Trade and glass production in Early Medieval Italy, England, and Denmark (late 6th - 11th century AD): compositional and isotopic analysis.

Camilla Bertini (BA, MA, MSc)

Thesis submitted to the University of Nottingham

for the degree of Doctor of Philosophy

April 2018

Abstract

Previous studies on Early Medieval Western European glass (Henderson, 1995b, 2000; Brill, 2006; Freestone and Hughes, 2006; Gaut, 2011; Willmott and Welham, 2015) suggest that natron-based raw glass and cullet were potentially made at the same workshops that were responsible for glass primary production during the Roman and Late Byzantine periods (Gorin-Rosen, 1995; Nenna et al., 1997; Freestone and Gorin-Rosen, 1999; Freestone et al., 2000; Freestone et al., 2002). Moreover, in Northern Italy plant ash-based glass (Verità and Toninato, 1990; Verità et al., 2002) is recognised in the same period as the natron to plant ash transition was occurring at the primary production workshops where such composition was originally produced (Henderson et al., 2004).

The fore mentioned analytical studies suggest a direct contact with the Levantine area for the Early Medieval period, but it has not been proven with certainty until now. Recycling and mixing practices at secondary glass workshops in Western Europe have also been investigated. Secondary workshops represent an intermediate hub between primary glass-making and the final distribution area of the finished objects, and therefore a unique chance to investigate secondary glass-working processes (recycling and mixing) that altered the original primary glass recipes at the very same place they were occurring.

To explore further the provenance of Early Medieval Western glass and secondary glass-working practices, three secondary workshops dated between the late 6th and 11th century AD have been analysed in this thesis: Comacchio (Northern Italy), Barking Abbey (England), and Ribe (Denmark).

A combination of EMPA-WDS (n= 201) and LA-ICP-MS (n= 141) analyses are used to investigate the characteristics of recipes traded between the late 6th and 11th century in these three workshops and

potentially redistributed locally together with mixing and recycling practices. Trace elements also provide a means to recognise mixing practices between non-recycled end-members.

Isotopic analysis has been previously successful in identifying the provenance of earlier dated Western glass materials and linked with primary production workshops (Degryse and Schneider, 2008; Degryse et al., 2009b; Ganio et al., 2012; Gallo et al., 2014; Degryse, 2014; Maltoni et al., 2015).

For the first time Sr and Nd isotopic analysis (55 and 39 samples respectively) are applied to Early Medieval Western European glass materials, with the aim to trace the provenance of their raw materials and link them to the primary workshops in the Levant and in Egypt. The potential of Sr and Nd isotopes in underlined mixing practices are also explored.

This thesis will argue for difference in both not only basic recipes, but also in secondary glass-making practices between the three sites, which both potentially mirror the use of different trade routes to move raw glass and cullet in the three areas studied.

Keywords: Early Medieval glass, Western European glass, EMPA analysis, LA-ICP-MS analysis, provenance glass studies, Sr isotopic analysis, Nd isotopic analysis, recycled glass, secondary glass-working practices, plant ash glass, natron glass, Barking Abbey, Comacchio, Ribe.

Acknowledgments

This thesis could not have been written without the assistance or support of a number of other people.

I would like to express my deep appreciation to both Professor Julian Henderson and Professor Christopher Loveluck for their constant academic and mental support, cooperation, constructive feedback as well as all the opportunities they offered me.

The project would not have been possible without the financial assistance of the Arts and Humanities Research Council, who paid for my tuition fees, and the Natural Environmental Research Council, who awarded me the grant to perform isotope analyses on my samples.

Dr. Simon Chenery and Professor Jane Evans have provided the best training and guidance I could ever hope with my LA-ICP-MS and isotopic analysis, and I feel extremely grateful for the opportunity that they gave to me. I am also thankful to all the Bgs community that made me feel welcome throughout my stay.

I could not forget to mention both Dr. Chrysanthi Gallou and Dr. Caroline Chenery, which have both provided me not only with their precious guidance and mentoring but also with their kind words when I was feeling low and stuck with my research.

I am grateful to Professor Sauro Gelichi (Ca Foscari University) that has been generous in allowing the taking of samples from his excavations at Comacchio – Piazza XX Settembre and the Newham Museum for lending me Barking Abbey glass samples. I also express gratitude to Dr. Grandi and Ferri for providing useful information on Comacchio settlement and glass material context.

I also would like to thank Dr. Will Bowden for being my second supervisor for the first part of my PhD, and Dr. Edward Faber that has lent his expertise in training me in sample preparation, the use of analytical

equipment during my MSc and the first year of my PhD at the University of Nottingham. I am equally indebted to the community of staff and postgraduates at the University of Nottingham for welcoming me five years ago when I moved to the Uk.

To Caterina, Giulia, Federica, Laura, Linda, Marianna, MariaGrazia, Solenn, and Vassia: you all provided me with endless encouragement and the greatest inspiration. Every day you remind me what strong and empowered women can accomplish with their brilliant minds and resilience.

To my all my friends that encouraged me along the way, you are too many to mention: I am grateful for all the support and encouragement you have all provided me during this difficult (but rewarding) time.

To my parents that supported me along the whole way, despite not understanding why their peculiar daughter persisted in wanting to be an archaeologist and a scientist. Questa tesi non esisterebbe senza il vostro supporto e spero che siate orgogliosi di quello che sono riuscita a creare.

To my friend that a long time ago doubted that “my mind was suitable to produce any kind of scientific research”, this dissertation proves you wrong.

Table of Contents

Title page I

Abstract II

Acknowledgements IV

Contents VI

List of figures IX

List of tables XIV

1 Introduction 1

1.1 Background 1

1.2 Aims and research questions 2

1.2.1 Aims and objectives 2

1.2.2 Research questions: 3

1.3 Thesis structure 9

2 Frameworks of interpretation for secondary glass production and trade of glass as raw materials and finished vessels in Western Europe between the late 6th and the 11th century AD. 11

2.1 Introduction 11

2.2 Glass as a material 14

2.2.1 Glass raw materials 17

2.3 Basic framework for interpretation of glass production's network 27

2.3.1 Definition of primary and secondary production 27

2.3.2 Glass making and working material evidence 28

2.3.3 Evidence for primary production between 7th and 11th century AD. 30

2.3.4 Glass trade evidence during Roman and Early Medieval period. 33

2.3.5 Some considerations on glass recycling 36
2.3.6 Models for glass production: centralised vs. local 39
2.4 Glass working evidence in Western Europe: Italy, England, and Southern Scandinavia. 42
2.4.1 Italy 43
2.4.2 Britain 48
2.4.3 Northern Europe 60
2.5 Previous analytical work 65
2.5.1 Recent trends in Byzantine and Early Medieval glass studies 65
2.5.2 Early Medieval glass analysis in Northern Italy, UK, