations (Table 7) are therefore difficult to interpret as they may indicate merely differences in the plant parts that were used for ashing, different geological environments where the plants grew and/or different plant species altogether.

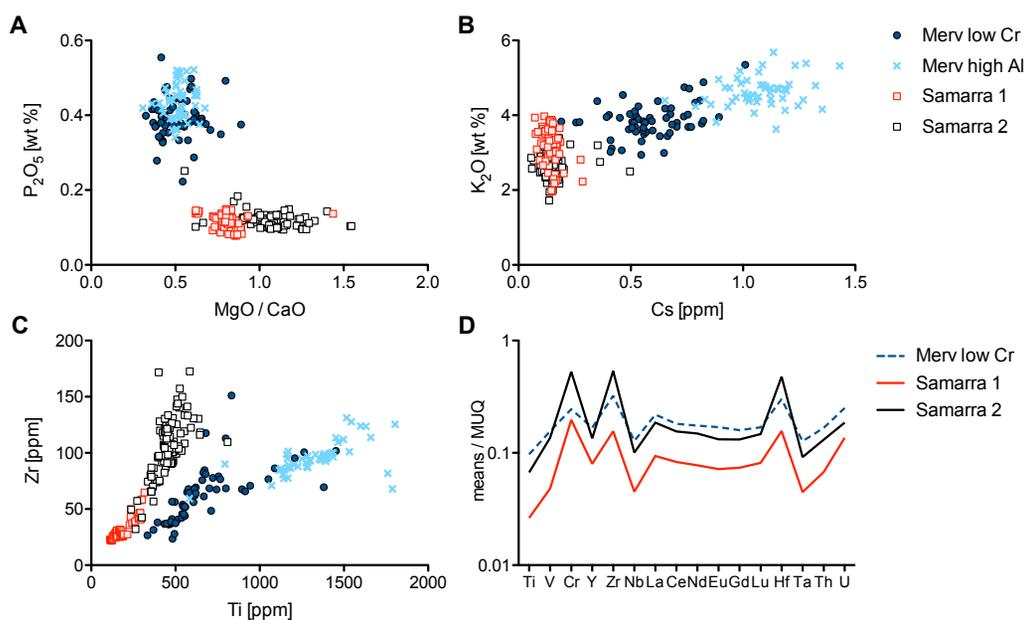


Fig. 56:

Comparison of Mesopotamian and Central Asian characteristics. (a) Phosphorus compared to magnesia to lime ratios show that Central Asian glasses represented by Merv low Cr and Merv high Al have on average higher phosphorus and lower MgO/CaO ratios than Mesopotamian glass from Samarra; (b) differences in potash and caesium levels indicate differences in the plant ash component; (c) zirconium and titanium are correlated in both the Samarra and the Merv samples, but at different ratios (slopes), in that Central Asian glass from Merv tends to have lower zirconium relative to titanium contents; (d) mean trace element patterns of Merv low Cr, Samarra 1 and Samarra 2 normalised to the average abundance in the earth's upper continental crust (Kamber *et al.* 2005). Please note that the REEs shown (La, Ce, Nd, Eu, Gd, Lu) act as placeholders for all the REEs that run perfectly parallel to the x-axis. Data sources: (Schibille *et al.* 2018a) for Samarra; (Meek *et al.* in preparation) for Merv.

Silica concentrations are highest in Samarra 1 ($SiO_2 = 70\%$) and lowest in Merv glasses ($SiO_2 = 65\%$), putting the minor and trace element patterns into more pronounced relief (Fig. 56c-d). Samarra 1 was obviously produced from an exceptionally clean silica source, rich in quartz and poor in accessory minerals, in the form of either quartz sand or quartz pebbles. In contrast, Merv low Cr has considerably higher aluminium, titanium and rare earth elements, especially in relation to chromium, zirconium and hafnium (Fig. 56d), suggesting the use of glassmaking sands contaminated with additional minerals such as kaolinite, feldspars, monazite and rutile (Wedepohl *et al.* 2011). Samarra 2 has a trace element profile that runs in parallel to Samarra 1 but with considerably higher concentrations across all the trace elements and REEs. The clearest differences between the glass from Samarra and that from Merv are therefore the concentrations of chromium, zirconium and hafnium relative to the other elements. The average

titanium to zirconium ratio of the Merv samples, for example, is approximately 11, those of Samarra 1 and Samarra 2 are about 6 and 4, respectively (Fig. 56c). The relative amounts of these accessory minerals distinguish the glassmaking sands used for the Merv glasses clearly from both Samarra groups, while the two Samarra types apparently derived from geologically related silica sources, also reflected in the parallel shape of the trace element profiles. The even distribution of the REEs in all three glass types suggests that the silica sources came from parts of the upper continental crust that ultimately derived from the primitive earth's mantle, in line with the observations made by Karl Hans Wedepohl and colleagues (Wedepohl *et al.* 2011).

The compositional characteristics of the glasses from Samarra and Merv reflect regional variations in the raw materials used for glassmaking in Mesopotamia and northeast Iran/Central Asia. There is some overlap with respect to the elements related to the plant ash component, but the silica sources show a clear distinction and identify regional specificities. Several criteria for differentiating between broad geographical production zones of early Islamic plant ash glasses have been proposed in the past (Henderson *et al.* 2016; Phelps 2018; Schibille *et al.* 2018a; Swan *et al.* 2017). For example, a trend has been observed whereby the magnesia to lime ratios decrease from east (Iranian plateau and Mesopotamia) to west (Egypt and the Levant) (Henderson *et al.* 2016; Phelps 2018). Although this geographical distinction appears to be partly true, MgO/CaO ratios are not always effective, as has been shown in the context of the glass assemblage from Siraf (Swan *et al.* 2017). In fact, the glass assemblage from al-Raqqa represents a good example for this phenomenon. Raqqa 1 and Raqqa 4 have very different MgO/CaO ratios, but the strontium and neodymium isotopes indicate an origin in the same geological environment. There is certainly a specific type of Mesopotamian glass, represented by Sasanian 2 from Veh Ardašīr, Samarra 1 and Samarra 2 and part of Raqqa 4, that indeed has very high magnesia and low lime and phosphorus levels. Some of the other Mesopotamian glasses, however, do not display such a clear pattern, and the magnesia to lime ratios fluctuate mostly between 0.5 and 1. The magnesia to potash ratios are generally greater than 1 ($\text{MgO}/\text{K}_2\text{O} > 1$), while the phosphorus levels are usually relatively low ($\text{P}_2\text{O}_5 < 0.3\%$). Glass tentatively attributed to a northeastern Iranian/Central Asian provenance has MgO/CaO ratios at around the 0.5 mark, and has typically somewhat higher phosphorus oxide values ($0.4\% < \text{P}_2\text{O}_5 < 0.8\%$) and lower MgO/K₂O ratios, which might serve as a starting point for a differentiation between these two production zones.

It has similarly been alleged that the chromium to lanthanum ratios increase from the Mediterranean in the west to Iraq and Iran in the east (Henderson *et al.* 2016; Swan *et al.* 2017). Elevated chromium relative to lanthanum, however,

appears to be specific to Mesopotamian glass productions in the strict sense, meaning those within the catchment area of the Tigris and Euphrates river system that has been shown to be rich in chromium and incidentally also rich in magnesium oxide (Freestone 1991; Shortland *et al.* 2007). This apparently also includes the coastal region of the Persian Gulf, as reflected in the main glass group from Siraf (Swan *et al.* 2017). Glass groups from sites further east, from Nishapur, Merv and Ghazni, have no elevated chromium to lanthanum ratios and are presumed to have been produced in eastern Iran and/or Central Asia. At the same time, it must be conceded that not all Mesopotamian glasses have elevated chromium values. If the glasses have been produced from a clean, quartz-rich silica source, the chromium levels can be inconspicuous and an attribution becomes more difficult. This is reflected, for instance, in Samarra 1 and, to a lesser degree, in Samarra 2 which have both been made from a silica source low in accessory minerals. To establish group structures and group affiliations, it is therefore necessary to consider in parallel a multitude of trace elements and their correlations, among which chromium, titanium, zirconium and neodymium appear to be the most promising. Even then, an unequivocal attribution may not be possible as long as no primary production sites with associated glass finds have been firmly identified and characterised. Neodymium isotopes may in the future help to determine the geological age and origin of sand deposits that have been exploited for the production of early Islamic glasses in various regions. Large-scale approaches have the potential to cast further light on possible origins and movements of vitreous material by a simple comparison of the ubiquity distribution of compositional groups across the Islamic world at a given time. For this, high-resolution analytical studies of substantial glass assemblages that are well-contextualised and robustly dated are needed for a better discrimination of compositional groups.

From the discussion above it is clear that the model of regional production zones advanced by Julian Henderson and colleagues (Henderson *et al.* 2016; Henderson *et al.* 2020) needs to be further refined, and that some of the glass groups from sites in western and central Asia need to be reassigned, most notably the glasses from Nishapur. This re-evaluation also has far-reaching consequences for the proposed flow of glass along the Silk Roads. The colourless glasses recovered in great abundance in Samarra have been shown to be more likely Mesopotamian, possibly from the region around Samarra itself, and not imported from Nishapur (Schibille *et al.* 2018a; Wypyski 2015). In other words, the movement occurred in the opposite direction; the colourless glasses from Nishapur most probably originated in the west and came from Samarra along one of the main arteries of the Silk Road network (Fig. 1). A Mesopotamian provenance can also be assumed for Nishapur 1b as well as many of the other samples with elevated chromium to

lanthanum ratios. Some of these glasses may have been imported from al-Raqqā (Henderson *et al.* 2016). Without more trace element analyses of the al-Raqqā assemblage, however, a compositional relationship between the two sites remains elusive. The remaining glasses from Nishapur are compositionally linked to the glass groups from Merv and may be affiliated to Central Asian glassmaking. It remains uncertain whether any of the glass finds were produced in or around Nishapur itself, at Merv or at yet another unidentified location during the ninth and tenth centuries CE. Since about 80% of the glasses from Merv for which we have LA-ICP-MS data have low Cr/La ratios, including the high Al variant, it seems likely that these glasses came from the area around Merv, from where they then travelled along the Silk Road in a westerly direction. Merv was, after all, one of the earliest Arab settlements in the northeastern province of Khurasan after the initial Arab conquest, and it would not be surprising if this settlement were accompanied by the establishment of an early glassmaking centre for primarily local use.

Several glassmaking centres seem to have been active at more or less the same time, which favours a glass production model that is increasingly decentralised and active on a much smaller scale in comparison to the Mediterranean production zones. Nonetheless, our data also strengthen the idea of a technological specialisation with respect to the highest quality colourless glass (e.g. Sasanian 2, Samarra 1) that was used as the base for expensive luxury objects such as vessels with facet-cut decorations (Henderson *et al.* 2016). Wheel-cut faceted vessels of all types (bowls, beakers, jars, bottles) appear to have been particularly sought after in the eastern regions of the Islamic world during the early Islamic period prior to the eleventh century (Kröger 1995, p. 123). Islamic facet-cut glass has its roots ultimately in the Sasanian period where it first appears at Veh Ardašīr in the second half of the fourth century CE (Mirti *et al.* 2008; Simpson 2014b). One of the facet-cut vessels from Veh Ardašīr (VA13) is a Roman manganese-decoloured glass, and half of the other faceted glasses correspond to the near colourless Sasanian 2 type (Mirti *et al.* 2008; Mirti *et al.* 2009), which bears some resemblance to Nishapur 1a and Samarra 1. All the faceted samples from Nishapur analysed belong to Nishapur type 1a. The technological and material connections suggest the existence of secondary workshops, perhaps in southern Mesopotamia, specialising in the production of facet-cut vessels for which they used a high quality, colourless or near colourless raw glass. The raw materials appear to have been carefully selected for this high-end colourless glass, suggesting a dedicated primary production event as well.

At Nishapur the majority of the faceted colourless vessels were recovered from Tepe Madraseh which, judging from the architectural structures and rich decorations, was a palatial complex or similar (Wilkinson 1987). The glasses found here were presumably no ordinary objects circulating among the lower social classes, but can be considered luxury ware, belonging to the household of an elite. Numerous passages in the Babylonian Talmud refer to the value and prestige of clear white glass. Especially interesting in this context is a comment on the use of white glass in contrast to (naturally) coloured glass. While white glass was reserved for the higher social classes, the use of naturally coloured glass during a wake was relegated to the poor (Moed Katan 27a). Another passage in the Babylonian Talmud makes reference to an ‘extremely valuable white glass’ that was broken at a wedding (Berakhot 31a; for both passages see also Simpson 2014b). So there is no doubt that colourless glass was more valuable and, by extension, more expensive and possibly more labour-intensive in its production than naturally coloured glass. Our analytical data imply a scenario wherein the manufacture of this high-quality colourless glass may have been concentrated in a single production zone, possibly even in a single primary production centre in Mesopotamia, from where it was widely distributed throughout the Islamic Empire, as evidenced by finds from Fustat in Egypt (Brill 1999), the Levantine coast (Phelps 2018), al-Raqqa (Henderson *et al.* 2016), Samarra, Nishapur, Merv and as far away as Japan (Abe *et al.* 2018). The production of naturally coloured glass does not require the same level of expertise and purity of raw materials and could have been achieved in different locations by less experienced craftsmen. The circulation of these naturally coloured glasses is accordingly more restricted, and even though the material still travelled, it did not do so over quite as long a distance as the colourless glasses and its circulation is not as systematic.

Distance can also be linked to questions of quantity and cost. Even if there was an active exchange of all sorts of goods and commodities along the Silk Road, large quantities of glass certainly posed challenges for overland travel due to its weight and fragility in the case of finished objects. It can therefore be assumed that materials traded over great distances overland were of a special economic, cultural and/or aesthetic value, and that the demand for them could not be met by local supplies. Isolated objects may end up in the archaeological record of a site for other reasons, for example ink wells that may have been in the personal possession of scholars and that could have travelled far despite being rather mundane objects. It is thus a desideratum of future research to analyse assemblages of glass large enough to distinguish the norm from the exception. This will provide a more quantitative insight into the dynamics of exchange and the trade in glass during the early Islamic period within and between different production zones and the

development of local glass industries. To distinguish populations of plant ash glasses successfully, trace element analysis by LA-ICP-MS is indispensable because it enables the rapid analysis of large numbers of samples, and because major and minor elements do not offer the necessary compositional resolution to categorise plant ash glasses. Selected strontium and neodymium isotope analyses can offer further confirmation of the validity of compositional groupings. The need to have elemental compositions alongside isotopic data must here be emphasised. Isotopes can distinguish the geological environments from where the silica and the plant ash originated, but they do not necessarily permit a fine-tuned differentiation of production groups. Furthermore, it must be taken into account that geologically similar but geographically potentially disparate settings can result in the same isotopic signatures, as we shall see in the context of glass from al-Andalus.

While there are some parallels in the development of the plant ash glassmaking industry in different regions, there are clear patterns that distinguish the organisation of the glass industry in Mesopotamia from that in Egypt and the Levant. In Mesopotamia plant ash glassmaking was rooted in and continued an ancient technology that included the exploitation of distinct raw materials, a specific type of plant ash and its processing, as well as unique colouring and opacifying techniques. The survival of Sasanian glassmaking traditions may be linked to the general adoption and preservation of old Persian administrative structures and fiscal systems, and the continued existence of the old Persian elite as part of the internal power structures (Kennedy 2009; Kennedy 2015). The locally ruled semi-independent principalities in Iran and further east had considerable financial autonomy and may have fostered regional industries, including glassmaking, which resulted in a multitude of mostly high magnesia plant ash glass types. The compositional differences within and between glass assemblages imply the parallel (possibly contemporaneous) existence of primary production centres and a reduced scale of production compared to the early Islamic glass production in Egypt and along the Levantine coast. At the same time, there is evidence of a technological specialisation in relation to high-quality colourless glass. The manufacture of this special type of colourless Mesopotamian glass may have been more centrally organised. It was demonstrably traded over long distances throughout the Abbasid caliphate, and as far afield as Japan. Nothing comparable is known from Egypt or Syria-Palestine, apart maybe from Roman antimony-decoloured natron glasses produced in Egypt. The range of distribution of the other, less specialised plant ash glass types is uncertain, because we still do not have sufficient reliable trace element and isotopic data. It may be expected that the reach of production zones and centres that were landlocked was somewhat more limited than that of those situated on one of the

main rivers (Euphrates, Tigris, Oxus) or on the coast (Levant, Persian Gulf). Like the glass industry in Egypt and the Levant, however, glassmaking in Mesopotamia and Central Asia was dependent on access to a profitable market in the form of relatively wealthy urban centres and/or caliphal or governors' residences. The development and prosperity of the early Islamic glass industry depended on the demand for its products, and the higher echelons of society and the caliphal courts in particular generated precisely this demand.

“From Polis to Madina” and the flux of glass in Spain

Investigations into the transformation of ancient glassmaking have mainly focused on the eastern Mediterranean, on Egypt and the Levant, because here the primary production of glass has a long history and because glassmaking has been firmly documented by archaeology and archaeometry alike. The supply of glass in the central and western Mediterranean regions relied instead on imports from the east, and from the late antique period onwards increasingly on the recycling of Roman and late antique natron glass (Bertini *et al.* 2017; Bertini *et al.* 2020; De Juan Ares *et al.* 2019a; Minini *et al.* 2008; Neri *et al.* 2019; Pactat *et al.* 2017; Pactat *et al.* 2021; Schibille and Freestone 2013). Studies of medieval Islamic glass from the western Mediterranean are surprisingly limited, and virtually non-existent as regards the Maghreb, with the exception of Šabra al-Manšūriya (Kairouan, Tunisia; Foy 2012a; Foy 2020), Sijilmâsa (Foy *et al.* 2020) and al-Basra in Morocco (Robertshaw *et al.* 2010). In this context, some glass finds and beads from Essouk-Tadmekka in the northern Malian region are also worth mentioning (Lankton *et al.* 2017; Nixon *et al.* 2017). The situation in Sicily is only now being explored (Colangeli 2022; Schibille and Colangeli 2021). As far as the Iberian Peninsula is concerned, while some attention has been paid to glass of the Roman period (Da Cruz 2014; Price 2004), Visigothic, Byzantine or Islamic vitreous materials have until recently not been subject to any systematic typological or analytical investigation (reviewed in De Juan Ares and Schibille 2017a), despite the very dynamic historical and archaeological research on early al-Andalus over the last two decades (e.g. Anderson 2014; Gutiérrez Lloret 2015; Gutiérrez Lloret 2018). Medieval Hispania is culturally and politically situated at the interface between the Roman, European and Arab worlds while cultivating strong economic ties with the Maghreb (Gaiser 2013). Discussions on its history and archaeology are therefore intrinsically linked to the processes of Islamisation and the establishment of al-Andalus, which encompasses the territories belonging to the *Dar al-Islam* during the Middle Ages. The social and cultural transformations that began with the Arab-Berber conquest of Hispania in 711 CE were not completed until the tenth century

CE (Casal García 2018; Gutiérrez Lloret 2015; Gutiérrez Lloret 2018). To examine how the Umayyad conquest of the Iberian Peninsula influenced the flux of glass and the development of a local, quintessentially Andalusian glassmaking industry, it is therefore necessary to adopt a comparative, inter-regional approach. The chemical analysis of a number of glass assemblages that date to this transitional period reveals a unique diachronic sequence of technological and cultural developments and changes in the connectivity of the Iberian Peninsula. However, this research is still in its infancy, and future projects will have to target the gaps in our knowledge in relation to the geographical and chronological patterns thus far observed.

One of the challenges that I have encountered is the limited number of Iberian glass finds, particularly from eighth- and ninth-century CE contexts, and their often poor state of preservation. The relatively small number of glass finds compared to previous centuries suggests that the Islamic conquest may have been accompanied by the cessation or at least contraction of glass supplies from the eastern Mediterranean (De Juan Ares and Schibille 2017a). Of the Islamic glass workshops known from al-Andalus (De Juan Ares and Schibille 2017a), only the glass remains of Puxmarina in Murcia have thus far been analysed (Carmona *et al.* 2008; Carmona *et al.* 2009; García Heras 2008; Jiménez Castillo *et al.* 1998). All other glass workshops have not been studied or were even destroyed without samples being preserved for analysis (Duckworth and Govantes-Edwards 2015). This chapter is essentially based on our own analytical data obtained within my ERC project, *GlassRoutes: Mapping the first millennium glass economy*, which has generated a considerable number of new data and information about the glass supply and its changes in the Iberian Peninsula from the late Roman period in the fourth century through to the Taifa principalities in the eleventh and twelfth centuries. The discussion includes data on the glass-working remains from a ninth- to tenth-century workshop in Pechina (Almería; De Juan Ares and Schibille *in press*), the glass finds from various sites in Córdoba, including the material from eighth- to early ninth-century Rabad of Šaqunda (Schibille *et al.* 2020a), from excavations in the western suburbs known as *Picinas Municipales de Poniente* (PMP) dating to the tenth and early eleventh centuries (De Juan Ares *et al.* 2021), from tenth-century Madīnat al-Zahrā' (Schibille *et al.*, *in preparation*) and the tenth-century mosaic tesserae from the Great Umayyad Mosque in Córdoba (Gomez-Morón *et al.* 2021). Later glass finds from Ciudad de Vascos (De Juan Ares and Schibille 2017b) and Albalat spanning the tenth to twelfth centuries are briefly touched upon to illustrate the continuing evolution of glassmaking technologies in the Iberian Peninsula (Fig. 57). In order to evaluate the scale of cultural and material transformations in the early medieval period it is equally necessary to consider briefly the developments prior to the Umayyad conquest in 711 CE. The

discussion therefore starts with a comparative and integrated assessment of the changes that occurred during the late Roman and Visigothic periods.



Fig. 57:

Map of the western Mediterranean, including the Iberian Peninsula, Sicily and the Maghreb, indicating sites mentioned in the text. Created using worldmap from ArcGIS hosted by Esri, USGS (<https://worldmap.maps.arcgis.com/apps/mapviewer/index.html>).

Late Roman and Visigothic glass from Hispania

There are few written sources referring to the production of glass in the Iberian Peninsula. The earliest is one by Pliny the Elder, who mentions that in Gallia and Hispania we find ‘sand subjected to a similar process’ (*iam vero et per gallias hispaniasque simili modo harena temperature*), which presumably refers back to the primary production of glass that he has described previously (*Natural History*, 36.66-67). In the seventh century, Saint Isidorus of Seville repeats Pliny’s passage (*Etymologies*, XVI.26; Barney *et al.* 2006). Hence, Isidorus’ text cannot be considered an independent source. Nonetheless, textual references such as these have provided the rationale for a large European research project exploring the isotopic signatures of silica sources along the Mediterranean coastline to probe the veracity of these literary sources (Degryse 2014). To my knowledge, no analytical nor archaeological evidence has thus far come to light that conclusively demonstrates the primary production of glass in the Iberian Peninsula prior to the establishment of Islamic al-Andalus. In contrast, at least 35 secondary glass workshops are known which date to the third to fifth centuries CE (Da Cruz and Sánchez de Prado 2012; Sánchez de Prado and Da Cruz 2014). Secondary glass-working evidently flourished in Roman Spain, implying ample supplies from the eastern Mediterranean. Remains of glass workshops become less frequent from the sixth and seventh centuries onwards and are typically associated with urban centres such as Barcelona, Cartagena and Alicante, as well as the new Visigothic foundation of Récopolis and the revived Tolmo de Minateda (Beltrán 2005; De Juan Ares and Schibille 2017a; Govantes-Edwards *et al.* 2020; Gutiérrez Lloret *et al.* 2003; Sánchez de Prado and Da Cruz 2014). As the analytical data on the glass assemblages from numerous sites throughout the Iberian Peninsula demonstrate, the glasses dating to the first to seventh centuries CE match the well-established primary glass production groups from Syria-Palestine and Egypt, thus confirming the centralised model of primary glass production and circulation during the Roman and late antique periods (reviewed in De Juan Ares and Schibille 2017a).

Recently, we have been able to refine the geographical scope and chronological sequence of glass imports between the fourth and seventh centuries CE. As with other western Mediterranean, central and northern European regions, Egyptian HIMT glass dominates the archaeo-vitreous record of Spain in the fourth and fifth centuries CE. The compositional results of the fourth- to fifth-century glass assemblage from Picola – *Portus Illicitanus* in Santa Pola (Alicante), the main sea harbour of the Roman *Colonia Iulia Ilici Augusta*, show that 87% of the glasses are of the HIMT type (De Juan Ares *et al.* 2019b). Given that Picola was an important port of entry for commodities imported via the sea route, it can be assumed that

the glass assemblage is representative of developments in the Iberian Peninsula more widely. The Iberian Peninsula is not, of course, a unified historical or geographical entity, but instead comprises a number of distinct geographic regions that exhibit diverse distribution patterns of, for example, ceramics (Reynolds 2009). From the data currently available it appears that the glass assemblage from Picola nonetheless reflects broader trends in the economic environment of the Iberian Peninsula as regards the long-distance import of bulk vitreous material from the eastern Mediterranean. Only a handful of glasses of Levantine origin have been identified, unlike Visigothic assemblages where Levantine glasses are in the majority from the second half of the sixth into the seventh centuries CE (De Juan Ares *et al.* 2019a). The analyses of the glass assemblages from three rural Visigothic sites in central Spain identified clear changes in the supply of glass to the Iberian Peninsula in the second half of the sixth century. Egyptian glasses in the form of Foy 2.1 and Foy 2.1 high Fe prevailed during the fifth and the first half of the sixth centuries, at which point these Egyptian groups were supplanted by Apollonia-type Levantine I glass alongside the now widely recognised late antique Magby glass type with a plant ash component that is again an Egyptian glass group (De Juan Ares *et al.* 2019a).

The glass from Recópolis – exception to the rule or genuine trend?

It has been argued that the evidence from Visigothic assemblages pointing to a geographical shift in glass supply from Egyptian to Levantine imports does not correspond to wider developments in the Iberian Peninsula and rather represents what the authors tentatively called the 'Reccopolis anomaly' (Govantes-Edwards *et al.* 2020). The city of Recópolis, located on the Tajo in the province of Guadalajara, Castilla la Mancha, was founded in 578 CE by the Visigothic King Leovigild, and there is evidence of a continuous urban development at Recópolis well into the early seventh century CE, reflected in the expansion of the palatine complex and numerous artisan workshops (Olmo Enciso 2008). It is not entirely clear when the city was finally abandoned, since some presence after the Umayyad conquest of the region in the eighth and ninth centuries CE is still attested to (Velázquez and Ripoll 2016).

The excavations yielded evidence of several glass furnaces that were originally interpreted by the archaeologists as primary production installations, at least one of which was part of the original fabric of the city (Castro and Gómez 2008). The vitreous materials recovered so far from Recópolis, with a total weight of about 30 kg, include glass waste and crucibles and vessels of a mostly functional and utilitarian character, with a preference for open forms. We have analysed 200

glass samples from different well-stratified and controlled contexts excavated by Lauro Olmo since the 1980s, including the workshop areas as well as some of the residential quarters. Chronologically the glass finds span the late sixth to early ninth centuries CE (i.e. into the Islamic period). The samples were selected from mostly diagnostic fragments to provide a representative overview of the different types and working debris. The colours range from virtually colourless and bluish or greenish aqua to dark amber (Gómez 2017).

The analytical data reveal the remarkable homogeneity of the glass corpus from Recópolis that separates into three main compositional groups, all of which are consistent with well-established soda-lime-silica groups of eastern Mediterranean origin: Foy 2.1, Apollonia-type Levantine I and Magby (Fig. 58). By far the largest compositional group (i.e. 76% or 151 samples) corresponds to Levantine I glass from Apollonia. Fifteen of these Levantine I glasses have exceptionally high lime concentrations ($\text{CaO} > 11\%$), and another 21 fragments show signs of some recycling in the form of elevated manganese levels ($\text{Mn} > 250$ ppm). Approximately 15% of the assemblage (i.e. 28 samples) is of the Foy 2.1 glass type, half of which has elevated iron concentrations ($\text{Fe}_2\text{O}_3 > 1.5\%$). Twelve samples, representing 6% of the assemblage, have potash and magnesia levels in excess of 1.5% and roughly match the composition of *Magby* glass. Finally, nine samples have compositions that cannot easily be classified, due to a considerable degree of recycling.

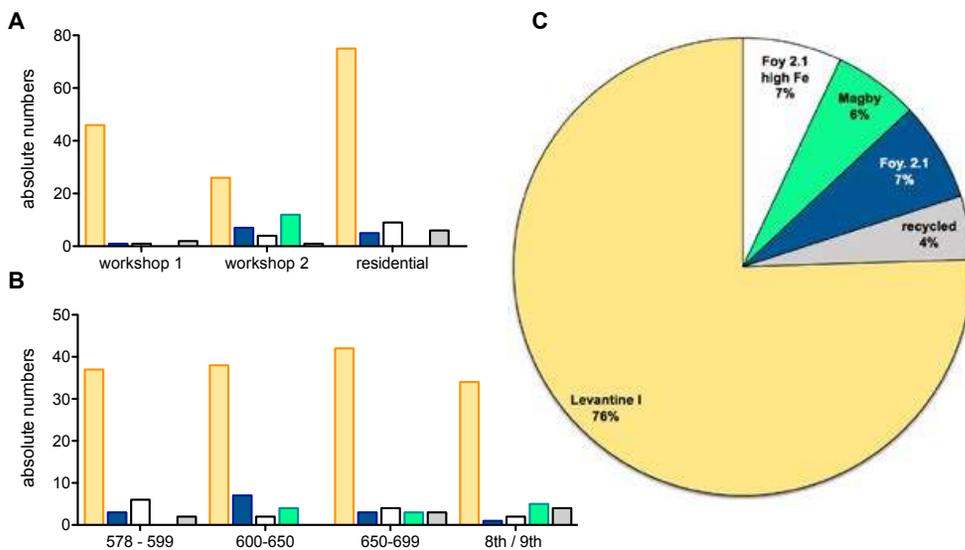


Fig. 58:

Distribution of compositional groups identified at Recópolis (n=200) across time and space. (a) Relative abundance of the different glass groups according to the find spot; (b) temporal pattern of the different glass groups; (c) ubiquity distribution of the compositional groups (Schibille, unpublished).

The detailed characterisation of these glass groups is beyond the scope of the present chapter, as they have all been discussed in chapters 1 and 2 on Egyptian and Levantine natron-type glasses. However, there are a number of special features that are worth pointing out. The Levantine glasses from Recópolis, for example, overall correspond closely to the sixth- to seventh-century Levantine I glasses from Apollonia, Beth She'an, Dor, Jerusalem and Sepphoris (Freestone and Gorin-Rosen 1999; Freestone *et al.* 2008b; Phelps *et al.* 2016; Tal *et al.* 2004). The calcium oxide contents of the Levantine glasses from Recópolis are highly variable, ranging from about 7% to 12.5%, which may be the result of variations in the chemical composition of the sand over time and/or contaminations from the furnace environment during secondary working and recycling (Al-Bashaireh *et al.* 2016; Chen *et al.* 2021). A large piece of cullet from Arsuf (No. 3682 in Brill 1999, Vol. 1 p. 60; Vol. 2 p. 87) has a comparable composition, with lime concentrations of about 11.5%, while the high lime levels of some glass-working debris from 'Aqir (Israel) have been attributed at least partly to contamination through furnace materials (Chen *et al.* 2021). The calcium contents of the high-lime (CaO > 11%) subgroup from Recópolis do not show a clear relationship with any of the other elements typically associated with contamination through fuel ash or furnace linings such as phosphorus, potassium or iron, even though magnesium oxide tends to be slightly elevated as well (Schibille, unpublished data). Otherwise the Levantine high Ca group exhibits similar features to the other Levantine glasses. The average trace element patterns confirm that the two Levantine groups are practically identical in terms of the geochemical nature of their silica sources. The natural carbonate and feldspar impurities of the Levantine silica sources probably account for some of the variations, and the compositional spread of the Levantine glasses may simply reflect different consignments of raw glass and secondary glass-working campaigns.

The Levantine I and Levantine I high Ca groups have astonishingly low levels of other recycling markers. Manganese levels are well within the range of natural impurities in the silica source (Mn < 250 ppm), antimony is typically below 5 ppm, and lead concentrations do not usually exceed 50 ppm. This implies that the Levantine glasses appear virtually pristine, and if they have been recycled recycling was limited and highly selective, not augmenting any of the colouring elements. By contrast, the antimony and lead contaminations in the Foy 2.1 groups and Magby glasses reflect the incorporation of some recycled cullet at some point in the life cycle of these glasses. Even in the case of the Foy 2.1 and Magby categories, however, the recycling remains minimal. It must also be taken into consideration that Foy 2.1 glasses frequently have elevated transition metals above the usual background values of sand sources to start with (Ceglia *et al.* 2019;

De Juan Ares *et al.* 2019a). The high incidence of unspoilte Levantine I glass at Recópolis is remarkable; in fact, it represents the largest assemblage of Apollonia-type Levantine I glass thus far recorded in the western Mediterranean. This not only provides clear evidence that sufficient quantities of fresh raw glass from the eastern Mediterranean arrived in Spain during the sixth and possibly seventh centuries, but it also shows that the Iberian Peninsula had active commercial contacts with the eastern Mediterranean which had no parallel in Italy or France at the time. The only exception at present is Sicily (Schibille and Colangeli 2021). These observations should come as no great surprise, as the sixth-century ceramic evidence from Benalúa (Alicante), for example, similarly contrasts with that of the northwestern Mediterranean, a fact which is perhaps indicative of a major trade link between the southeastern coast of the Iberian Peninsula and the Levantine coast, possibly via Sicily in the sixth to seventh centuries CE (Reynolds 2009, p. 117).

At Recópolis raw glass chunks were identified to be from only the Levantine I and the Magby compositional groups (Gómez 2017), suggesting that at least these two types were imported as raw glass, while glass cullet was also collected and recycled. Levantine I glass makes up virtually all the finds from workshop 1 (Fig. 58a), which is contemporaneous with the foundation of the city and which was active until the first decades of the seventh century CE (Gómez 2017). The furnaces of workshop 2 apparently operated until the end of the seventh century CE (Gómez 2017). Here, Levantine I makes up about half of the finds, while Magby glass makes its first appearance (Fig. 58a-b). The foundation of the city of Recópolis appears to have been accompanied by the establishment of a glass workshop which in the first instance obtained its raw material practically exclusively from the Levantine coast in the form of raw glass. A short time later, other glass groups (Foy 2.1, Foy 2.1 high Fe, Magby) appear on the scene and supplement Levantine I glass. The different glasses were used in workshop 2 at about the same time without extensive mixing and recycling, even though recycling is evident in some of the Levantine glasses that were also recovered from workshop 2. A simple explanation for this selective use of different glass groups is that Levantine I glass was imported as raw glass, while Foy 2.1, which is a slightly earlier glass type, may have exclusively been worked from cullet, suggesting that fresh and recycled glass may have been kept separate.

The analytical data confirm that the glass workshops at Recópolis were dedicated to extensive secondary glass-working and they had access to sufficient raw glass to minimise the necessity of recycling. We found no evidence of primary production; the three identified glass groups are all of eastern Mediterranean origin. The importance of the glass assemblage from Recópolis lies in the very

exact foundation date and the contemporaneous establishment of a secondary glass workshop. The chronological range of the different primary glass groups confirms the overall temporal developments that we have previously observed with respect to three rural Visigothic sites (De Juan Ares *et al.* 2019a). The most striking similarity is the clear prevalence of Levantine glass from the last quarter of the sixth century onwards (Fig. 58b). Sufficient new raw glass from the Levant evidently arrived in Recópolis and literally outlasted the Visigothic period. Levantine I glass is the largest group until well into the eighth (possibly ninth) century, which may indicate that the imported glass had been securely stored to be processed later. The relative abundance of recycled material increases at Recópolis in the second half of the seventh century, but the degree of recycling is by far not as pronounced as in other places. No heavily recycled Foy 2.2 has been identified, unlike in the rural areas of Gózquez and El Pelicano (De Juan Ares *et al.* 2019a), in Narbonne (Foy *et al.* 2003b) and the Crypta Balbi in Rome (Mirti *et al.* 2000; Mirti *et al.* 2001). The explanation may be that Recópolis, as an important urban centre with large-scale secondary production facilities, was able to maintain a certain standard in the glass that was used or, more prosaically, that glass-working came to an end as soon as shortages in supplies occurred that would have affected the quality of the glasses, and that are therefore not seen in the archaeological record. Our study of the rural Visigothic sites indicated a notable drop in glass finds from the middle of the seventh century that is not evident from the data at Recópolis, where the absolute numbers remain stable. This, however, may be due to sampling strategies.

The overwhelming presence of Apollonia-type Levantine I glass in Visigothic Spain raises some questions about the supply patterns of glass more generally, because of the virtual absence of Levantine I glass prior to the middle of the sixth century CE. According to Govantes-Edwards and colleagues (2020), the glass assemblage from Recópolis is the exception to the rule in sixth- and seventh-century Spain and inextricably tied to the ideological programme of the Visigothic monarchy, inspired by the Byzantine Empire. Why this should lead to a preference for Levantine glass over Egyptian imports is unclear. Although I agree that more data, especially for the seventh century, are needed for us to be certain about the more fine-grained developments of glass supply in the Iberian Peninsula, the broad trends are beginning to emerge. The last quarter of the sixth century brought a major increase in imports of Apollonia-type Levantine I to the Iberian Peninsula, to inland sites such as Recópolis and the rural settlement of El Pelicano and Gózquez near Madrid (De Juan Ares *et al.* 2019a) as well as the Visigothic-period settlement of Tolmo de Minateda located about 120 km west of Alicante (Schibille *et al.* in preparation). Earlier glass assemblages consist almost

exclusively of Egyptian glass groups (HIMT, Foy 2.1), and Egyptian glasses continue to turn up in the archaeological record throughout the latter half of the first millennium (Foy 2.1, Foy 2.2, Magby). The prevalence of Egyptian glass is well illustrated by the finds from the glass factory at the coastal settlement of Benalúa-Alicante. The Benalúa finds form an important glass assemblage that is typologically and compositionally exceedingly homogeneous. Approximately 95% of the glass finds analysed (n=242) are of the Foy 2.1 compositional group with little internal variation, and only a handful of samples have a Levantine I composition (Schibille, unpublished data). This suggests that Levantine glass was not imported on a large scale before the end of the sixth century CE. The spectacular increase in the presence of Levantine I glass at Recópolis thus marks a turning point in the supply patterns of vitreous material in the Iberian Peninsula.

The glass assemblages from Benalúa (sixth century) and Tolmo de Minateda (seventh to ninth centuries) reflect a general surplus of Egyptian glass in the Iberian Peninsula. In Tolmo this includes HIMT, Foy 3.2, Foy 2.1 and Magby glass, that were evidently carefully collected for recycling. With the exception of Magby, these are all older glass production groups (i.e. pre-seventh century), possibly indicating a general decline in imports. At Tolmo de Minateda, we have observed a unique pattern of trace element contamination which must have been introduced into a Foy 2.1 base glass during secondary glass-working or recycling. About a third of the Foy 2.1 samples exhibit unusually high lithium contents alongside high levels of transition elements. They also have higher rubidium and lower strontium to lime ratios, while the potassium levels do not show any conclusive trend. The glass layers in some crucible fragments that were recovered from Tolmo have exceptionally high lithium levels, too, clearly confirming an increase in contamination as a result of local glass processing. Only some Foy 2.2 samples from the Rabad of Šaqunda (Córdoba) exhibit similar compositional characteristics (Schibille *et al.* 2020a). Interestingly, elevated lithium levels are typical of Iberian plant ash glass produced during the early Islamic period (e.g. Fig. 64b). It thus seems that the incorporation of some Iberian raw material during the secondary processing of these Foy 2.1 samples foreshadows later developments.

It is unclear how the Arab conquest of Egypt and Syria-Palestine, which was complete by the middle of the seventh century, affected the influx of fresh glass to the Iberian Peninsula. The compositional characteristics of seventh- to eighth-century glass assemblages from most sites that we have studied show an increase in recycling of late antique glass types, while the total number of glass finds is drastically decreasing (De Juan Ares *et al.* 2019a). The same is true for the period immediately after the Arab conquest of the Iberian Peninsula and the establishment

of al-Andalus in 711 CE. Glass recycling continued well into the eighth century. A new local production in Córdoba that first appeared in the period between the second half of the eighth and the first quarter of the ninth century changed all that.

The first local production of glass in Islamic al-Andalus

The 'invention' of glassmaking – the case of Šaqunda

There is still much that we do not know about the developments in the production and circulation of glass in the Iberian Peninsula after its integration into the Umayyad Empire in the early eighth century CE. Some Egyptian glasses in the form of natron-type Egypt 2 reached Iberia until the ninth century (De Juan Ares and Schibille 2018). Islamic soda ash glass from the Levant and Mesopotamia makes an appearance in Iberia by the early ninth century as well (Schibille *et al.* 2020a). By contrast, Egyptian plant ash glass is extremely rare. For example, out of more than 200 samples of glass from Madīnat al-Zahrā' near Córdoba dating from the tenth century that we have analysed only one fragment appears to be an Egyptian import (Schibille, unpublished). It is not yet clear when the first soda ash glass was locally produced in the Iberian Peninsula. The earliest known Islamic glass workshops located in Almería and Córdoba date to the ninth century CE, but they may have been merely secondary working installations (De Juan Ares and Schibille 2017a). The archaeological evidence suggests that glassmaking and glass-working activities experienced a revival in the eleventh and twelfth centuries CE (Duckworth *et al.* 2015; Jiménez Castillo 2006). However, our analytical and isotopic study of glass finds from the Rabad of Šaqunda (Córdoba) has revealed the development of local lead glass production already at the end of the eighth or first two decades of the ninth century CE (Schibille *et al.* 2020a).

The vitreous material from the Rabad of Šaqunda is scientifically interesting because it represents the earliest Islamic glass assemblage of considerable size from the Iberian Peninsula with an impeccable chronology that casts a clear light on the transformation in the production and supply of glass in the western Mediterranean. Córdoba had been chosen as the seat of government soon after the Arab conquest and became the capital of the newly independent Umayyad Emirate in 756 CE. The Umayyad Amir, 'Abd al-Rahman I, expanded and embellished his new capital city, first and foremost with the construction of the Great Mosque and the Alcazar (Casal García 2018). Due to rapid population growth, the urban area expanded to the south bank of the Guadalquivir, to the area that was to become the suburb of Šaqunda. Šaqunda was created *ex novo* around the middle of the eighth century with no pre-Islamic occupation, and it was literally razed to the ground a

mere 70 years later in connection with a popular uprising in 818 CE (Casal García 2018). A ban on building in this part of the city that was imposed by the Amir al-Hakam I was in effect until modern times. Excavations begun in 2001 thus unearthed an early Islamic suburb almost untouched by later developments (Casal García 2018).

Three excavation campaigns in an area of 22,000 m² yielded relatively little vitreous material, especially when compared to Late Antiquity and the Visigothic period (De Juan Ares *et al.* 2019a; Schibille *et al.* 2020a). The glasses from Šaqunda differ from Visigothic assemblages also in terms of their functionality and typology. While large open tableware constitutes the bulk of Visigothic assemblages, this is mostly absent in Šaqunda, being largely replaced by closed forms such as unguentaria, bottles and beakers (Schibille *et al.* 2020a). A surprisingly large number of glass bangles (n = 9) were recovered; these are in fact the oldest known Islamic glass bracelets from al-Andalus (Créssier 1993; Malalana Ureña and Hernández 2014). Thus, the formal repertoire of the Islamic glass assemblage from Šaqunda represents a clear departure from Visigothic traditions. With regard to its composition, the assemblage is an interesting mix of natron glass, some soda-rich plant ash glasses, as well as a unique type of high-lead glass. The major part of the assemblage (i.e. about 60%) still adheres to the natron glass recipe, and virtually all of the samples show elevated levels of transition metals, particularly elevated antimony and lead, indicative of a significant contribution of recycled material. The original base glass material includes Foy 2.1 or its recycled variant, Foy 2.2 (Foy *et al.* 2003b), Levantine I glass and two fragments of Egyptian origin. One of these samples is a silver-stained fragment with low alumina and lower than usual lime concentrations (about 4.5%), but which otherwise exhibits Egypt 2 characteristics (De Juan Ares *et al.* 2020; Schibille *et al.* 2020a). The other specimen is a typical Egypt 2 sample. The overall group structure of the natron glasses demonstrates, on the one hand, extensive recycling of older glass groups and, on the other hand, the import of Islamic natron-type glasses from Egypt in the second half of the eighth or early ninth century CE. This import, however, appears to relate only to isolated, finished objects, rather than the trade in raw glass *en-masse*.

The second most important group of glass in Šaqunda is high-lead glass of a distinct dark yellowish green or amber colour. The samples contain mainly lead (PbO ~ 52%) and silica (SiO₂ ~ 34%), with considerable levels of alumina (Al₂O₃ ~ 5%) (Fig. 59). Different types of high-lead glasses appeared in the ninth to tenth centuries CE across Europe and the Islamic world, including lead silica glasses consisting of very high lead (PbO ≥ 57%) and silica as the main constituents, as well as several variants of potash lead and soda-ash lead glasses with lower lead oxide contents and considerable amounts of alkali and alkaline

earth elements (De Juan Ares and Schibille 2017b; Duckworth *et al.* 2015; Gratuze *et al.* 2003; Gratuze *et al.* 2014; Gratuze *et al.* 2017; Mecking 2013; Wedepohl *et al.* 1995). Sayre and Smith (1961) were the first to identify Islamic lead glass as a distinct category, but numerous sub-types have since been characterised due to the increasing volume of data (Brill 1989; Krueger 2014; Pollak 2017; Sayre and Smith 1961; Schibille *et al.* 2020a; Shindo 2006). The origins of lead silica glass in the eastern Islamic world are not known, and it is also unclear how high-lead glasses from different geographical regions are related in terms of their technologies and the use of raw materials. Since Islamic high-lead glass postdates variants of lead glass from China, Korea and Japan, it has been proposed that the technology originated in East Asia (Brill 1989; Brill and Stapleton 2012; Gan 2009; Henderson *et al.* 2018; Liu *et al.* 2012; Wypyski 2015). There is now considerable evidence in support of the hypothesis that Islamic lead glass may have originated in Central Asia. This includes the etymology and use of the term *mīnā*, comparative lead isotope data, and the fact that two of the earliest fragments of emerald green lead silica glass from Samarra can be linked to Samarra group 2 (Schibille *et al.* 2018a). The evolution of glass in the western Mediterranean appears to follow a different trajectory. The lead slag glass from Šaqunda was more likely an independent technological innovation, because of its compositional peculiarities and the fact that it predates all other known high-lead glasses. The lead glass smoothers from Melle may be an exception as they seem to appear at around the same time. Whether this is coincidental or whether there was an exchange of savoir-faire between Carolingian France and Umayyad al-Andalus is impossible to say at this point.

Islamic and central European high-lead glasses are distributed along a silica and lead oxide mixing line, with the silica lead glasses at one end of the spectrum and the European potash glasses at the other, while the Islamic soda-ash lead glasses lie in between the two end members (Fig. 59a). When comparing the lead glass from Šaqunda with published high-lead and alkali lead glasses, they are clearly distinct. Although they are close to the Islamic lead silica glasses *stricto sensu*, the Šaqunda samples (except for one fragment) have slightly lower lead and higher alkali and alkaline earth concentrations (Fig. 59b). In comparison to Islamic soda-ash lead glasses from the Iberian Peninsula, including samples from Córdoba itself on the northern bank of the Guadalquivir, the Šaqunda samples have somewhat higher lime and potash, but lower overall alkali concentrations as a consequence of the substantially lower soda contents. In addition, the Šaqunda glasses are comparatively rich in alumina and iron oxide (Fig. 59c). This composition appears specific to the high-lead glass from Šaqunda, and there is no other known example of high-lead glass that has the same compositional features. Instead, the high-lead

glass from Šaqunda shows striking similarities with monochrome and bichrome lead glazes from Córdoba that date to the second half of the ninth century (Salinas and Pradell 2018). Hence, there appears to be a technological and material link between the production of lead glass and lead glazes in al-Andalus. The important observation here is that the lead glass predates glazes by about half a century (Salinas *et al.* 2021). A technological transfer from glassmaking to glazes has been proposed in the context of the use of lead stannate in the production of yellow opaque glazed pottery in Egypt and Syria in the eighth century (Tite *et al.* 2015).

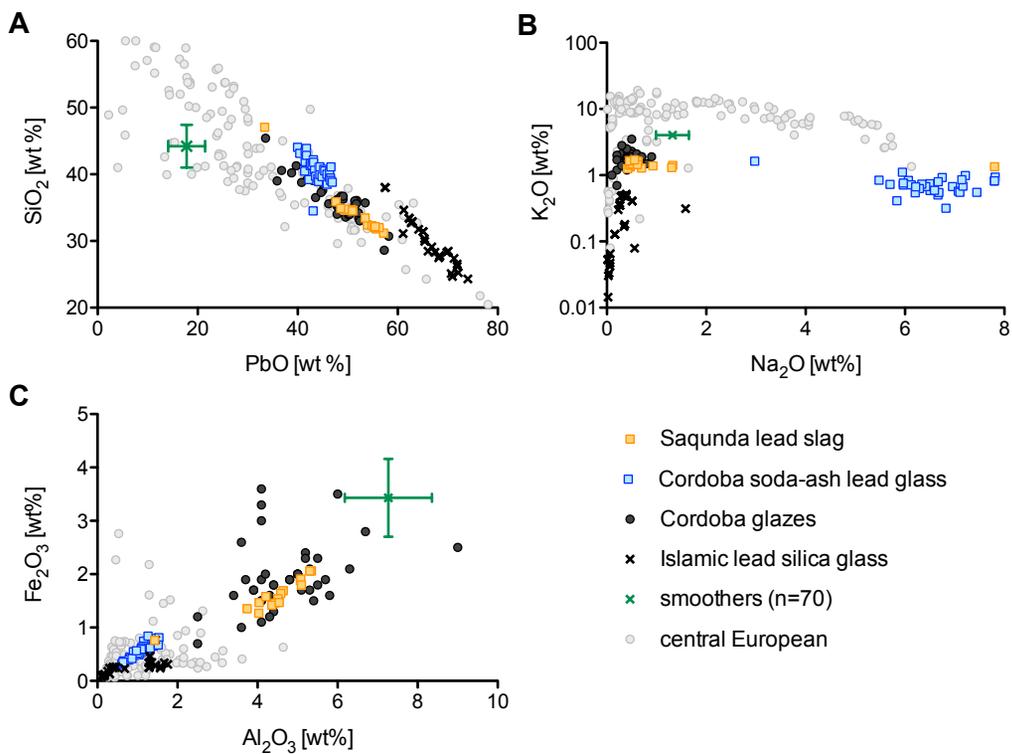


Fig. 59:

High lead glass from Šaqunda compared to published data on different types of high-lead glass. (a) Silica and lead oxide levels illustrate different mixing ratios, with silica lead glasses at the high PbO end of the spectrum and central European potash lead glasses at the high silica end; (b) potash and soda contents reflect the use of different raw materials for silica-lead glasses, potash-lead glasses and soda-ash lead glasses; (c) iron versus aluminium oxides highlight the distinctive nature of the high-lead glass from Šaqunda displaying a similar trend to the high-lead smoothers from Melle in France. Data sources: (Gratuze *et al.* 2003) for smoothers; (De Juan Ares *et al.* 2021) for soda-ash lead glass from Córdoba; (Bergmann *et al.* 2008; Brill 1999; Kuisma-Kursula and Räisänen 1999; Mecking 2013; Wedepohl *et al.* 1995; Wedepohl *et al.* 2010) for central European potash lead glasses; (Brill 2009) for Islamic silica lead glasses; (Schibille *et al.* 2020a) for Šaqunda.

The high-lead glass from Šaqunda with elevated alumina, iron, barium and antimony contents was clearly not a simple mixture of quartz and lead oxide that underlies more stereotypical Islamic high-lead silica glasses from the Near East. Instead, these compositional features are reminiscent of high-lead smoothers produced at around the same time in France and found throughout medieval Europe (Gratuze *et al.* 2003; Gratuze *et al.* 2017). Given these similarities, we arrived at the conclusion that the glass from Šaqunda ultimately represents lead slag from smelting processes. Lead isotope data revealed a local origin, linking the high-lead glass to the silver and lead mining areas north of Córdoba (Schibille *et al.* 2020a). The Šaqunda assemblage thus marks the beginnings of a local Iberian glass industry, which may have been triggered by bottlenecks in the glass supply from Egypt and the Levant. It may also have been inspired by the spread of silver mining in the region, which in turn was probably motivated by the introduction of a monometallic silver-based monetary system and the establishment of a mint in Córdoba in the early eighth century CE (Barceló 1975). The high-lead slag glass from Šaqunda dating to the eighth to early ninth centuries was relatively short-lived and was not widely distributed. Thus far I have identified only three glass samples of this type of slag glass outside Córdoba. This lead slag glass was, as we shall see, only the first step in a longer process towards an independent Iberian glass industry.

Historical sources attribute the invention of a new way of glassmaking in al-Andalus to the ninth century CE, specifically to the Andalusian polymath Abū l-Qāsim ‘Abbās b. Firnās (809-887 CE; Al-Makkari 1840, p. 148). The analytical and isotopic data show that glass, albeit an unusual type of glass, was indeed produced in al-Andalus as early as in the first quarter of the ninth century, possibly even earlier. This is shortly after the Abbasid uprising in the east and shortly after Umayyad al-Andalus had become an independent emirate. The compositional make-up of the glass assemblage of Šaqunda in its entirety suggests the demise of glass supplies from the eastern Mediterranean, the concurrent increase in recycling practices and eventually the implementation of a new glassmaking recipe based on the use of lead waste (slag) from silver and/or lead mining. This new glass manufacturing technique was subsequently refined by replacing lead slag with litharge and introducing some additional alkali to the batch to modify the properties of the vitreous material. In fact, a single colourless glass fragment analysed from Šaqunda is an early example of such a soda-ash lead composition with about 33% lead oxide, 47% silica and almost 8% soda that was to become typical of tenth-century glass assemblages from the area around Córdoba. This type of soda-ash lead glass will be discussed in greater detail in the context of the glasses from Madīnat al-Zahrā’.

Before moving on to the alkaline-lead glasses from al-Andalus, it is important to note that there is no evidence for the production of soda-rich plant ash glass in Córdoba. Only six samples from Šaqunda have a plant ash glass composition. Three of them were archaeologically dated to the occupational phase of the rabad (756 – 818 CE), making them the oldest plant ash glasses identified in al-Andalus to date. The other three were attributed to the tenth century instead. The plant ash glasses are highly variable in terms of both the plant ash component and the silica source. Hence, as a group the plant ash glasses are a complete hotchpotch, severely limiting the historical and archaeological interpretation of the data. Suffice it to say at this point that the three earlier samples resemble more or less contemporaneous Mesopotamian glasses. Specifically, one fragment (MIR 068) matches the Samarra 1 or 2 composition, while the other two may be related to glasses from al-Raqqa (Fig. 60). The three tenth-century plant ash samples have very different compositional signatures marked by high silica-related elements such as alumina, titanium and zirconium. These characteristics fit well with what we believe to be regionally produced plant ash glass (De Juan Ares and Schibille 2017b).

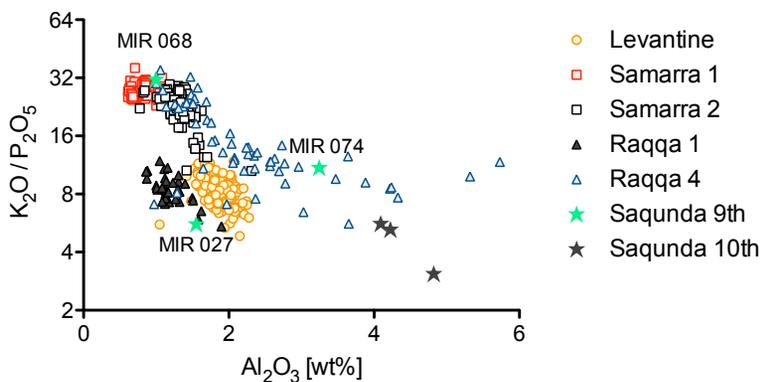


Fig. 60:

Soda-rich plant ash glasses from Šaqunda compared to reference groups. Potash to phosphorus ratios versus alumina concentrations indicate similarities between the eighth- and ninth-century samples from Šaqunda and Mesopotamian glasses from Samarra and al-Raqqa, while the tenth-century samples have a different base glass composition. Data sources: (Henderson *et al.* 2004) for Raqqa; (Schibille *et al.* 2018a) for Samarra; (Phelps 2017) for Levantine Tyre-type plant ash glass; (Schibille *et al.* 2020a) for Šaqunda.

The glass workshop in Pechina (Almería)

The first mention of the production and use of soda ash for the manufacture of glass is found in Catalonia and dates to the end of the twelfth century CE (Gudiol 1936), although the trade in soda ash is documented in written sources in connection with soap making as early as in the ninth century (Gómez 1957, p. 302). The earliest archaeologically confirmed primary production sites of soda-ash glass in Iberia date to the twelfth century CE at Puxmarina in Murcia, which is also the only one from where glass remains have been analysed (Carmona *et al.* 2008; Carmona *et al.* 2009; García Heras 2008; Jiménez Castillo *et al.* 1998). However, thanks to the compositional characteristics of the glass retrieved from Ciudad de Vascos (De Juan Ares and Schibille 2017b) and Baýyāna-Pechina (Almería) (De Juan Ares and Schibille in press), it has been demonstrated that the production of soda-ash glass in the Iberian Peninsula must have started much earlier than the activities in Murcia would suggest. Initially, the remains of a furnace, crucibles and vitreous slag that were recovered at Baýyāna-Pechina in the 1980s were interpreted as evidence of a primary glass workshop (Acién Almansa *et al.* 1990; Castillo Galdeano and Martínez Madrid 2000; Duckworth and Govantes-Edwards 2015). It now seems clear that Pechina was more probably a secondary workshop. Large quantities of vitreous slag were retrieved from the first phase of occupation which extended from the middle of the ninth century to the first third of the tenth. The vitreous slag proved to be associated with metallurgical activities rather than glass or glaze production.

The site was subsequently converted into residential quarters during a second phase which lasted from the beginning of the Caliphate in 929 CE to the second half of the tenth or beginning of the eleventh century CE. The archaeologists assume that the furnace of the supposed glass workshop continued to operate throughout this residential phase (Castillo Galdeano and Martínez Madrid 2000). Thirty-eight glass samples that were recovered during excavations carried out in the 1980s (Acién Almansa *et al.* 1990) were selected for analysis, including vessel fragments, two chunks and crucible fragments. The glass finds represent four different types of base glasses: natron, plant ash, soda-ash lead and lead silica glasses. In contrast to the glasses from Šaqunda, there are only two lead silica glasses ($\text{PbO} > 60\%$) among the assemblage, while the other samples are soda-ash lead glasses with much lower lead (PbO about 10% - 34%) and significant soda, magnesia and potash contents. The scale of recycling among the natron and plant ash glasses is also different. The natron glasses from Pechina ($n = 6$) comprise two HIMT, one Levantine I, Foy 3.2 and one Magby glass and only one sample that has undergone extensive recycling. Many of the Pechina plant ash glasses have antimony and lead concentrations in excess of natural impurity levels, suggesting

the incorporation of some recycled material, which is in contrast to the plant ash glasses from Šaqunda that do not show signs of recycling.

The plant ash glasses from Pechina are compositionally very heterogeneous. They have very high soda (16% - 19%), relatively high magnesia (2.6% - 4.8%), moderate potash (2% - 3.5%) and lime (5% - 8.5%) contents and highly variable phosphorus (0.15% - 1%; Fig. 61a). They may be separated into two groups based on their silica-related elements but with overall comparable trace element profiles (Fig. 61b-c). One sub-set of samples (group 1) has lower concentrations of all minor and trace elements and somewhat higher silica and soda concentrations, implying that the raw materials used for group 1 were overall cleaner, with lower contaminants than the ones underlying the glasses of group 2. A correlation matrix for all the plant ash glasses shows strong correlations ($R > 0.8$) between alumina, titanium, zirconium, niobium, thorium, uranium and many of the REEs. One sample (PE 005) shows different patterns and is probably a Mesopotamian import, judging from its high magnesium and low phosphorus oxide contents together with a high chromium to lanthanum ratio ($Cr/La > 5$). The other plant ash glasses from Pechina have distinct compositional characteristics, reflected among other things in the relative low zirconium to thorium concentrations for which no match was found amongst glasses from the Levantine coast, Egypt or Mesopotamia (Fig. 61b). They do, however, have certain similarities with the tenth- and eleventh-century glass finds from Ciudad de Vascos: they are compositionally close to Vascos groups 3, 4 and 5, which have been interpreted as Iberian glass made from local raw materials (De Juan Ares and Schibille 2017b). Differences in the abundance of accessory minerals may be explained by the heterogeneity of the silica source in time and space, which leads to variability in the absolute concentrations of silica-dependent elements, while the ratios between the elements remain fairly constant. The plant ash glasses appear only during the second phase at Pechina (after 929 CE), very much like Šaqunda, where the Iberian plant ash glasses likewise date to the tenth century CE. This means that the technological transition towards a specifically Iberian primary manufacture of plant ash glasses had taken place by the middle of the tenth century CE, but not necessarily much earlier. The centre of this production of Iberian soda-ash glass is not known. In Pechina itself there is no evidence of the primary production of plant ash glass and the variable compositions and high incidence of recycling appear to argue against local primary production activities (De Juan Ares and Schibille in press).

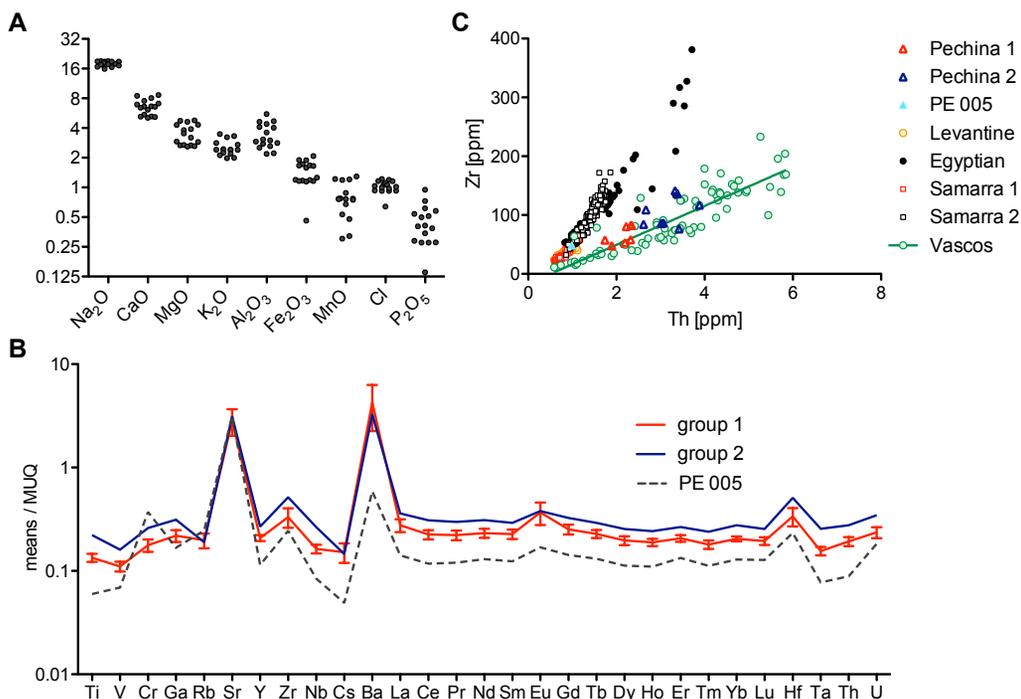


Fig. 61:

Major, minor and trace element patterns of the soda-rich plant ash glasses from Pechina (Almería). (a) Scatter plot of major and minor elements of all the Pechina plant ash glasses; (b) mean trace elements of the two plant ash groups normalised to the abundances in the upper continental crust (Kamber *et al.* 2005); (c) zirconium and thorium levels clearly distinguish the Pechina glasses from Levantine, Egyptian and Samarra plant ash glasses, while highlighting the similarities with groups 3, 4 and 5 from Vascos. Data sources: (Schibille *et al.* 2019) for Egyptian glass; (Phelps, 2017) for Tyre-type Levantine glass; (Schibille *et al.* 2018a) for Samarra; (De Juan Ares and Schibille in press) for Pechina; (De Juan Ares and Schibille 2017b) for Vascos.

There may, however, have been some secondary working of plant ash glasses and/or production of high-lead glass at Pechina. Two crucible fragments recovered from the second occupation phase (> 929 CE) are lined with a thick layer of glass of up to about half a centimetre. This layer has significant lead oxide contents (8%-16%) as well as soda (about 14%), magnesia (approximately 4%) and potash (2%-3%). The crucibles were evidently used to melt a mixture of a high-lead component and a plant ash glass or its raw ingredients, producing a composition similar to that of the soda-ash lead glass from Pechina. Eleven glass samples were made from a glass with a high lead content in addition to considerable concentrations of alkali and alkaline earth metals. They differ from both the Šačunda high-lead glass and

other plant ash lead glasses from the Iberian Peninsula. The main difference is the content of lead relative to the glassy elements. The Pechina samples contain significantly lower levels of lead than the more typical soda-ash lead glasses from Spain so far analysed (Fig. 62a). The glasses nonetheless seem to be closely related in terms of the elements associated with the silica source such as aluminium and iron oxides (Fig. 62b). Some of these soda-ash lead glasses date to the first phase of Pechina (mid ninth century to 929 CE). As mentioned, there appears to be a close relationship between the manufacture of lead glass and the development of glazing technologies in al-Andalus, and this is also visible in the analytical data on the materials from Pechina. Investigations into the production of glazed ceramics in Pechina which is attested to for the ninth century revealed that in a first step the potters produced leaded glass, which was then crushed and applied to biscuit-fired ceramics to produce a continuous glaze (Salinas and Pradell 2018; Salinas *et al.* 2019a; Salinas *et al.* 2019b). Thus, the production of leaded glass necessarily preceded the production of lead glazes in the Iberian Peninsula (Salinas *et al.* 2021).

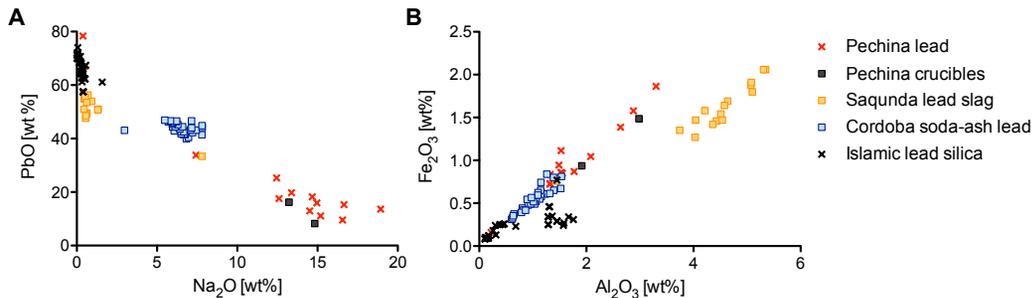


Fig. 62:

High-lead glasses from Pechina (Almería) compared to different types of Islamic high-lead glasses. (a) Lead and sodium oxides indicate the relative proportion of the lead component to the glass raw materials; (b) iron and aluminium oxides show the same strong positive correlation in all the soda-ash lead glasses from the Iberian Peninsula, suggesting a common source of the vitreous material. Data sources: (De Juan Ares *et al.* 2021) for Córdoba; (Brill 2009) for Islamic silica lead glasses; (De Juan Ares and Schibille in press) for Pechina; (Schibille *et al.* 2020a) for Šaqunda.

The results of lead isotope analysis of two high-lead glasses from Pechina in comparison with the available geological information from different mining districts in the Iberian Peninsula demonstrate that the lead used for the Pechina glass is distinct from that used for the Šaqunda high-lead glasses (Fig. 63). In fact, no unambiguous match was found among the published isotopic data. The

different isotopic ratios show that the samples from Pechina are close to the isotopic field defined by samples from the Roman mines of Cartagena (Trincherini *et al.* 2009), and closer still to some ore deposits from the Province of Almería and specifically the eastern Betic Cordillera (Murillo-Barroso *et al.* 2019). A handful of samples from Cerro Minado (Sierra de Almagro) and Sierra Almagrera are more or less within the isotopic range (i.e. within the Euclidean distance) of the Pechina samples for all three lead isotope ratios (Fig. 63). The two districts, located about halfway between Almería and Cartagena, are adjacent to each other. Cerro Minado was one of the most important mining districts in the area in prehistoric times due to opencast mining, and it is known particularly for its iron ores and various copper sources, while the Sierra Almagrera deposits are rich in galena, silver and copper sulphides (Murillo-Barroso *et al.* 2019). Thus, even though there is no clear isotopic match for the Pechina glass, an origin in the southeast of the Iberian Peninsula seems to be the most likely provenance of the lead component. The fact that the lead from Pechina differs from the other Andalusian high-lead and soda-ash lead glasses suggests a local production of these types of glasses, using more or less locally accessible plumbiferous materials.

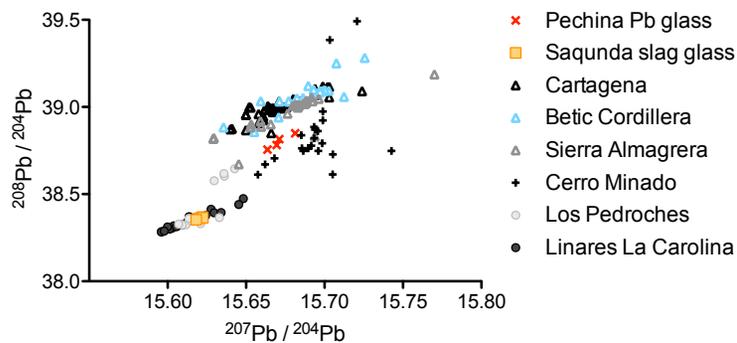


Fig. 63:

Lead isotope ratios of two Pechina glasses (repeated measurements) compared to Iberian high-lead glasses and relevant ore deposits in the south of the Iberian Peninsula. Data sources: (Klein *et al.* 2009; Marcoux 1997; Murillo-Barroso *et al.* 2019; Santos Zalduegui *et al.* 2004; Trincherini *et al.* 2009), as well as some data from <http://oxalid.arch.ox.ac.uk/>; (Schibille *et al.* 2020a) for Saqunda; (De Juan Ares and Schibille in press) for Pechina.

The archaeological remains and analytical results corroborate the existence of a glass workshop at Pechina. Some crucibles have been recovered that were shown to have been used for the production of lead glazes (Salinas *et al.* 2019b), while the crucibles with a mixture of lead and alkali glass presented above suggest that

they were used for the production of mixed glasses instead. This is not to say that the primary production of raw glass from a mixture of silica and plant ash necessarily occurred at Pechina as well. The variability of the plant ash glasses, and in particular their content of recycling markers, makes it more likely that only secondary working and/or recycling of glass was practised here. The procedures involved in producing soda-ash lead glass differ from those for more common plant ash glasses, not least due to the considerably lower softening points of lead and soda-ash lead glass than of soda silica glasses (Wedepohl *et al.* 1995). Hence, the production of the two types of glasses require very different levels of expertise and different sets of glass-working skills.

The glass from Madīnat al-Zahrā' – the Brilliant City

The caliphal city of Madīnat al-Zahrā', located about 7.5 km west of Córdoba as the Nazgûl flies (Fig. 57), was founded by 'Abd al-Rahman al Nasir ('Abd al-Rahman III) in 936 CE, some eight years after he had claimed the title of caliph. The new city occupies three terraces on the slope of the Sierra Morena mountain range, with the Alcazar distributed over the upper two terraces and the lowest level being used for markets and the housing of soldiers and the general populace (Anderson and Pruitt 2017; Salinas *et al.* 2019c). Madīnat al-Zahrā's beauty and splendour were legendary, and literary sources typically have recourse to hyperbole when describing the city (Vallejo 2013). The city prospered as the capital of the Umayyad caliphate during the second half of the tenth century until its destruction between 1009 and 1013 CE, associated with its sacking by the Berbers and the fall of the caliphate (Salinas *et al.* 2019c; Vallejo 2013). Its ruins fell into oblivion for almost 1,000 years and were identified as the caliphal city of 'Abd al-Rahman III only in the nineteenth century. Since 1911 the palatine buildings and administrative centres on the upper terraces in particular have been excavated and partially reconstructed (Vallejo 2013). Among the archaeological finds of Madīnat al-Zahrā' is a relatively substantial corpus of vitreous materials, recovered mostly from inside the Alcazar and the drainage system. This suggests that glass circulated particularly among the tenth-century elite. The aim of ongoing doctoral research by Ana Zamorano is to relate the glass finds stored in the Archaeological Museum of Córdoba to specific contexts and their function, and to establish a formal repertoire of typologies and techniques. This will undoubtedly serve as an essential reference tool for future research on early Islamic glass from al-Andalus more generally.

In a joint project we selected 265 samples of different vessel types and window glass fragments, as well as 53 mosaic tesserae, for LA-ICP-MS analysis (Schibille and Zamorano in preparation). The majority of the glasses have natural aqua shades (greenish, bluish, yellow), but include some copper blues and manganese purple fragments as well. Many of the samples were recovered from the drainage system that was used as a dumping ground for domestic waste and broken glass and ceramics (see also Salinas *et al.* 2019c). The mosaic tesserae come mainly from surface finds and include red, green, yellow, dark purple, white/aqua and a very few dark cobalt blue pieces, as well as a single gold leaf tessera. The analytical data on the tesserae will be discussed separately in direct comparison with the mosaic tesserae from the Great Mosque of Córdoba, as they turned out to be of an unusual base glass composition.

The glass assemblage from Madīnat al-Zahrā' splits into an alkali lead group and a plant ash glass group. Unexpectedly, we identified a handful of modern glasses with no chlorine and relatively high boron, arsenic and selenium levels, which are difficult to explain at a site that was supposedly undisturbed until the early twentieth century. One of these glasses resembles the remains of an alembic with a distinctly pink colour and a very thin fabric, and one wonders whether this may be somehow related to the archaeological activities at the beginning of the twentieth century. Also among the assemblage was a lump of Egypt 2 glass that is likely to date from before the tenth century and is equally difficult to explain. By far the largest group is made up of soda-ash lead glass which forms a relatively tight cluster with on average 41.5% PbO and 43% SiO₂, and a combined alkali and alkaline earth (Na₂O, MgO, K₂O) content of approximately 9%. The composition of the plant ash glass, on the other hand, varies greatly (Fig. 64a). The plant ash glasses can be attributed mostly to Levantine or Mesopotamian base glasses as well as a very few Iberian specimens, a single fragment that may be an Egyptian plant ash glass and possibly two Sicilian imports (Fig. 64b). All but the Levantine and Egyptian plant ash glasses have elevated lithium contents; the Mesopotamian types also have high chromium to lanthanum ratios. The Iberian samples are marked by high thorium relative to zirconium, while the two Sicilian pieces have low Th/Zr ratios (Fig. 64c-d). The Th/Zr ratios can therefore be used to discriminate between glasses of Iberian, Sicilian and eastern Mediterranean origin, as shall be discussed later.

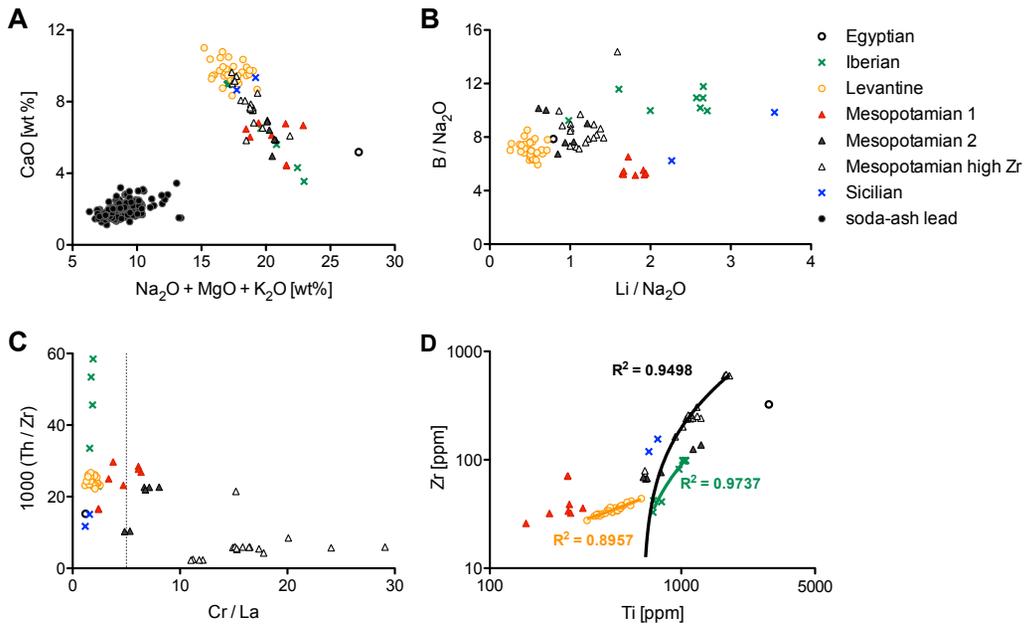


Fig. 64:

Separation of the glass assemblage of Madinat al-Zahrā' into distinct compositional groups. (a) Lime versus the combined concentrations of soda, magnesia and potash confirm that the high-lead samples are alkali lead glasses; (b) boron and lithium relative to soda concentrations of the plant ash glass from Madinat highlight the differences in the plant ash component of the Levantine, Mesopotamian and Iberian type glasses (the high-lead glasses are not included); (c) high Th/Zr ratios identify the Iberian plant ash glass, while high Cr/La ratios distinguish the majority of the Mesopotamian specimens; (d) different zirconium and titanium correlations substantiate the differentiation of the plant ash glass into distinct regional production groups. Data source: (Schibille and Zamorano in preparation).

The Levantine glass forms a well-defined group that resembles the plant ash glass from Tyre. The Mesopotamian finds represent instead different Mesopotamian populations. One set of samples (Mesopotamian 1) has been produced from a quartz-rich silica source poor in accessory elements (Fig. 64d), coupled with a plant ash component rich in magnesium and poor in phosphorus. These compositional features are consistent with the colourless Samarra 1 type. Another sub-group has characteristics similar to those of the low Zr glass from Siraf (Iran) and some of the earlier Sasanian glasses from Veh Ardašīr (Fig. 65a). At first glance, some samples with high zirconium levels resemble the main high zirconium group from Siraf that is believed to have been produced in or around Siraf (Swan *et al.* 2017), but the majority of the Madinat al-Zahrā' high Zr group tends to have higher chromium relative to titanium concentrations, except for a subset of four samples

(Fig. 65a). Interestingly, the Mesopotamian finds in Madīnat al-Zahrā' divide into a series of discrete clusters that represent differing glass production events, providing significant insights into complex glass supply dynamics. The logical conclusion is that individual groups of finished objects arrived in al-Andalus as a result of an exchange or gift-giving mechanism rather than trade in the traditional sense. The Mesopotamian samples include facet-cut and engraved vessels, and all of the fragments that contain notable levels of cobalt (Co > 30 ppm). The cobalt colourant appears to be associated with elevated Ni, Zn, As, In, Fe, Sn and Sb, while zinc is also correlated with copper. The zinc levels are consistent with Islamic cobalt sources, however, the relatively low cobalt to nickel ratios are reminiscent of the late antique cobalt colourant found, for example, in Apollonia-type Levantine I glasses (Fig. 65b-c). This trace element pattern associated with the cobalt colourant shows similarities in composition to the cobalt used to colour the high-chromium glass group from Nishapur.

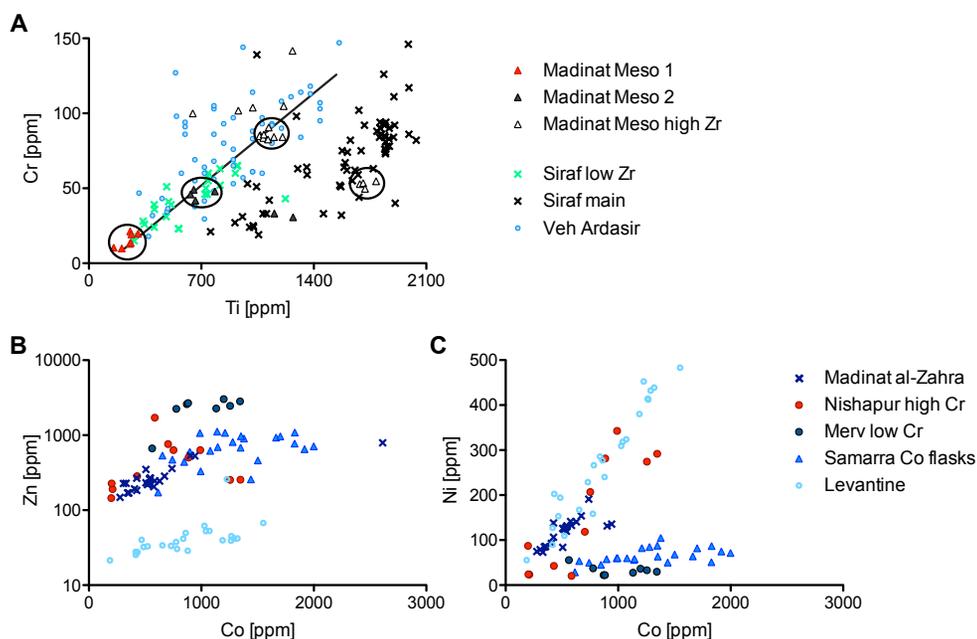


Fig. 65:

Compositional characteristics of the Mesopotamian plant ash glasses from Madīnat al-Zahrā'. (a) Chromium and titanium concentrations compared to glass from Siraf and Veh Ardasir; (b) the cobalt coloured samples from Madīnat al-Zahrā' have elevated zinc levels reminiscent of an Islamic cobalt source; (d) cobalt and nickel contents underpin the similarities to the high-chromium glass from Nishapur that is believed to be of Mesopotamian provenance. Data sources: (Swan *et al.* 2017) for Siraf; (Mirti *et al.* 2008; Mirti *et al.* 2009) for Veh Ardasir; (Schibille and Zamorano in preparation) data for Madinat al-Zahrā'; (Schibille *et al.* 2016) for Byzantine glass weights representing late antique Levantine natron-type glass; (Schibille *et al.* 2018a) for Samarra; unpublished data on Nishapur (courtesy of Mark Wypyski).

The relative proportions of lead, alkali and alkaline earth elements demonstrate that the high-lead glasses from Madīnat al-Zahrā' are of the plant ash lead glass type. The main ingredients are lead, silica and a soda-rich plant ash with high soda, moderate magnesia and potash and relatively low lime concentrations (Fig. 66a). As such they clearly differ from the high lead glasses from Šaqunda as well as early Islamic silica lead glasses from the Near East. The silica component of the soda ash lead glass from Madīnat al-Zahrā' is also different from that of the Šaqunda glasses, but bears some resemblance to lead silica glass from the eastern Islamic world. The lead silica glasses from the eastern Mediterranean and the soda ash lead glasses from Madīnat al-Zahrā' have low alumina to silica ratios, indicative of the use of a quartz-rich raw material poor in accessory minerals (Fig. 66b). The use of a clean silica source recalls Arab textual sources, all of which describe the use of (white) pebbles, possibly quartz pebbles, for the production of leaded glass (*mīnā*) (Schibille forthcoming).

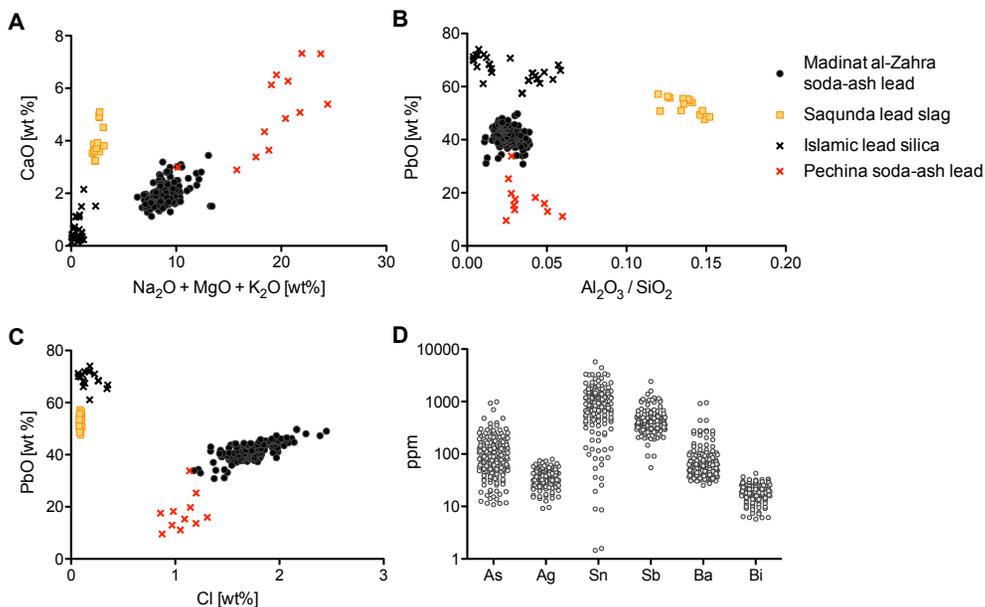


Fig. 66:

Compositional characteristics of the soda-ash lead glasses from Madīnat al-Zahrā' in comparison with other high-lead glasses. (a) Lime compared to the combined soda, magnesia and potash contents confirms that the glasses are alkali lead glasses; (b) lead and alumina to silica ratios highlight similarities between the plant ash lead glasses from Madīnat and Islamic lead silica glass in the strict sense in terms of the silica source, while the Šaqunda lead glass is clearly different; (c) lead shows a positive correlation with chlorine in the soda-ash lead glasses from Madīnat al-Zahrā'; (d) trace elements related to the lead source of the Madīnat al-Zahrā' high-lead glass are highly varied and include As, Ag, Sn, Sb, Ba and Bi. Data sources: (Brill and Stapleton 2012) for Islamic lead silica glass; (Schibille and Zamorano in preparation) for Madīnat al-Zahrā'; (Schibille *et al.* 2020a) for Šaqunda; (De Juan Ares and Schibille in press) for Pechina.

Perhaps the most surprising feature of the soda-ash lead glasses from Madīnat al-Zahrā' is their high chlorine concentration, up to about 2.5%, which is about twice the usual chlorine content of conventional natron-type and soda-rich plant ash glasses (Fig. 66c). Chlorine appears to be associated with lead oxide, which suggests that the lead raw material underlying these glasses was accompanied in one way or another by chlorine. The simplest explanation is that chlorine was added separately to the batch material. Alternatively, the chlorine could itself be a by-product of yet another metallurgical process, namely the cementation process to purify gold. Sodium chloride (common salt) was used in antiquity to convert the silver contained in gold to silver chloride (Ramage *et al.* 2000, p. 11). If the silver is subsequently recovered through a cupellation procedure, chlorine is incorporated in the glassy waste-product that may then find its way into a high-lead glass. The instructions in the early twelfth-century *De diversis artibus* by Theophilus specify the use of a mixture of salt, powdered brick and urine (Brepohl 2013, book 3, chapter 33). This recipe was approximated in our laboratory some years ago and the experimental results included a number of amber-coloured glass droplets containing up to 3% chlorine, with less than 2% sodium and over 70% lead oxide (Fig. 67). The two-step experiments consisted of a cementation process in which salt and powdered brick were added to purify the gold, followed by a cupellation process to recover the silver from the silver chloride. In this second step, everything from the cementation experiment that was not gold was recovered, crushed and mixed with lead and heated, producing a kind of slag, argentiferous lead, and the aforementioned high-lead, high-chlorine glass droplets (M. Blet-Lemarquand, personal communication). The use of a similar glassy waste product as the starting material is a plausible explanation for the increased chlorine levels in the Madīnat al-Zahrā' soda-ash lead glasses.

Medieval textual sources offer an alternative interpretation. In his second book, which is devoted to glass-working and colouring, Theophilus describes the production of a high-lead glass for rings by mixing ash, salt (sodium chloride), powdered copper and lead (cineres, sal, pulverem cupri et plumbum; Brepohl 2013, book 2, chapter 31). Heraclius' *De Coloribus et Artibus Romanorium* contains a chapter dedicated to the question on how to make lead glass (Merrifield 1849, book 3, chapter VIII). A compilation of different texts, the third part of the treatise may be more or less contemporary to or a little later than Theophilus' work. Here, Heraclius explains how to prepare powdered lead oxide and to mix it with sand in a ratio of 2:1 (Merrifield 1849, book 3, chapter VIII, p. 216). The author then instructs people to 'do as before directed for making glass' (book 3, chapter VII). Whether this means the melting of the lead silica mixture with ash, the preparation of which he details in chapter VII, is not entirely clear (Brepohl 2013, p. 191).

Arabic alchemical and technological literature on the colouring of glass and the production of *mīnā* prescribe the use of *natrūn*, meaning either potassium nitrate or sodium carbonate or bicarbonate (Al-Hassan 2009). *Mīnā* has been variably translated as enamel, glaze or lead glass, but may also simply refer to glass (Holakooei 2016; Krueger 2014). While glass according to the so-called Karšūnī manuscripts is composed of sand and alkali, the basis of *mīnā* are pebbles and burnt lead (Berthelot and Duval 1893, p. 155; Krueger 2014). Several recipes in the *Kitāb ad-Durra al-Maknūna* (The Book of the Hidden Pearl) explicitly advises adding *natrūn* or a *natrūn* solution to a mixture of pebbles and lead oxide (recipe 35) or a pulverised glass mixture (recipe 18), or washing the raw materials in salt water (recipe 45; Al-Hassan 2009). If common salts (sodium chloride) were used for this purpose, then this could explain the high chlorine content in Andalusian soda ash lead glasses. None of the other glasses with a high lead content, neither Islamic nor Central European lead glass, tend to contain as much chlorine. High chlorine contents can thus be considered a reliable marker for a specifically Iberian manufacturing process of soda ash lead glass, which was produced between the ninth and the eleventh centuries CE.



Fig. 67:

Lead glass droplets with high chlorine contents ($1.6\% < \text{Cl} < 3.3\%$) that resulted from a cementation experiment (courtesy of Maryse Blet-Lemarquand).

Other elements that have been introduced as part of the lead component are arsenic, silver, tin, antimony and bismuth, with arsenic and tin being more variable than the other elements (Fig. 66d). Lead is one of the most important by-products of silver production, and some experimental results have shown that antimony, tin, bismuth and silver are oxidised to litharge at different stages of the cupellation process

(L'Héritier *et al.* 2015). According to a series of experiments, tin and antimony tend to form a solid phase at the beginning of the cupellation process, which may have been used in ancient times as yellow pigment (L'Héritier *et al.* 2015; Mass *et al.* 2002). According to the authors, a small proportion of both elements is retained in the initial part of the litharge. Bismuth undergoes some oxidation in the early stages of the cupellation process and increases dramatically in the last fraction of the litharge alongside silver, which is oxidised only at the very end (L'Héritier *et al.* 2015). The absolute amounts of bismuth are conditional on the initial quantities of the element in the starting material. When these experimental results are applied to the analytical data on soda-ash lead glasses from Madīnat al-Zahrā', it appears that the lead component of these glasses probably corresponds to litharge formed during the earlier stages of the cupellation process, since the Ag and Bi contents are relatively low and the As, Sn and Sb levels are elevated (Fig. 66d). Since no experiments have been carried out on the impact of further processing of litharge on the trace element patterns, this is but a preliminary attempt to explain the compositional characteristics of the high-lead glass from Madīnat al-Zahrā'.

Lead isotope analysis of ten samples from Madīnat al-Zahrā' compared to the isotopic ratios of different mining regions in southern Spain and of the high-lead glasses from Šaqunda and Pechina reveals different lead sources (Fig. 68). Eight of the samples have all three isotopic ratios within the Euclidean distance of the high-lead glasses from Šaqunda and they can therefore be attributed to either of the two mining districts of Linares la Carolina and Los Pedroches, both less than 100 km from Córdoba (Schibille *et al.* 2020a). One of the other samples has lead isotope characteristics similar to those of the Pechina high-lead glasses and the isotopic fields of the Roman mines of Cartagena (Trincherini *et al.* 2009) and the eastern Betic Cordillera, specifically the mines from Cerro Minado (Sierra de Almagro) and Sierra Almagrera (Murillo-Barroso *et al.* 2019). The match, however, is only approximate. One sample falls outside the range of the lead sources from the south and the southeast of the Iberian Peninsula, and may be the result of the mixing of lead from different sources and/or the use of lead from an unidentified mining area. It is interesting that the lead used for the production of the soda-ash lead glass at Madīnat al-Zahrā' was obtained from different sources, which would necessarily result in intermediate isotopic signatures if lead sources and/or glass melts were mixed. Different Iberian lead sources have been exploited from the Phoenician through to the Roman and Islamic periods and traded widely in the form of either metal or galena. Lead isotope analyses of Islamic ceramic glazes have shown that lead from Spain and/or Sardinia was supplied to Islamic potters for the production of lead glazes even as far away as Fustat in Egypt (Marzo *et al.* 2009; Wolf *et al.* 2003).

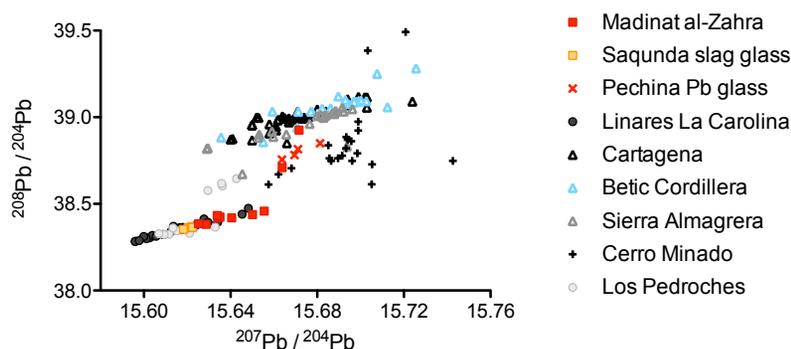


Fig. 68:

Lead isotope ratios of 10 soda-ash lead glasses from Madīnat al-Zahrā' compared to relevant ore deposits in the south of the Iberian Peninsula and the data from Šaqunda and Pechina. Data sources: (Klein *et al.* 2009; Marcoux 1997; Murillo-Barroso *et al.* 2019; Santos Zalduegui *et al.* 2004; Trincerini *et al.* 2009), as well as data from <http://oxalid.arch.ox.ac.uk/>; (Schibille and Zamorano in preparation) for Madīnat al-Zahrā'; (Schibille *et al.* 2020a) for Šaqunda; (De Juan Ares and Schibille in press) for Pechina.

The majority of the lead used at Madīnat al-Zahrā' appears to derive from a single local pool, and this applies to both the vitreous material as well as lead metal objects (e.g. lead pipes, sewer gate, clamps from column capital; Gener *et al.* 2014). In other words, the supply of lead was in large part obtained from a common source, providing basic structural elements and architectural features for the initial construction of the city, including material for the production of architectural glasses. At least 70% of the total glass supply at Madīnat al-Zahrā', including window panes and lighting devices, consists of soda-ash lead glass. These objects are either colourless or have a weak aqua colour in contrast to the glass from Šaqunda, which is typically yellowish green or amber in colour due to the high content of mineral impurities. The high-lead glass from Šaqunda may have been a direct precursor to the soda-ash lead glass from Madīnat al-Zahrā', insofar as lead slag was simply melted down and shaped. The finds from Šaqunda therefore mark the beginning of experimentation and the gradual emancipation of a local glassmaking industry in Islamic al-Andalus. The slag was replaced with litharge and at the same time an ash component was added. It is these soda-ash lead glasses that constitute more than 70% of the vitreous material in the palatial city of Madīnat al-Zahrā', as well as about 50% of tenth- to eleventh-century glass assemblages from domestic contexts in Córdoba (De Juan Ares *et al.* 2021; Duckworth *et al.* 2015).

Domestic assemblages in Córdoba and the advent of Iberian plant ash glass

About half of the tenth-century glass recovered from residential areas of a western suburb of the medieval city of Córdoba known as Picinas Municipales de Poniente (PMP) is also a soda-ash lead glass (De Juan Ares *et al.* 2021). This confirms earlier observations that this type of glass is typical of the caliphal city (Duckworth *et al.* 2015). The dwellings where the glass objects were found were built in the middle of the tenth century and destroyed sometime in the first third of the eleventh century; thus these assemblages are roughly contemporary with Madīnat al-Zahrā'. Indeed, the samples show exactly the same compositional features: high concentrations of soda and magnesia and moderate levels of potash, as well as relatively low concentrations of lime and remarkably high chlorine contents (De Juan Ares *et al.* 2021). Trace elements associated with the source of lead (Ag, Sn, Sb, Bi) again indicate the use of litharge in the production of these soda-ash lead glasses, rather than slag as was the case at Šaqunda. Examples of soda-ash lead glass have been found at various sites in the Iberian Peninsula, including the Christian kingdoms in the north of the peninsula (De Juan Ares *et al.* 2018), Ciudad de Vascos in the centre (De Juan Ares and Schibille 2017b), Portugal in the west (unpublished) and Pechina in the east (De Juan Ares and Schibille in press). But it is in Córdoba and its surroundings that this type of glass is most common. The density of finds in and around Córdoba and the homogeneous lead isotope signatures of most of these glasses, consistent with the mining districts north of the caliphal capital, strengthen the case for a local or at least regional primary glassmaking centre, specialising in the manufacture of high lead glasses. There are some exceptions to the rule; for example, two samples from Pechina and one or two samples from Madīnat al-Zahrā' have isotopic fingerprints that point to the exploitation of lead sources in the eastern Betic Cordillera. It can therefore be argued that the main producer of soda-ash lead glass was located in the Córdoba region, but that there were also minor producers in other parts of the Iberian Peninsula that exploited different ore deposits. The peak of the production of this quintessentially Andalusian glass was in the tenth century, although a slightly earlier appearance cannot be excluded and eleventh- to twelfth-century examples have also been discovered (De Juan Ares and Schibille 2017b).

Unlike soda-ash lead glass, plant ash glass does not seem to have been produced in Córdoba at that time. In Córdoba (De Juan Ares *et al.* 2021) and Madīnat al-Zahrā' (Schibille and Zamorano in preparation) only isolated examples of soda-ash glass dating to the tenth century can be linked to an Iberian production, while relatively large quantities of Levantine and Mesopotamian plant ash glasses have been identified. Of the 32 plant ash glass fragments from the western suburb of Córdoba that have been analysed, more than half are Levantine

imports. The remaining plant ash glasses are more or less equally divided between Mesopotamian, Iberian and Sicilian specimens (Fig. 69). There was clearly some production of plant ash glass in al-Andalus in the tenth century, as the finds from Pechina, Madīnat al-Zahrā', Córdoba and Šaqunda demonstrate, but the centre of production was probably not in the vicinity of Córdoba itself.

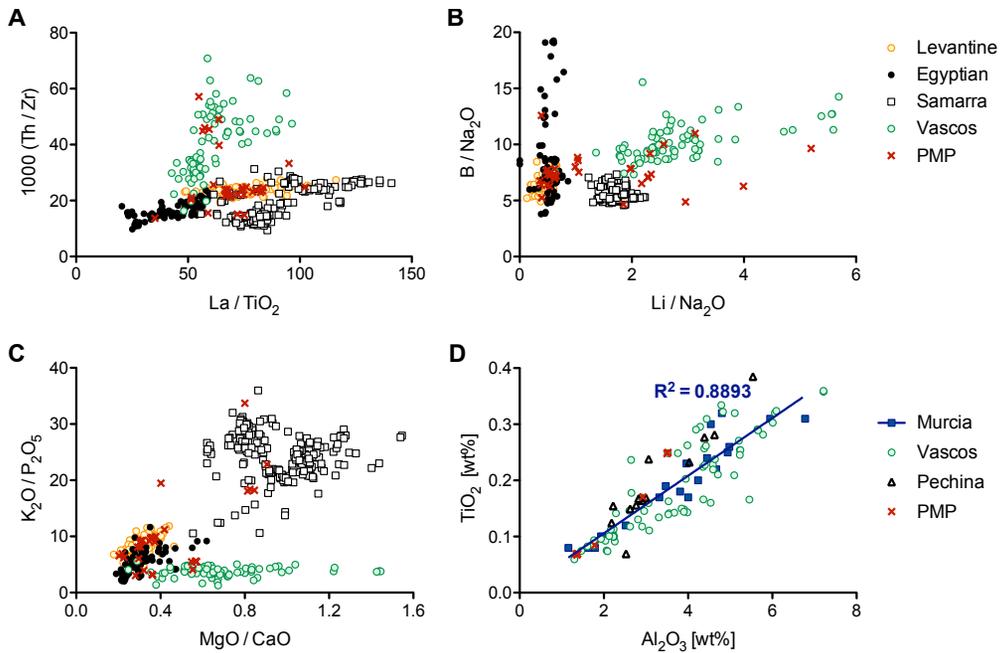


Fig. 69: Compositional discriminants of Iberian plant ash glass. (a) Th/Zr and La/TiO₂ ratios enable the plant ash glass from Córdoba (PMP) to be affiliated to the different glass reference groups, representing Levantine, Egyptian, Mesopotamian and Iberian plant ash glasses; (b) Iberian plant ash glass tends to have elevated lithium relative to soda concentrations; (c) the regionally different plant ash groups differ in terms of the K₂O/P₂O₅ and MgO/CaO ratios, reflecting differences in the plant ash constituent; (d) Iberian plant ash glasses are highly variable in terms of titanium and aluminium oxide concentrations. Data sources: (De Juan Ares *et al.* 2021) for Córdoba PMP; (Schibille *et al.* 2019) for Egyptian glass; (Schibille *et al.* 2018a) for Samarra; (De Juan Ares and Schibille 2017b) for the Ciudad de Vascos; (Phelps 2017) for Tyre-type Levantine glass; (De Juan Ares and Schibille in press) for Pechina; (Carmona *et al.* 2009) for Murcia.

Iberian plant ash glasses are characterised by highly fluctuating compositions, and the Iberian origin of the plant ash glasses is accordingly deduced from a multi-factorial process based on exclusion. A combination of trace elements, particularly elevated lithium concentrations and generally high thorium to zirconium ratios, can exclude eastern Mediterranean (Levantine, Egyptian) and Mesopotamian sources

(Fig. 69a-b). In addition, compositional markers such as chromium to lanthanum ratios that are typical of eastern Islamic glass types have to be checked as well. Using these criteria, we were able to establish an Iberian provenance for some of the tenth-century glasses from various sites in Córdoba and Baýyāna-Pechina as well as Ciudad de Vascos (tenth to twelfth centuries; De Juan Ares and Schibille 2017b) and Albalat (Cáceres; twelfth century). In addition to these trace element discriminants, Iberian plant ash glass is high in soda and has high but variable magnesium concentrations, as well as moderate concentrations of potassium, phosphorus and calcium (Fig. 69c). The elements related to the silica source, such as aluminium and titanium, are highly diverse, suggesting different small-scale melting events. Alumina contents of the Vascos assemblage, for example, range from around 1% to over 7% and titanium oxide from 0.06% to 0.36% (De Juan Ares and Schibille 2017b), covering almost one order of magnitude. Large compositional variations are evident even within a single glassmaking workshop, as illustrated by the glass fragments and production remains collected from the twelfth-century workshop at Puxmarina in Murcia (Fig. 69d; Carmona *et al.* 2009). The glass from Murcia contains different absolute amounts of aluminium and titanium, yet the ratio remains fairly constant and shows a high correlation coefficient ($R^2 = 0.8893$). The differences in absolute quantities therefore do not prove that these glasses were manufactured from a different silica source, let alone in different locations. On the other hand, the fact that the majority of Iberian glasses appear to be on the same regression line could indicate a common origin. It may then be reasonably hypothesised that the primary production of soda-ash glass was located along the east coast of the Iberian Peninsula between Murcia/Alicante and Almería long before the archaeologically attested activities at the twelfth- and thirteenth-century workshops at Puxmarina and Belluga in Murcia (Carmona *et al.* 2009; Duckworth *et al.* 2015).

Neodymium and strontium isotopes provide further information on the relationships between the plant ash glass groups we have identified at Ciudad de Vascos and glass reference groups from the eastern Mediterranean and Mesopotamia. Based on trace element data, Vascos 4 was attributed to an Iberian production, whereas Vascos 2 could be affiliated to Levantine plant ash glass and Vascos 1 was believed to be of possible Egyptian provenance (De Juan Ares and Schibille 2017b). At the time of publication, we refrained from attributing Vascos 3 and Vascos 5 to any specific place of origin, due to insufficient evidence. New isotope data have now confirmed that the two samples of Vascos 2 (VS 019, VS 076) have neodymium isotope ratios that correspond to a provenance in the eastern Mediterranean ($> -7 \epsilon_{Nd}$), in keeping with our previous proposal that these glasses represent Levantine imports (Fig. 70). One of the samples is consistent

with glass from Tyre in terms of both strontium and neodymium isotopes; the other fragment has the same isotopic signature as the glass from the Serçe Limani shipwreck. The glasses belonging to Vascos 4 instead have very low neodymium isotope ratios (median = $-11.83 \epsilon_{Nd}$), values that are more typically encountered either in the western Mediterranean (Degryse 2014) or in continental Syria, for example in the furnace glass from al-Raqqa (Henderson *et al.* 2020). Unlike the plant ash glass from al-Raqqa, however, Vascos 4 has higher $^{87}Sr/^{86}Sr$ isotope ratios and a different trace element profile. Thus, even though an inland Syrian source cannot be completely excluded, it is more likely that Vascos 4 represents an Iberian production, using plants from the coastal regions of eastern Spain. Isotopic data on silica sources collected along the Iberian coastline indeed provide a close match. Specifically, sands in the region south of Cartagena (e.g. Las Marinas) bear similarities with Vascos group 4 in terms of the low neodymium isotope ratios, while samples from the coastal stretches north of Murcia as well as north of Valencia have strontium isotope ratios consistent with those of Vascos group 4. It is perfectly feasible that the plant ash was collected in a different region from the sand deposits exploited for glass production. We can then make the tentative assumption that glassmaking was established in the southeast of the Iberian Peninsula as early as in the tenth century. The original interpretation of Vascos 1 as probably Egyptian can no longer be maintained. Thanks to a larger set of Iberian glass compositions and the very low neodymium isotope ratio of one of the samples belonging to Vascos 1 (VS 022), it can now be inferred that these glasses either are the result of a western Mediterranean plant ash glass production or originated in inland Syria (Fig. 70). The samples of Vascos 1 do not show the high thorium to zirconium ratios that are typical of Iberian glasses, and import from other regions is quite possible. The extent of the market for Iberian glass ultimately remains uncertain, as there is still a distinct lack of reliable comparative data on trace elements and isotopes.

The growing body of geochemical analyses of Islamic-period glass over the last decade allows us to trace more precisely the evolution of an Islamic glassmaking tradition in the Iberian Peninsula. Still, most of this evidence remains circumstantial and new groups of plant ash glass have been defined by exclusion rather than by positive attribution. Trade between the eastern Islamic world and the western Mediterranean is manifested in the exchange of vitreous materials, but also in the transfer of a plant ash glassmaking technology. However, the uniqueness of the lead slag glass from Šaqunda and its very early dating (< 818 AD) strongly suggest an independent development in al-Andalus that has no equivalent in the Islamic world, and that even predates the transition from natron to plant ash glass in Egypt and possibly the Levant. The production of soda ash glass appeared a

little later in Spain. It is difficult to determine the exact time of this transition, but by the tenth century several types of Iberian soda ash glass were in circulation in the Iberia Peninsula.

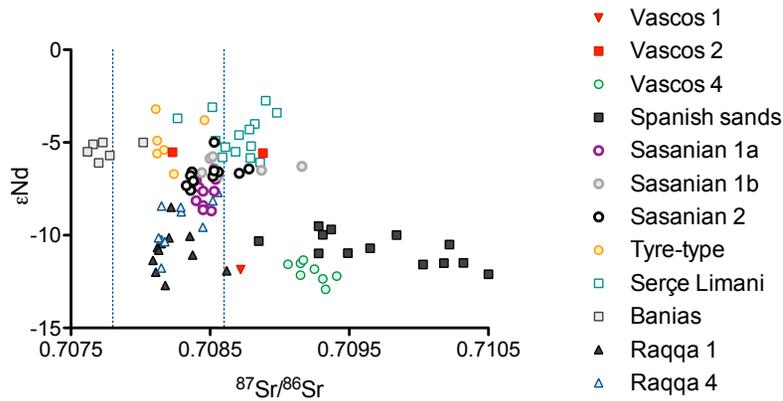


Fig. 70:

Neodymium and strontium isotope data on some glass from Vascos in comparison with eastern Mediterranean and Mesopotamian plant ash glasses. Data sources: (Degryse *et al.* 2010a) for Baniyas and Tyre; (Ganio *et al.* 2013) for Veh Ardašīr; (Henderson *et al.* 2020) for al-Raqqa, Beirut and Damascus vessels, as well as Serçe Limani; (Brill and Stapleton 2012) for some Serçe Limani stontium isotopes; please note that nominal neodymium values have been assumed between -3.1 and -5.8 in steps of 0.3 to compensate for the lack of Nd isotopes. (Degryse 2014) for Spanish sands; unpublished data on the Ciudad de Vascos (Schibille).

Mosaics from Madīnat al-Zahrā' and the Great Mosque of Córdoba

The Great Mosque of Córdoba is arguably one of the most important religious structures of early medieval al-Andalus, and it is the only one with monumental Islamic mosaic decorations dating from the tenth century. The mosque was originally commissioned by Abd al-Rahman I (731-788 CE), founder of the Umayyad dynasty of al-Andalus and the Emirate of Córdoba, who had fled the massacre of his family in Damascus during the Abbasid revolution of 750/51 CE (Guichard 2013, p. 11). The edifice served as a dynastic symbol from the start and set the tone for an Andalusian imperial aesthetic and architectural tradition (Guichard 2013, p. 13). Finished by his son, Hisham I, the edifice composed of 11 naves and 12 corridors from east to west was repeatedly modified and extended over the following centuries. Al-Hakam II's (961-976 CE) tenth-century expansion was perhaps the most significant, both aesthetically and culturally (Khoury 1996;

Puerta Vélchez 2013). The original structure was enlarged by 12 bays and a new *maqsura* was built. It was al-Hakam II who added intricate mosaic decorations to the mihrab façade, the central dome and the two lateral doors leading to the *bayt al-mal* (treasury) on the left and the *sabat* (the passage connecting the mosque with the caliphal palace) on the right (Fig. 71; Puerta Vélchez 2013). The mosaics consist of geometric and floral motifs with Kufic inscriptions consisting of both Qur'anic verses and historical statements in gold lettering on a dark blue or red background or in dark blue letters on a gold background (George 2009; Khoury 1996). The mosaics were first mentioned in the twelfth century by Muhammad al-Idrisi, who specified that the mosaics had been sent by the Byzantine emperor, Constantine VII (905-959 CE; Stern *et al.* 1976). By the fourteenth century the story had become more elaborate. According to Ibn Idhari (writing in c. 1312), the Byzantine emperor (malik al-Rum) sent 320 quintals (an estimated 16 tons) of mosaic tesserae (*fusayfisā'*) as well as a mosaicist/artisan at al-Hakam II's request to help in the endeavour to emulate al-Walid's Great Mosque in Damascus (Bloom 1988; Puerta Vélchez 2013, p. 35). This description clearly echoes earlier Arab sources that make similar claims with respect to the eighth-century mosques in Medina and Damascus and should be read as part of the same literary tradition.

The interpretation of the mosaic and its material hinges on its state of preservation and the transformations that have occurred since the mosaics were first executed in the tenth century CE. From archival material it is clear that the mosque and its mosaics underwent numerous modifications, starting with the building's conversion into a Christian church after the so-called Reconquista in 1236 CE (Palomar *et al.* 2022). The mosaics were covered and gradually fell into disrepair. After being hidden for nearly six centuries and largely forgotten, the mosaics were finally uncovered in the eighteenth century. This led to the first of a series of at least four major restoration campaigns since the eighteenth century (Torres Balbás 1936). According to historical sources, these early interventions consolidated the existing remains without altering the layout or style of the architecture (Romero de Torres 1949), while the restoration of the mosaics of the *bab bayt al-mal* façade in the early twentieth century meant the complete replacement of the original mosaics with facsimiles that were installed by Mauméjean master glassmakers in 1916 (Palomar *et al.* under review; Stern *et al.* 1976). The original material from the *bab bayt al-mal* mosaic was thus lost entirely, as was confirmed by the analysis of 13 tesserae from this area (Gomez-Morón *et al.* 2021). Other parts of the mosaic decorations have also been partly replaced.

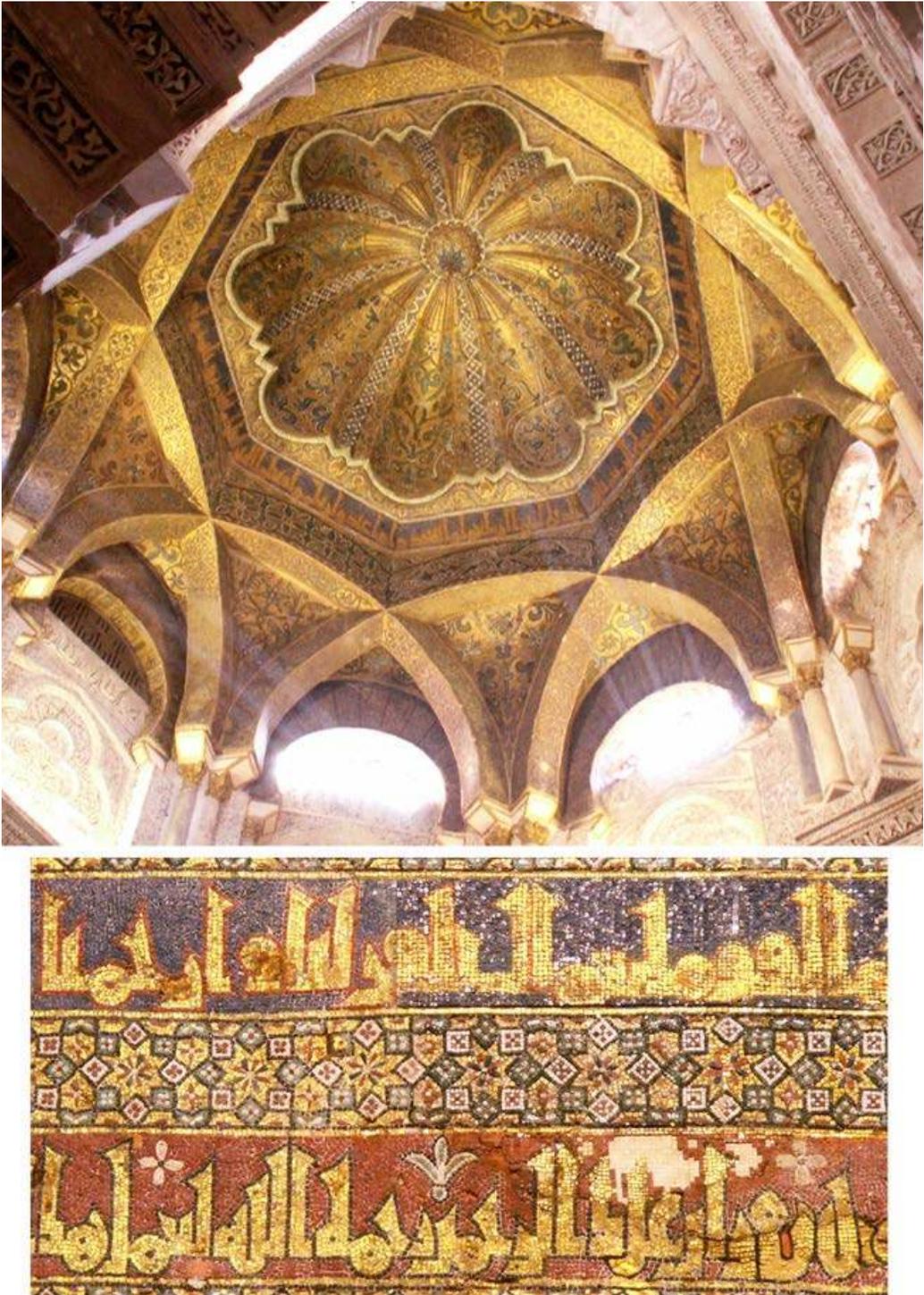


Fig. 71: The mihrab dome and a detail of the inscription from the sabat door of the Great Umayyad Mosque of Córdoba.

The extant tenth-century mosaics in the Great Mosque of Córdoba are unique in al-Andalus, with the possible exception of Madīnat al-Zahrā', where fragments of wall mosaics and loose tesserae have been found. Even Roman and late antique wall mosaics are rather rare in the Iberian Peninsula (James 2017; Pedraz 2018). The remains of the mosaics in Córdoba and Madīnat al-Zahrā' are also the only ones recorded in any Islamic context from the tenth century (Leal 2020). The materials and artistic affiliations of the mosaics are therefore of extraordinary historical and technological significance. We have analysed 91 mosaic tesserae from the Great Mosque in Córdoba (Gomez-Morón *et al.* 2021) and 53 samples which were selected from among the loose tesserae found in Madīnat al-Zahrā' (Schibille and Zamorano in preparation). Even though these were mostly surface finds, there is no reason to suspect a post eleventh-century deposition of mosaic tesserae at the site. The Madīnat al-Zahrā' samples can thus be considered reliable and well-dated reference material for the tesserae of the Great Mosque which was deemed necessary because of the repeated restoration campaigns that potentially obscured the original material. Here I will only briefly describe the compositional characteristics of the mosaics because the majority of them proved to be of a Byzantine base glass, which implies a completely different field of inquiry and which is beyond the scope of the present investigation of Islamic glass.

Both mosaic assemblages are highly variable but exhibit comparable group structures that mirror a multifaceted supply system. All the opaque yellow and green samples from Madīnat al-Zahrā' (n=13) and the mosque (n=7) are high-lead silica glasses ($\text{PbO} > 65\%$) with substantial amounts of tin (2% - 8%; Fig. 72) and virtually no alkali or alkaline earth elements ($\text{Na}_2\text{O} + \text{MgO} + \text{K}_2\text{O} + \text{CaO} < 1\%$). They have elevated arsenic, silver, antimony and bismuth contents indicative of the use of litharge from silver cupellation. Similar compositions are known from medieval glass beads and rings throughout Europe (e.g. Neri *et al.* 2018; Siemianowska *et al.* 2019) and ultimately resemble the yellow vitreous pigment known as *anima* rather than glass in the strict sense (Matin 2019; Moretti and Hreglich 1984). At present it is almost impossible to determine whether the yellow and green tesserae were imported or produced locally. The opaque yellow glazed ceramics from Madīnat al-Zahrā', for instance, are believed to have been imported to al-Andalus rather than produced locally, because they were relatively scarce and concentrated in the Alcazar together with other luxury wares (Salinas *et al.* 2019c). These yellow glazed ceramics tend to have lower lead and higher tin content than the yellow and green tesserae in line with yellow and green glazes from the eastern Mediterranean (Fig. 72). Lead isotope analyses may shed some light on the provenance of the raw materials and relationship between glass and glazes, but no invasive analyses are currently permitted.

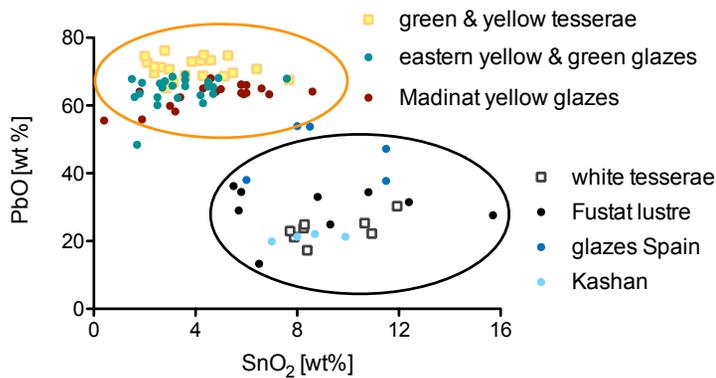


Fig. 72:

Lead and tin levels of the white/aqua (black ellipse) and yellow/green tesserae (orange ellipse) from Madīnat al-Zahrā' and the Umayyad Mosque in Cordoba compared to published glaze data from Madīnat al-Zahrā', Egypt, Syria and Iran. Data sources: (Matin 2019), supplementary tables 1 & 2 and references; (Molera *et al.* 2018; Salinas *et al.* 2019c); (Gomez-Morón *et al.* 2021) for Córdoba; (Schibille and Zamorano unpublished) for Madīnat al-Zahrā'.

A group of eight white and/or aqua-coloured opaque samples from Madīnat al-Zahrā' have high levels of lead ($17\% < \text{PbO} < 31\%$) and tin ($8\% < \text{SnO}_2 < 12\%$), as well as considerable amounts of alkali and alkaline earth elements. A subgroup of these white tesserae have very low levels of silica-related elements, suggesting the use of quartz pebbles as the silica source that was mixed with a lead-tin-calx as judged by the relatively constant lead to tin ratios (Fig. 72). We are reminded of the *Kitāb ad-Durra al-Maknūna (The Book of the Hidden Pearl)*, according to which white pebbles and lead oxide are the main raw ingredients for producing white *mīnā* (Al-Hassan 2009, p. 145). Given the low lead to tin ratios ($\text{PbO} / \text{SnO}_2 < 3.5$), the calx would have been a simple mixture of PbO and SnO₂ which was then combined with silica and alkali or a pre-formed glass to produce a glass opacified by SnO₂ (cassiterite) particles (Matin 2019). None of the published tin opacified glasses from the tenth century have even remotely comparable lead and tin concentrations, and the only vitreous material with similar patterns is some glazes from twelfth-century Kashan (Iran), some tenth- to eleventh-century lustre samples from Fustat (Matin 2019, and references therein), and possibly some glazes from the ninth- to tenth-century Vega of Granada (Molera *et al.* 2018). The Islamic tin-glaze technology developed in the eastern Mediterranean in the eighth century and was adopted in al-Andalus in the second half of the ninth (Molera *et al.* 2018). Archaeological and textual evidence documents the technological link between glaze production and glass during the early Islamic period (Allan 1973; Molera *et al.* 2009). In al-Andalus, there is strong evidence of a technological transfer from high-lead glassmaking to the introduction of lead glazes in the second

half of the ninth century CE (Salinas *et al.* 2021). Hence a technological link between tin glazes and lead-tin opacified mosaic tesserae is conceivable and, the white tesserae recovered at Madīnat al-Zahrā' may very well have been produced in a nearby workshop. None of the mosaic tesserae from the Great Mosque proved identical in composition; only one white tessera (MAQ O 015) is compositionally very similar, but for its elevated boron levels (Gomez-Morón *et al.* 2021).

The largest group of tesserae (n=46) from the Great Mosque and about a third of the samples from Madīnat al-Zahrā' (n=14) have elevated boron concentrations that can be attributed to raw materials from Asia Minor. High-boron glasses have up to now been identified especially among Byzantine assemblages and/or glass finds from Asia Minor dating between the sixth or seventh century (e.g. Aphrodisias, Labraunda) and the twelfth or thirteenth (e.g. Zeyrek Camii, Hagia Sophia, Pergamon, Kubad-Âbâd, Hişn al-Tīnāt), while fifteenth-century Iznik glazes can also be included (e.g. Brill 2002; Brill 2005b; Schibille 2011; Swan *et al.* 2018; Tite *et al.* 2016, and references therein). An origin in Turkey was first proposed by Robert Brill (Brill 1968; Brill 2002; Brill 2005b), and this has since been reinforced by the compositional data on a range of thermal waters from western Asia Minor (Tite *et al.* 2016). Published data on high-boron glasses and glazes highlight the immense variability of vitreous materials with elevated boron levels. The alumina contents, for example, range from below 1% to about 12%, and lime concentrations can be as low as 2% and almost as high as 16% (Fig. 73a). Altogether, there appears to be some sort of watershed at approximately 4% Al₂O₃, a threshold that separates subtypes of geologically very different silica sources. The alkali, alkaline earth and boron concentrations, however, do not follow the same subdivision, underscoring the potential existence of several compositional sub-categories of high-boron glasses.

The tesserae from Madīnat al-Zahrā' and the Great Mosque of Córdoba belong to the low alumina type of high-boron glasses with low silica-related impurities, indicative of a relatively pure quartz-rich silica source (Fig. 73a). They do not form a homogeneous group, but reflect differences in the fluxing agent as well as the silica source that are symptomatic of high-boron glasses more generally (Schibille 2011; Tite *et al.* 2016). The blue tesserae are invariably those with the lowest levels of accessory elements. They contain very low potash, magnesia and lime levels, as well as low alumina, zirconium and titanium contents, and relatively high soda concentrations. These data suggest that the production of cobalt blue glass was a specialised technology based on the use of particularly clean starting materials. Cobalt blue glasses in medieval contexts have frequently been shown to be exceptional (e.g. Cox and Gillies 1986; Gratuze 2020), and the tenth-century examples from Córdoba and Madīnat al-Zahrā' offer an additional dimension to

the production of and trade in this type of glass. The other high-boron tesserae from Córdoba and Madīnat represent more conventional compositions. They have moderate alkali and alkaline earths, as well as aluminium, zirconium and titanium levels comparable to those of contemporary glasses. Some twelfth-century samples from the Zeyrek Camii (Pantokrator church), a handful of probably thirteenth-century tesserae from Hagia Sophia in Istanbul (Schibille, unpublished data), two samples from tenth- to eleventh-century Bari (Neri *et al.* 2019) and possibly some isolated glazed tiles from the Seljuq Palace of Kubad-Âbâd (Freestone *et al.* 2009b) and Aphrodisias (Brill 1999) bear compositional similarities to the tesserae from Córdoba. They all have comparable lanthanum to titanium and thorium to zirconium ratios, unlike the cobalt blue tesserae which have notably higher thorium relative to zirconium, for which one sample from Pergamon provides a match

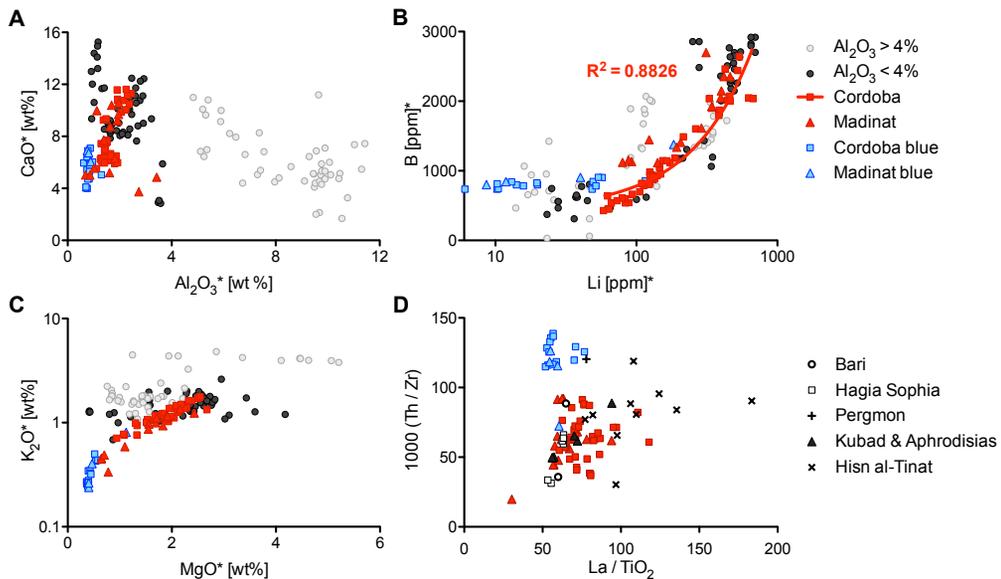


Fig. 73:

Elements related to the fluxing agent of the high-boron tesserae from the Great Umayyad Mosque of Córdoba (Gomez-Morón *et al.* 2021) and Madīnat al-Zahrā' (Schibille and Zamorano unpublished) compared to published data on glasses and glazes with elevated boron. (a) Lime and alumina levels suggest the subdivision of high-boron glasses into high alumina ($\text{Al}_2\text{O}_3 > 4\%$) and low alumina ($\text{Al}_2\text{O}_3 < 4\%$) sub-types; (b) boron and lithium are typically strongly correlated; (c) potash and magnesia contents are likewise correlated in the mosaic tesserae from Córdoba and Madīnat al-Zahrā', while they show a great variability among the high-boron glasses in general; (d) Th/Zr and La/TiO₂ ratios of the high-boron tesserae compared to the low aluminium subtype of high-boron glasses and glazes. With respect to the silica source, the mosaic tesserae from Madīnat al-Zahrā' and Córdoba show similarities with tesserae from Hagia Sophia (Schibille unpublished), Aphrodisias (Brill 1999) and possibly some glazed Seljuq tiles from Kubad Abad (Freestone *et al.* 2009b), two fragments from Byzantine Bari (Neri *et al.* 2019), and group 3 from Hişn al-Tināt (Swan *et al.* 2018). Asterisks indicate reduced and normalised compositions.

(Fig. 73d). In short, the compositional features of the tesserae from Madīnat al-Zahrā' and the Great Mosque of Córdoba are consistent with glasses and glazes manufactured in western Asia Minor using a mineral soda flux particularly rich in boron, lithium, strontium and caesium. It should be emphasised, however, that this attribution is based purely on the distribution of high-boron glasses to date and the composition of thermal waters from western Asia Minor (Tite *et al.* 2016). No primary production location of this type of glass has yet been identified, and the number of available compositional data is still limited. In particular, no trace element data on middle Byzantine mosaic tesserae have yet been published. The highly variable compositions in relation to the alkali and alkaline earth element concentrations make attribution difficult and suggest the exploitation of different evaporite deposits, and differences in the silica source confirm the existence of several subtypes of high-boron glass in the late first millennium CE. An important observation is that the two mosaic collections from tenth-century Córdoba are the largest assemblages of high-boron glasses so far found outside the realm of the Byzantine Empire.

The remaining tesserae from the two sites have a soda-rich plant ash signature. Only two gold leaf tesserae from the mosque have a base glass composition that corresponds to that of plant ash glass from the Levantine coast (Fig. 74). The red plant ash tesserae from both Córdoba and Madīnat (including one black sample) have significantly lower lime and higher lithium concentrations as well as notably higher thorium to zirconium ratios consistent with Iberian plant ash glass from Pechina and Ciudad de Vascos. These features suggest that this group of copper red mosaic tesserae were the product of an Andalusian glass workshop, which is rather unexpected. Not much is known about the organisation of tesserae production in general, but it is assumed that during the Roman and late antique periods mosaic tesserae and/or the glass cakes from which they were cut were produced in possibly specialised secondary workshops, from where they were acquired (Foy 2007). Evidence from fourteenth-century Orvieto offers an alternative scenario. Documentary material makes it clear that the procurement of tesserae for the monumental decorative programme of the cathedral in Orvieto involved multiple sources including the production on site, for which a dedicated furnace was specially installed (Harding 1989). A similar chain of events may have taken place at Córdoba. On the one hand, there is clear evidence of the long-distance import of Byzantine material right across the length of the Mediterranean. On the other hand, some of the mosaic material may have been produced locally. This includes not only some of the red tesserae, but also a handful of samples from the Mosque of Córdoba that show signs of the mixing and recycling of a Byzantine high-boron glass with an Iberian high-lead glass (Gomez-Morón *et al.*

2021). There were even reused Roman cobalt blue tesserae opacified with calcium antimonate ($\text{Ca}_2\text{Sb}_2\text{O}_7$), one at Madīnat al-Zahrā' and another from the Mihrab dome of the Great Mosque.

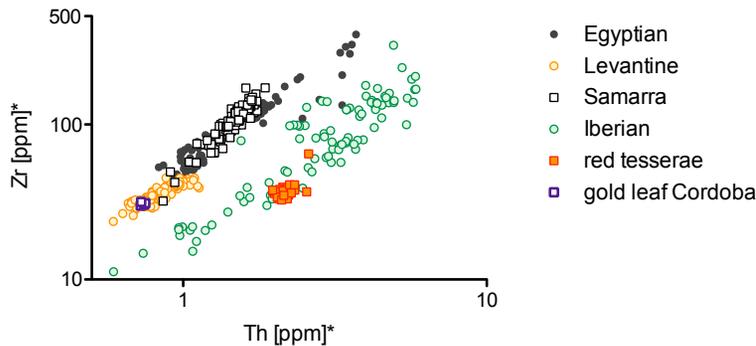


Fig. 74:

Mosaic tesserae from Madīnat al-Zahrā' and the Mosque in Córdoba with a plant ash base glass compared to glass reference groups. Iberian plant ash glass has a zirconium to thorium correlation that is clearly distinct from Levantine, Egyptian and Mesopotamian plant ash glasses. Some of the red tesserae from both Córdoba and Madīnat al-Zahrā' match the composition of Iberian plant ash glass, while two gold leaf tesserae from the Great Mosque in Córdoba correspond to Levantine plant ash glass. Data sources: (Schibille *et al.* 2018a) for Samarra; (Schibille *et al.* 2019) for Egyptian glass; (Phelps 2017) for Tyre type Levantine glass; (De Juan Ares and Schibille 2017b) for Iberian samples; (Gomez-Morón *et al.* 2021) for Córdoba; (Schibille and Zamorano) for Madīnat al-Zahrā'.

The mosaics of the two sites have more or less the same colour palette. The main colours of the mosaics are cobalt blue, copper turquoise/blue, black, purple, red, green and yellow, and the main opacifiers are either relatively large quartz inclusions, small crystals of tin oxide/lead stannate and/or air bubbles. Air bubbles and quartz particles are particularly abundant in the cobalt blue samples. Relatively homogeneously dispersed lead stannate together with big quartz inclusions is evident in the yellow samples, while the red tesserae show a typical stratified morphology. The red tesserae from both Madīnat al-Zahrā' and the Great Mosque of Córdoba have relatively high iron levels independently of the base glass, whereas there appears to be a tendency for higher copper and lower lead contents in the tesserae of the high-boron type. Given the small number of samples, however, this may not be a real phenomenon. Lead concentrations can vary considerably and no one glass colouring recipe can be established. Nonetheless, the red tesserae seem to follow ancient traditions of copper opaque red glasses. The major colourants in low-copper low-lead opaque red glasses are usually sub-micrometric metallic copper particles where the iron serves predominantly as a reducing agent (Barber *et al.* 2009). The blue samples have cobalt concentrations typically below 500

ppm accompanied by elevated copper, impeding a clear characterisation of the cobalt source. The cobalt does not appear to be associated with either zinc or nickel, and in this respect corresponds to the Roman cobalt sources that prevailed until the fourth century CE (Gratuze *et al.* 2018; Fig. 75). Hence, the cobalt signature differs clearly from contemporary Islamic cobalt sources, including the cobalt blue vessel glass fragments from Madīnat al-Zahrā' that are accompanied by elevated zinc concentrations.

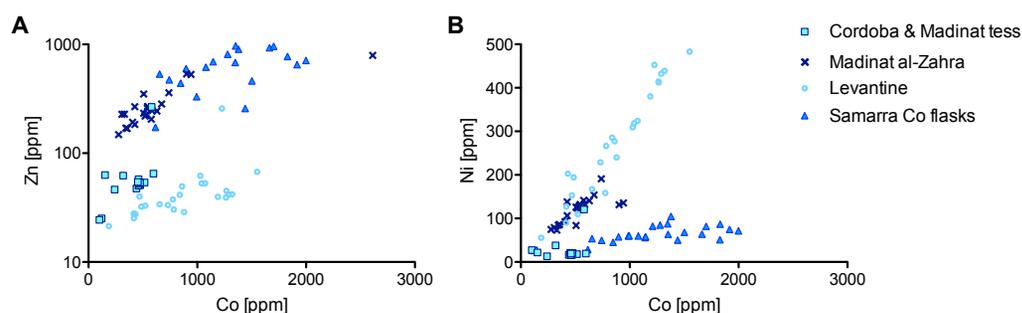


Fig. 75:

Characteristics of the cobalt colourant used in the high-boron blue tesserae from Madīnat al-Zahrā' and the Mosque in Córdoba in comparison with late antique and Islamic cobalt blue glasses. (a) Zinc and cobalt levels of the tesserae are reminiscent of Roman and late antique cobalt sources distinct from Islamic cobalt which has typically elevated zinc levels; (b) the tesserae also have low nickel relative to cobalt consistent with Roman cobalt sources (Gratuze *et al.* 2018). Data sources: (Schibille *et al.* 2016) for late antique Levantine natron-type glass; (Schibille *et al.* 2018a) for Samarra; (Gomez-Morón *et al.* 2021) for the tesserae from the Great Mosque in Córdoba; (Schibille and Zamorano unpublished) for Madīnat al-Zahrā' including tesserae and other blue samples with a likely Mesopotamian origin.

The differences in group structures between Córdoba and Madīnat al-Zahrā' probably relate to the design of the mosaics and different aesthetic requirements. The mosaic programme at Madīnat al-Zahrā' made extensive use of white and aqua-coloured tesserae, whereas the decoration of the Great Mosque consisted mostly of gold, blue, red and green (Fig. 71). The uneven use of colours and glass groups within the assemblages of Córdoba and Madīnat al-Zahrā' could have a chronological explanation (Fig. 76). The overwhelming majority of the tesserae from the Great Mosque are of the Byzantine high-boron type, and what I believe to be Iberian plant ash tesserae make up only a minimal part of the assemblage. At Madīnat al-Zahrā', by contrast, the high boron and Iberian samples are represented equally. Something clearly changed in the supply chain for mosaic tesserae between these two mosaic programmes. If we assume that Byzantine mosaic tesserae arrived in Córdoba for the decoration of the Great Mosque, as the literary

sources claim, and that these Byzantine tesserae were then complemented by local materials, we might reasonably conclude that work on the mosaic decoration of Madīnat al-Zahrā' commenced after the decoration of the Great Mosque in Córdoba.

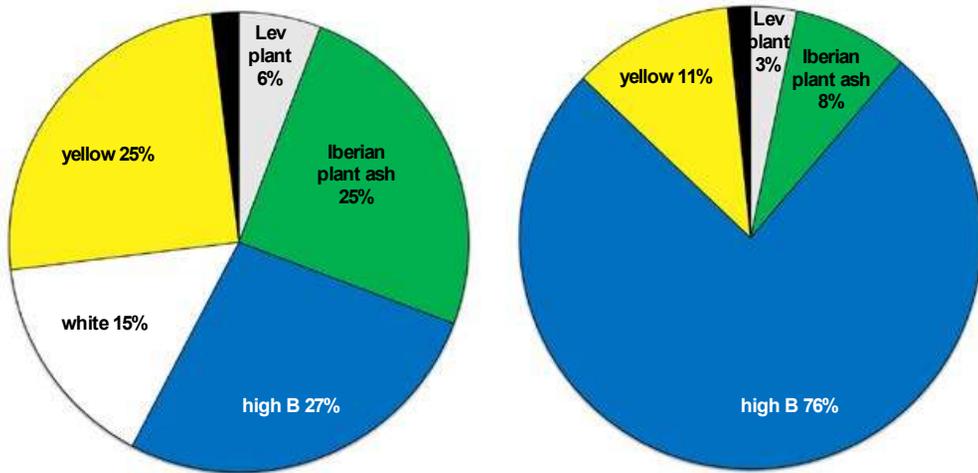


Fig. 76: Camembert showing the ubiquity of glass groups in the mosaic assemblage from Madīnat al-Zahrā' and the Great Mosque of Córdoba.

The glass supply in eighth- to tenth-century al-Andalus

In the archaeological record of Hispania, glass finds become increasingly scarce in the wake of the Muslim conquest of the Iberian Peninsula (711 – 714 CE). Recycling of older natron glasses is on the rise since the seventh century, as is evident from Visigothic contexts, and becomes the norm in eighth- to early ninth-century Šaqunda. A few Islamic natron-type glasses from Egypt reach the Iberian Peninsula until the ninth and first half of the tenth centuries. Egypt 2 glasses, for example, have been recovered from ninth- or tenth-century contexts in Vascos (De Juan Ares and Schibille 2017b), as well as Šaqunda. Some of the earliest Islamic soda-rich plant ash glasses known to date were also found among the eighth- to early ninth-century glasses from Šaqunda. These plant ash glasses correspond to Mesopotamian compositional groups, a fact which appears to confirm that plant ash glassmaking was still not firmly established anywhere else in the Islamic world, either in Egypt or along the Levantine coast, and most certainly not in the Iberian Peninsula. The finds from Šaqunda furthermore provide evidence for the innovation of a new glassmaking technology resorting to the use of local lead slags from silver or lead mining activities. This type of lead glass was short-lived and has

been identified only sporadically outside Córdoba. The lead glass from Šaqunda appears to be the direct forerunner of the soda-ash lead glass that dominates the archaeo-vitreous record of al-Andalus in the tenth century.

There is an enormous chronological gap in the available data on well-dated and contextualised glasses after Šaqunda (ca. 756 - 818 CE). Only two soda-ash lead glasses were retrieved from contexts attributed to the earlier phase at Pechina (mid-9th century to 929 CE). The Iberian plant ash glass from Pechina and the crucibles that may have been destined for the production of soda-ash lead glass all date to the second phase after 929 CE. In this respect, the glass finds from the palace city of Madīnat al-Zahrā' offer the most comprehensive insights into the nature of glass supply and production in the tenth century, and the findings are surprising. With an *ex nihilo* foundation in 936 CE and a lifespan of a mere 70 years, the analytical data paint a detailed picture of selective imports alongside a sophisticated Andalusian glass production based on the exploitation of litharge from nearby lead and silver mines. About 70% of the glasses from Madīnat al-Zahrā' are soda-ash lead glasses, comprising different types of vessels as well as circular window panes with folded, hemmed edges. Approximately a quarter of the glass finds analysed are imported Levantine and Mesopotamian soda-rich plant ash glasses, and only about 3% match the characteristics of an Iberian plant ash glass production. The mosaic decorations in Madīnat al-Zahrā' and the Great Mosque of Córdoba offer yet another perspective. The tesserae are a combination of what appear to be Iberian plant ash glass and Byzantine high-boron glasses. The convergence of the two sets of data underpins the significance and validity of the findings. The samples from Madīnat al-Zahrā' thus validate the identification of the original parts of the mosaic decoration in the Great Mosque.

The spatial and chronological distribution of different glass types and the fluctuations in absolute numbers over time allow some tentative conclusions. After a drought of fresh glass in the seventh and eighth centuries, local craftsmen apparently started experimenting with lead slag which forms a glassy mass. The glass tends to be strongly coloured (dark amber and bottle green) and probably posed challenges during its transformation into artefacts, which may explain why this slag glass had a short period of existence. During the ninth century a new type of lead glass was developed, this time using litharge rather than slag and some additional soda-rich plant ash, probably to improve the material qualities. Litharge offers a cleaner option and the glasses are typically only weakly coloured and often colourless with only a slight tinge. The considerable number of soda-ash lead glasses that have been found, their concentration around Córdoba and most significantly their lead isotopic signatures provide solid evidence that the production centre was somewhere close by.

The earliest analytical evidence of a potential regional plant ash glass production dates to the ninth (Tolmo de Minateda) and tenth century (Pechina, Madīnat al-Zahrā', Córdoba). We should note that there are four plant ash glasses dated to the eighth to ninth centuries among the samples from Córdoba analysed by Chloé Duckworth and colleagues (2015). Without any trace elements and further details about the archaeological context and more robust dating of the samples, the attribution of these glasses remains inconclusive. Written documentation from later centuries claims that a new way of glassmaking was invented in al-Andalus in the ninth century, while the first mention of a glass workshop is in relation to eleventh-century Sevilla (Jiménez Castillo 2006). During the Taifa period, Málaga, Murcia and Almería were known as glassmaking centres (Jiménez Castillo 2006). The beginnings of plant ash glass production are therefore elusive, but there is enough evidence to suggest that the production of lead glass preceded the production of plant ash glass in al-Andalus. By the tenth century an Iberian glassmaking tradition, including plant ash glasses, soda-ash lead glasses and possibly even yellow, green, red and white mosaic tesserae, was well established. The yellow and green high-lead tesserae and the high-lead white samples from Madīnat al-Zahrā' and Córdoba have a close affinity with contemporary ceramic glazes. The red tesserae with Iberian characteristics are unexpected but with some compositional parallels in some glass beads, and suggest the presence of skilled glass workers. The very existence of the mosaics in both Madīnat al-Zahrā' and Córdoba speaks to the fact that craftsmen and artisans came from somewhere other than al-Andalus (James 2017, p. 332). There is no history of mosaic making in Islamic Iberia prior to or after the decoration of the mosque of Córdoba and Madīnat al-Zahrā'. It thus seems likely that craftsmen may have been recruited from elsewhere, most probably the eastern Mediterranean. Whether the newly anointed Umayyad caliph indeed asked the Byzantine emperor for help, who then sent a master-mosaicist, as some of the historical sources would make us believe, is arguable. As Liz James has pointed out, this may have simply been a good story rather than a true one (James 2017, p. 333). This said, there were diplomatic contacts between Constantinople and Córdoba in the ninth and tenth centuries, whereas the customs records do not show any commercial links between the Byzantine Empire and the Umayyad Caliphate in al-Andalus (Constable 1996, p. 39). Byzantine embassies were received in the courts of Madīnat al-Zahrā' and Córdoba that served to strengthen the political allegiances across the Mediterranean. The choice of mosaics for the decoration of the most important religious edifice in Córdoba may have been a visual expression of these diplomatic ties (Anderson and Pruitt 2017, Signes Codoñer 2004). Monumental mosaic decorations in the medieval Mediterranean had considerable cultural and political value and played an instrumental role in

expressing political legitimacy and lineage (James 2017). The new decorative programme for the mosque of Córdoba by al-Hakam II may be seen as a response to, or as an expression of a caliphal rivalry vis-à-vis the Fatimid conquest of Egypt in 969 CE (Anderson 2014; Anderson and Pruitt 2017). The evocation of the great Umayyad mosques of Damascus and Jerusalem was meant to assert the legitimacy of the Umayyads in Córdoba and their claim to the caliphate (Bloom 1988; James 2017; Khoury 1996). Even the legend of the Byzantine supply of tesserae for the creation of the mosaics of Damascus was recreated to underscore this message. While we were able to demonstrate that this story was true as regards the mosaic decorations of Córdoba and Madīnat al-Zahrā', in the case of the Great Mosque of Damascus the legends made for a powerful but purely fictional narrative.

Tenth-century Córdoba was the largest urban centre in the Iberian Peninsula, famous for its intellectual and commercial activities and strategically located on the Guadalquivir up-stream from Seville (Constable 1996, p. 22). Historical sources inform us of the presence of merchants from Egypt and Khurasan in the tenth century (Constable 1996, p. 36). The import of Mesopotamian and Levantine plant ash glasses does not therefore come as a surprise. There is also ample evidence of trade in Córdoba glass to other regions of the Iberian Peninsula and possibly further afield. Soda-ash lead glasses as well as Iberian plant ash glasses have been identified among the glass assemblages from twelfth-century Albalat, tenth- to twelfth-century Vascos (De Juan Ares and Schibille 2017b), eleventh- to thirteenth-century Murcia (García Heras 2008), and Silves (Schibille, unpublished). Lead isotope analyses of a few soda-ash lead glasses from these sites (except Murcia) confirm their common origin. Islamic soda-ash lead glass from al-Andalus even made its way into Christian territories, for instance to the castle of Gauzón on the north coast of Spain (De Juan Ares *et al.* 2018). Some tenth- to twelfth-century glass finds from Sicily resemble Iberian plant ash glasses (Schibille and Colangeli 2021), and several finds from the Maghreb (e.g. in Šabra al-Manšūriya, Sijilmâsa) show characteristics that are different from the plant ash glasses typically encountered in the Islamic east, even though an identity with Iberian plant ash glass could not yet be demonstrated. The lack of high resolution analyses of glass from medieval sites in the western Mediterranean and north Africa makes it difficult to sketch a more detailed picture of the range of commerce in Andalusian glass. Only a global research approach that considers the types of glass between the Straits of Gibraltar to Mesopotamia and Central Asia can provide conclusive information about the scope of material and technological exchange. For example, ceramics originating in al-Andalus have been found in Fatimid Cairo, the west African region of Gao as well as numerous Italian towns (Constable 1996, p. 190). Close contacts between the north African coast and al-

Andalus are well documented in historical sources, and have been confirmed by investigations into ceramic materials (Gutiérrez Lloret 2011). In the ninth century, al-Ya‘qūbī describes the route from Tunisia along the coast to a place called Tanas (Ténès) from where one crosses the ‘main channel in a day and a night and arrives in the region of Tudmir (Murcia)’ (Gordon *et al.* 2017, p. 191). This axis of communication was strengthened by the foundation of Pechina (Fig. 57). The discovery of numerous Islamic shipwrecks off the coast of Provence dating probably to the ninth or tenth century illustrates the active networks of exchange between north Africa, al-Andalus, the Balearics and along the coast of Provence and perhaps down the Italian coast to Sicily (Richarté-Manfredi 2017). Two glass fragments from the Batéguier shipwreck found close to the Ile Sainte-Maguerite close to Cannes can be attributed with a fair degree of certainty to an Iberian origin (unpublished data), confirming the transport of if not the trade in Iberian plant ash glass.

Glass and the processes of Islamisation

The number and quality of glass finds in the Iberian Peninsula had their highs and lows. As with other Roman provinces, fresh glass from the eastern Mediterranean arrived in Iberia in great abundance throughout the Roman period and into the sixth century, with a notable decrease between the seventh and eighth centuries, followed by a steady revival, first in the form of local lead and soda-ash lead glass and then locally produced plant ash glasses alongside the import of mostly Mesopotamian and Levantine plant ash glasses, in the ninth and more extensively in the tenth century CE. This revival of glass supply and the development of a local glassmaking tradition were indirectly related to the wider processes of Islamisation, seen also in the introduction of glazed ceramics (Molera, *et al.* 2018), and may have been conditioned by the geopolitical transformations from a single, universal caliphate under the Umayyads and Abbasids in the eighth and ninth centuries into three competing caliphates in the tenth century. Just as the architectural designs of Umayyad Córdoba are the result of a shared Mediterranean Islamic visual language, ‘a synthesis of Syrian Umayyad, Byzantine, and Visigothic materials, techniques, and motifs’ (Anderson and Pruitt 2017), so too is the vitreous material from Córdoba and Madīnat al-Zahrā’ a combination of characteristics common to Mediterranean glass assemblages more generally alongside local variations. From a formal point of view, the number of closed forms increases over the first Islamic centuries, whereas large bowls and dishes common during the Visigothic period disappear entirely during the caliphate, being replaced by smaller hemispherical and truncated cone-shaped drinking vessels (De Juan Ares and Schibille 2020).

Glass and the compositional data on glass finds from well-defined archaeological contexts can be seen as a valid indicator of the wider social and cultural transformations in relation to manufacturing traditions and exchange systems. There is no conclusive evidence of any technological transfer from the eastern Mediterranean to al-Andalus, but some links with the Maghreb as regards the organisation of workshops are apparent. The investigation of the archaeological remains at Şabra al-Manşūriya has revealed a glassmaking workshop (primary production and secondary working) that at the same time served the manufacture of glazes (Foy 2012a; Foy 2020). The well-documented glass workshops from Murcia at Puxmarina and Belluga that were active in the twelfth century seem also to have combined primary and secondary workshop activities, covering the entire production cycle from the raw materials to the finished products, including possibly even the processing of lead (Foy 2017; Jiménez Castillo *et al.* 1998). Evidence from the tenth-century ceramics workshop at San Nicolás in Murcia furthermore suggests an intimate link between the production of glass and glazes (Molera, *et al.* 2009; Molera, *et al.* 2018). It is conceivable that the influences that we see in aspects of urban planning, architectural decorations and artistic forms between the Maghreb and al-Andalus may also have had an effect on manufacturing processes and the organisation of glass workshops. Future work needs to consider the consumption patterns and manufacturing traditions in relation to vitreous materials from both the Maghreb and the Iberian Peninsula, in order to open new perspectives on the developments of and innovations in glassmaking in the Islamic west as well as the transfer of technological know-how and recipes.

Western expansion: Sicily and the Maghreb

Byzantine, Islamic and Swabian Sicily

Analytical studies of Sicilian glass from late antiquity and the Middle Ages are few and far between. This presents a critical gap in our understanding of the supply networks of primary glass from the traditional glassmaking centres of the Levant and Egypt to the western Mediterranean and the changes in it, given the island's strategic position and diverse geo-political history. Studies carried out thus far have focused on mosaic tesserae from the Villa del Casale near Piazza Armerina dating to the late Roman period (Croveri *et al.* 2010; Di Bella *et al.* 2014; Verità *et al.* 2017a), glass finds from the Church of Santa Agata la Vetere in Catania spanning the second to eighth centuries (Barbera *et al.* 2012), some glass fragments from the fourth to seventh centuries from Ganzirri north of Messina (Arletti *et al.* 2010), and finally the remains of a late antique secondary

glassworks in the amphitheatre of Catania (Fig. 57; Di Bella *et al.* 2015). All of these glasses correspond to well-established natron-type groups from the eastern Mediterranean, including Roman, HIMT, Levantine I and Foy 2.1-type glasses. An article examining the material characteristics of twelfth- to thirteenth-century mosaic tesserae from the Cathedral of Monreale in Palermo (Verità and Rapisarda 2008) and another one on the composition of fourteenth-century glass from the Castle of Poggio Diana near Agrigento (Panighello *et al.* 2013) are the only two publications so far to have investigated Sicilian plant ash glass.

Francesca Colangeli's doctoral thesis (Colangeli 2022) addresses precisely this lack of data about the circulation of glass in Sicily in the late antique and medieval periods, and the gradual development of a local glassmaking tradition. The thesis focuses on the vitreous material of western Sicily (Palermo, Castello della Pietra, Mazara del Vallo) as well as sites in the centre of the island (Castronovo, Piazza Armerina) in order to explore regional similarities and differences. As part of this research we have analysed 250 glass samples, which considerably enriches our knowledge of the glass economy in Sicily and how it may have been impacted on by wider geopolitical trends (Colangeli 2022). The glass finds from Mazara del Vallo, a town on the west coast of Sicily, provide interesting insights into the diachronic developments in the supply and distribution of glass that seem to reflect the situation at least in the western part of the island more generally (Schibille and Colangeli 2021). The glass finds from Mazara span the seventh to thirteenth centuries, thus exactly the period in which the primary production of and trade in glass in the Mediterranean underwent fundamental transformations. It was also the time during which Sicily was subject to numerous geopolitical upheavals, passing from the control of the Byzantines to the Aghlabids in the ninth century, then to the Normans in the eleventh century, and changing hands again to the Swabians and later to the House of Aragon in the thirteenth century CE.

The supply and distribution patterns of regional glass groups in Mazara del Vallo are reminiscent of those in Spain. The glass from the Byzantine phase in the seventh and eighth centuries is plain and simple Apollonia-type Levantine I glass without any clear recycling indicators (Schibille and Colangeli 2021). This parallels the observations made in relation to Visigothic Spain (De Juan Ares *et al.* 2019a). It is tempting to infer from this coincidence that Levantine glass may have been supplied to eastern Spain through redistribution from the west coast of Sicily. The glass then would have been traded in the form of raw glass chunks rather than finished objects. However, I am not aware of a secondary glass production workshop that was active in Sicily at the time, and the non-specific typology (i.e. small goblets of the Isings 111; Schibille and Colangeli 2021) does not help to elucidate the matter further.

A marked change in the supply and circulation of glass occurred during Sicily's Islamic period. The tenth- and eleventh-century glass finds from Mazara del Vallo are soda-rich plant ash glasses with moderate magnesia and potash levels that at first glance resemble Islamic plant ash glass from the Levant or Egypt. The Sicilian glass, however, shows a distinct difference in the lithium and boron profiles (Fig. 77a). Most of the plant ash glasses from Mazara have significantly higher lithium compared to Levantine, Egyptian and Mesopotamian plant ash glasses and match in this respect plant ash glass of supposedly Iberian origin. Judging from the elements related mostly to the silica source, the Islamic plant ash glass from Mazara does not correspond to any known contemporary plant ash group from the Eastern Mediterranean, the Iberian Peninsula or even Italy. A key feature of the Mazara glass is relatively high zirconium concentrations, especially relative to thorium and titanium (Fig. 77b). Whereas zirconium and titanium concentrations of plant ash glass from the Levant, Egypt and the Iberian Peninsula usually distribute along the same regression line, the glass from Mazara clearly deviates, showing higher zirconium to titanium ratios. The raw material for the glass from Mazara must therefore have been obtained from a different geological and geographical source. We argue that the trace element pattern of the Islamic glass from Mazara del Vallo represents a new primary production of soda-rich plant ash glass, and that this primary production is likely to have been in Sicily itself, since these compositional features have no parallel among known Islamic glass assemblages, with the possible exception of a single sample from Utica in Tunisia (see below). Surprisingly, the compositional make-up of most of the glasses

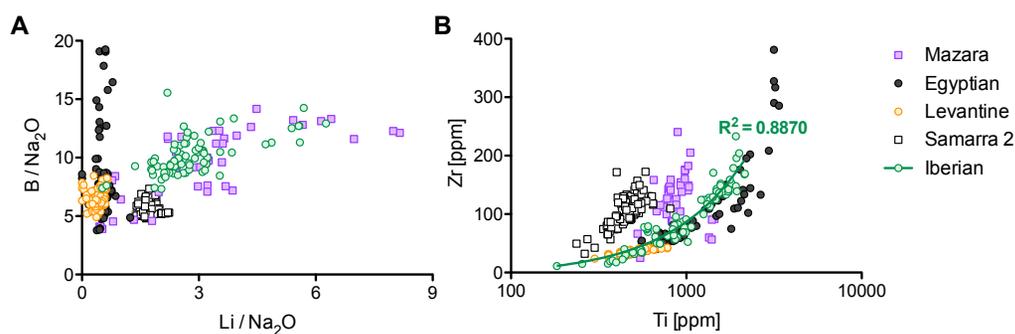


Fig. 77:

Comparison of the plant ash glass from Mazara del Vallo (Sicily) with glass reference groups from the Levantine coast, Egypt, Mesopotamia and the Iberian Peninsula. (a) Early Islamic glass from Mazara tends to have elevated lithium levels like Iberian glass groups; (b) Sicilian glass differs clearly from all reference groups in terms of their zirconium relative to titanium concentrations. Data sources: (Schibille and Colangeli 2021) for Mazara del Vallo; (Phelps 2017) for Tyre-type Levantine glass; (Schibille *et al.* 2019) for Egyptian glass; (Schibille *et al.* 2018a) for Samarra; (De Juan Ares and Schibille 2017b) for the Ciudad de Vascos.

recovered from Mazara did not change dramatically when Sicily passed to the control of the Normans and the Aragonese. This continuity of glass compositions corroborates the existence of a Sicilian glassmaking centre. Very few glass objects of Mesopotamian, Levantine and Iberian origin have been identified among the Mazara assemblage (Schibille and Colangeli 2021). The import of Iberian glass appears to increase after the twelfth century, when Sicily was no longer under Islamic control (Colangeli 2022).

The temporal mapping of the glass from Sicily reveals shifting long-distance trade networks between the fifth/sixth centuries and the seventh, and again in the tenth century. Published data on late Roman/late antique glass assemblages identified mostly Egyptian glass groups. The glass from the secondary workshop in the Roman amphitheatre of Catania is mostly fourth- to fifth-century HIMT glass (Di Bella, *et al.* 2015). HIMT, Foy 2.1 and Foy 3.2 make up the assemblages in Ganzirri and the church of St Agata la Vetere in Catania (Barbera *et al.* 2012). Based on these admittedly limited data, it can be concluded that most of the glass in circulation in Sicily in the fourth to sixth centuries was of Egyptian origin. In the late seventh and eighth centuries it was Levantine glass from Apollonia that supplied the west coast of Sicily instead. These developments seem to run in parallel to those of the Iberian Peninsula. It is still unclear what might have triggered this reorientation. The simplest explanation is a reorganisation of maritime trade networks. Egypt did export large quantities of glass during the eighth century, but it appears that this export was almost exclusively destined for the Levantine coast (Adlington *et al.* 2020; Phelps *et al.* 2016). Both Islamic natron-type glasses, Egypt 1 and Egypt 2, have turned up only occasionally in the western Mediterranean (De Juan Ares *et al.* 2021; Neri *et al.* 2019; Schibille *et al.* 2020a), suggesting that the long-distance exchange of bulk material from Egypt was severely curtailed by that time.

The analytical data on tenth- and eleventh-century glass from Mazara show a marked contrast between Sicily and the Italian Peninsula. In the latter, recycling of natron glass was the main source of supply during the latter part of the first millennium CE. Sicily, on the other hand, appears to have been well integrated into the Islamic sphere of influence, which is clearly reflected in the prevalence of finds of soda-ash glass typical of Islamic glassmaking traditions as well as in the typology of the plant ash glass from Mazara which has parallels in the archaeological record of Šabra al-Manšūriya (Tunisia) (Colangeli 2021; Foy 2012a; Foy 2020). Whether there was also some form of technological connectivity between Sicily, North Africa and the Iberian Peninsula with respect to the production of soda-rich plant ash glass remains to be seen, but at present there are virtually no trace element data on vitreous material from northern Africa.

Islamic glass in the Maghreb

Only a single tenth-century glass fragment from Utica (Tunisia) has been analysed, and its composition is almost identical to that of the Sicilian plant ash glass from Mazara del Vallo, in terms both of the silica source as well as the plant ash component (Schibille and Colangeli 2021). Judging from the major and minor element composition of the vitreous material from Şabra al-Manşūriya (only SEM-EDXA data have been published; Foy 2020), there are some compositional affinities with this site, too. Common features of some of the glasses from Şabra al-Manşūriya and Mazara del Vallo include moderate concentrations of magnesium, potassium, aluminium and titanium. A technological and material link between early Islamic glass production in Tunisia and Sicily is therefore quite possible.

Only two analytical studies of vitreous materials give trace element data on glass from the Maghreb. They include ninth- to tenth-century glass beads from medieval al-Basra in Morocco (Robertshaw *et al.* 2010), and 15 glass fragments from Sijilmâsa dating to the thirteenth century (Foy *et al.* 2020). Glass beads are a very specific group of objects that pose different problems with regard to their origin, due to the relatively small quantity of glass required in their production and the considerable impact of recycling on their composition. Many of the glass beads from al-Basra with soda-ash characteristics appear to be of Mesopotamian origin, while others have Iberian characteristics. As for the glass from Sijilmâsa, a city that played a key role in trans-Saharan trade, its composition shows clear analogies with Islamic soda-ash glass found in the Iberian Peninsula, dated to between the tenth and twelfth centuries. They are characterised by high levels of soda and lithium, moderate levels of magnesium and potassium, and low lime contents (Foy *et al.* 2020). The glass from Sijilmâsa is also perfectly compatible with Iberian glass from the tenth to twelfth centuries when one considers elements associated with the silica source such as aluminium, titanium, chromium, zirconium, and thorium. However, it must be emphasised once more that we do not yet have enough information and analytical data to be able to distinguish Maghrebian and Iberian glass productions. What we can say at this point, however, is that the glass used in Sijilmâsa has all the characteristics of glass produced in the western Mediterranean.

Emancipation of western Islamic glassmaking

Geochemical analyses of Islamic glass assemblages from the western Mediterranean have increased considerably over the last decade and allow us to trace more precisely the birth of an independent Islamic glassmaking tradition in the Iberian Peninsula and Sicily. Most of this evidence remains circumstantial, and

new groups of soda-ash glass have been defined by exclusion. The singularity of the lead glass from Šaqunda and its early date (< 818 CE) point to an independent development in Iberia. Sodium-ash glass appeared a little later in al-Andalus, perhaps at the same time as the first ash glasses in Sicily. The exact timing of this transition is difficult to determine, but by the tenth century several types of soda ash glass were in circulation in the Iberian Peninsula. Sicilian plant ash glass is also known to date from the tenth or even late ninth century. What is sorely lacking at this stage is high-resolution analytical data on Maghrebian glass in order to shed light on the overall material and technological relationship within the western Mediterranean. Only high-resolution analyses of well-contextualised glass with precise chronologies and typologies will allow for a better understanding of changes in production, more precise discrimination between production groups, and the extent of regional markets.

In conclusion – geographical and chronological dimensions

This study set out with a deceptively simple objective, namely to define robust compositional discriminants between early Islamic plant ash glass groups of different geographical origins by collating and evaluating the available evidence, both published data and unpublished data that we have generated in our laboratory over the course of the last five years. Many of the published data present their own challenges, insofar as they sometimes lack the necessary analytical resolution and are often based on insecure archaeological contexts and/or dating of the materials. The data are therefore inevitably incomplete and unevenly distributed in terms of their geographical and chronological scope. A clear compositional classification of plant ash glasses is further complicated by the use of two highly variable base glass ingredients, the silica source, which is seldom a clean quartz and more often a ‘dirty’ sand, and plant ash which is by its very nature highly heterogeneous. Differential treatments of the plant ashes, which we know little about, can have an additional impact on the final glass composition.

In the past, eastern Mediterranean plant ash glasses were differentiated into Mediterranean and Mesopotamian production zones based on differences in the fluxing agents (Freestone 2006; Henderson *et al.* 2016; Phelps 2018). The story is much more complex, however, as was recently illustrated on the basis of the strontium and neodymium isotope ratios of numerous early Islamic plant ash glasses (Henderson *et al.* 2020). At al-Raqqa, for example, the discrepancy between compositional and isotopic data yields seemingly contradictory results. The compositional characteristics of the fluxing agents of plant ash glass groups Raqqa 1 and Raqqa 4 (e.g. magnesium, potassium, phosphorus) appear to represent different production recipes belonging to Mediterranean and Mesopotamian traditions, respectively, whereas the strontium and neodymium isotopic signatures point to a common geological/geographical region of origin of the raw materials, most likely in inland Syria (Henderson *et al.* 2020). The elements of the plant ash component alone can thus be misleading, and multidimensional comparisons of isotope fingerprints and trace elements associated with both the plant ash and

the silica source is additionally required for one to construct a more accurate framework of plant ash glass categories.

The group structures of the assemblages considered here provide a first unified assessment of regional glass production groups. Some of the compositional parameters that I have used to distinguish between different geographical origins have been borrowed from previous studies and other contexts. It was found, for instance, that the criteria that separate Egyptian from Levantine natron-type glasses (Th/Zr and La/TiO₂ ratios) apply also to plant ash glasses. Similarly, the elevated chromium to lanthanum ratios that distinguish Mesopotamian from Egyptian Late Bronze Age vitreous materials also characterise Sasanian and early Islamic glasses produced in Mesopotamia, albeit to a lesser extent. To illustrate the effectiveness of these discriminants and to visualise the systematic differences between these populations, I have chosen six representative macro-regional production groups. I have selected data on Egyptian glass weights (Schibille *et al.* 2019), Tyre and other Levantine glasses (Phelps 2018), as well as samples from Samarra (Schibille *et al.* 2018a), Merv (Meek *et al.* in preparation), Ciudad de Vascos (De Juan Ares and Schibille 2017b) and Mazara del Vallo (Schibille and Colangeli 2021). Glasses from the six production zones can be largely separated by a combination of six ratios: K₂O/P₂O₅, MgO/CaO, Li/Na₂O, Th/Zr, La/TiO₂ and Cr/La (Fig. 78).

The precision with which the different regional groups are defined and delimited varies. Mesopotamian plant ash glasses (exemplified by the Samarra 2 group) are easily recognised, due to their high K₂O/P₂O₅, MgO/CaO, Li/Na₂O and Cr/La ratios. Egyptian glasses (Islamic glass weights) tend to have the highest share of heavy elements reflected in some of the lowest Th/Zr and La/TiO₂ ratios. A sub-group of Egyptian plant ash glasses has elevated B/Na₂O ratios, the implications of which need further investigation. Levantine plant ash glasses (Tyre-type) usually have the lowest heavy elements values and slightly higher K₂O/P₂O₅ ratios compared to Egyptian glasses. Both the Levantine and Egyptian groups have on average lower magnesia to lime ratios than glasses from the other production zones, with the exception of Sicilian glass. Islamic plant ash glass from Sicily differs from eastern Mediterranean groups in terms of their higher lithium content relative to soda and a distinct zirconium to titanium signature. The two remaining groups from Central Asia and the Iberian Peninsula exhibit greater compositional variability in relation to the silica source and are still not sufficiently well established. In terms of the fluxing agent, Iberian plant ash glass has some of the lowest potash contents in relation to phosphorus, whereas their magnesia levels can be quite high, resulting in magnesia to lime ratios not dissimilar to those of Mesopotamian and Central Asian assemblages (Fig. 78a). The Iberian plant ash glasses, together with Sicilian samples, tend to have the highest Li/Na₂O ratios,

again reflecting differences in the plant ash component or working processes. There are some notable compositional similarities between the Iberian and Central Asian glasses in that both regional productions can have relatively high alumina and thorium concentrations (Fig. 78c-d). These commonalities were unexpected, but in all likelihood a material link can be excluded due to the geographical distance involved.

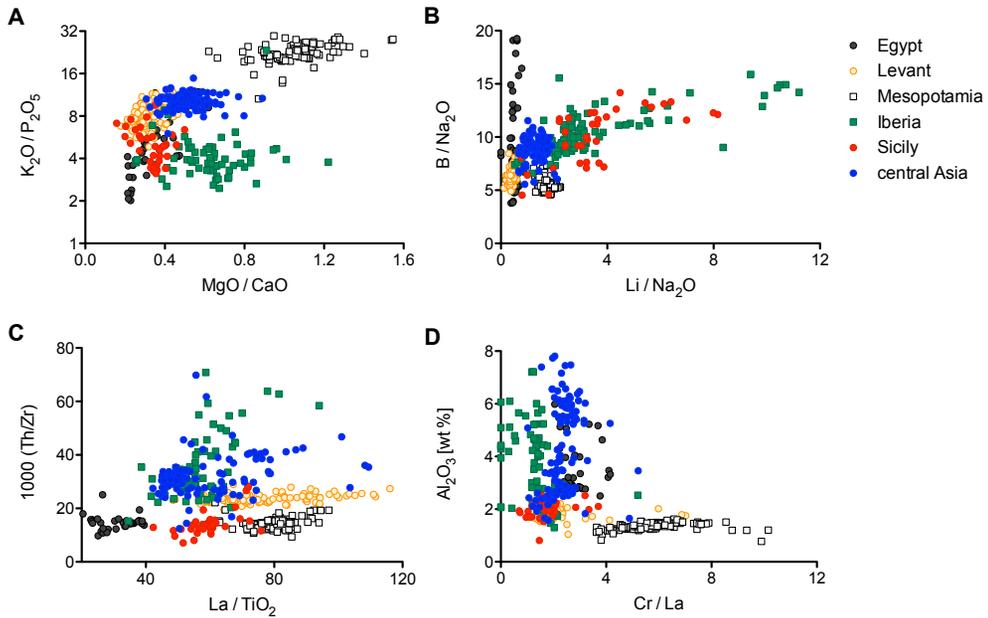


Fig. 78:

Compositional discriminants between the six major plant ash glass production regions. (a) K_2O/P_2O_5 and MgO/CaO ratios define differences in the plant ash component; (b) B/Na_2O and Li/Na_2O confirm regional differences in the fluxing agent and/or working processes; (c) Th/Zr and La/TiO_2 ratios clearly separate the different plant ash glasses in terms of the silica source; (d) elevated Cr/La ratios and low alumina contents distinguish Mesopotamian glasses from all other regional production groups. Note that for the sake of clarity the most conclusive assemblages from each region have been selected. Data sources: (Schibille *et al.* 2019) for Islamic glass weights E2, E3, E4; (Phelps 2018) for Tyre-type P1 Levantine plant ash glass; (Schibille *et al.* 2018a) for Samarra 2; (De Juan Ares and Schibille 2018) for Vascos 3 & 4; (Schibille and Colangeli 2021) for Sicilian plant ash glass; (Meek *et al.* in preparation) for Merv.

In general, it is much easier to determine compositional differences than to demonstrate identity between individual production groups. For instance, it is at present not possible to define strict thresholds of thorium to zirconium ratios between the Iberian and Central Asian plant ash glasses and Levantine glass because of the large compositional variability of both Iberian and Central Asian production groups. However, at ratios of thorium to zirconium above 30 ($1000 \times Th/Zr > 30$)

it is reasonably safe to assume that the glasses are not Levantine. Below this value, other criteria such as the lithium, phosphorus and magnesium contents need to be consulted. Given the heterogeneity of the Iberian and Central Asian glasses with regard to silica-related elements, some of which vary over one order of magnitude, these two regional groups still need to be further refined and defined more precisely. What transpires from this cursory survey is that none of the criteria alone is sufficient to assign glass to a specific regional production group. Instead, all the criteria should be taken into account, both in the negative (to exclude possible associations) and in the positive (to support identity).

The identified compositional discriminants of plant ash glass assemblages highlight the need for a multidimensional comparison of a range of trace elements, particularly zirconium, thorium, lanthanum, titanium and chromium, in addition to elements associated with the fluxing agent, such as lithium, potassium, phosphorus, magnesium and calcium. Using a large-scale approach based on high-resolution compositional data where available, this study has thus revealed significant regional differences in the organisation and scope of the glass industry alongside more global developments and changes in economic connectivity and interregional exchange. Many of the transformations began as early as shortly after the disintegration of the Western Roman Empire in the fifth century, but gathered pace after the Arab conquest, as commercial activities shifted to Damascus and the Bilâd al-Shâm in the late seventh century. The caliphal focus on Damascus manifested itself, for instance, in the import of large consignments of glass tesserae for the mosaic decoration of the Great Umayyad Mosque of Damascus and various palatial residences. This illustrates the gradual and steady demise of Levantine natron-type glassmaking as opposed to the still flourishing Egyptian primary glass industry based on the exploitation of mineral natron sources. For the first time large quantities of Egyptian glasses arrived in the Levant which had been mostly self-sufficient and which fed a global late antique glass market. It must be conceded that mosaic tesserae may represent a special case and that the full scale and impact of glass imports including vessel glass to the Levant remains to be determined. However, there is evidence that by the mid-eighth century Egyptian imports had gained the upper hand over local production in Syria-Palestine.

Two and a half centuries later, the trade in glass was in the opposite direction, when Tyre-type plant ash glasses were used for the production of Egyptian glass weights during the Fatimid period in the late tenth century. In the meantime, the glass industry in the Levant had evidently recovered, changes which may have been driven by innovations in the technology of glass manufacture and the use of plant ash as the main fluxing agent. The archaeological and compositional evidence suggests that this new glassmaking recipe may have been inspired by

Mesopotamian glassworkers who were brought to places like al-Raqqa where they established primary and secondary glass workshops. At al-Raqqa, plant ash glasses belonging to the Raqqa 1 and Raqqa 4 groups seem to have been produced concurrently after the city had been chosen as the caliphal residence in 796 CE, making Raqqa 1 the earliest known Islamic plant ash glass of the Syro-Palestinian type, characterised by moderate magnesia and potash concentrations. Soon afterwards, several compositional plant ash groups were in circulation. In Mesopotamia glassmaking continued, using old Sasanian traditions and local raw materials. The characteristics of the ninth- to eleventh-century glass finds from Siraf show the adoption of different plant ashes or ashing processes, implying a certain degree of globalisation in the glassmaking technologies across the Islamic world.

The temporal scale of Egyptian glassmaking follows a different course, possibly as a result of the decentralised administrative system of the Umayyad and Abbasid caliphates and Egypt's relative independence for about a century, between 868 and 969 CE. Fatimid glass weights from the last quarter of the tenth century are the earliest securely dated plant ash groups attributed to an Egyptian provenance. Although the earlier production of plant ash glasses cannot be ruled out, natron glasses were still manufactured in the second half of the ninth century, until about 870 CE, providing a *terminus post quem* for the large-scale production of plant ash glasses in Egypt. This coincides with the restrictions on the extraction of natron imposed by the then director of finances, Ibn al-Mudabbir. Be this as it may, the transition to plant ash glassmaking occurred much later in Egypt than in the Levant, a fact which can be explained at least in part by the presence of natural natron deposits in Egypt. The start of a systematic production of plant ash glasses in Egypt seems to be related to the establishment of the Fatimid Caliphate and the emergence of Cairo as the capital in the last quarter of the tenth century, giving rise to a new dynamism in the Egyptian glass industry.

The main difference between the traditional glassmaking regions and the more marginal production zones in Central Asia, the Iberian Peninsula and Sicily may have been the scale of production and the range of the distribution networks. The manufacture of glass in Egypt, the Levant and Mesopotamia occurred on a much larger scale, at least in the early stages of Islamic glassmaking until the eleventh century CE. Judging from the heterogeneity of glass assemblages in eastern Iran/Central Asia, the Iberian Peninsula and Sicily, the volume of production in these regions must have been significantly smaller. Nothing is known about the beginnings of primary glass production in Central Asia. By contrast, the compositional characteristics of glass assemblages in al-Andalus bear witness to Iberian glassmaking innovations between the second half of the eighth century and

the first quarter of the ninth century in the form of lead slag glass. Soda-ash lead glasses and a local plant ash glassmaking technology were subsequently developed in the Iberian Peninsula. In parallel, finished glass objects were still being imported from the eastern Mediterranean, especially from the Levant and Mesopotamia, demonstrating that the Iberian market began to play an increasing role. Egyptian plant ash glasses are rarely found. By the tenth century the production of soda-rich plant ash glass in the Islamic tradition appears to have been firmly established in the Iberian Peninsula and Sicily alike. The distribution and possible production of plant ash glass in the Maghreb remains a missing piece in the jigsaw puzzle of the Mediterranean glass industry.

Geopolitical trends may consistently have had an impact on the production of and trade in glass. The emergence of Damascus as the caliphal capital, accompanied by the commissioning of numerous monumental building campaigns, evidently changed commercial patterns and the circulation of vitreous materials. The foundation of new caliphal residences in Greater Syria and Mesopotamia but also in the Iberian Peninsula appears to have triggered an intensification of local industrial activities. When the centre of political and economic power shifted from Damascus to Baghdad after the Abbasid revolution of 750/751 CE, the western Mediterranean region was at first marginalised, causing shortages in the supply of glass from the east. This in turn may have stimulated the invention of lead glassmaking in Iberia, possibly in response to an increasingly independent Umayyad Emirate that had been established in al-Andalus. The early Islamic glass economy thus underlines the connectivity and divisions of the Islamic world on a regional and global level, and begins to reveal the diverse economic, political and cultural mechanisms that have shaped the transformations of the glass industry.

The interconnectivity of the early Islamic world makes the complete lack of analytical data from the Maghreb particularly acute. The corridor of communication extended from the southeastern corner of al-Andalus, along the northern shores of the Maghreb to the central Islamic regions in the east. At the risk of opening a can of worms, the current definition of Egyptian, Iberian and Sicilian plant ash glasses makes assumptions based on incomplete data. There is no way of knowing what role, if any, the Maghreb played in the introduction of plant ash glassmaking in the western Mediterranean or its re-introduction in Egypt. A broad and systematic study of glass assemblages from northern Africa is sorely needed to bring into focus the commercial and technological relationships among different regions of the early Islamic Mediterranean and beyond. This requires the largest possible dataset and large-scale comparative studies of well-dated and contextualised assemblages with high-resolution analytical methods. The integration of these

data into the framework presented here can complement and ultimately modify and refine our geographical and chronological model of the early Islamic glass industry. There is still plenty of research to be done.

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The ancient glass industry changed dramatically towards the end of the first millennium. The Roman glassmaking tradition of mineral soda glass was increasingly supplanted by the use of plant ash as the main fluxing agent at the turn of the ninth century CE. Defining primary production groups of plant ash glass has been a challenge due to the high variability of raw materials and the smaller scale of production. *Islamic Glass in the Making* advocates a large-scale archaeometric approach to the history of Islamic glassmaking to trace the developments in the production, trade and consumption of vitreous materials between the eighth and twelfth centuries and to separate the norm from the exception. It proposes compositional discriminants to distinguish regional production groups, and provides insights into the organisation of the glass industry and commerce during the early Islamic period. The interdisciplinary approach leads to a holistic understanding of the development of Islamic glass; assemblages from the early Islamic period in Mesopotamia, Central Asia, Egypt, Greater Syria and Iberia are evaluated, and placed in the larger geopolitical context. In doing so, this book fills a gap in our current knowledge of the history of Islamic glass.

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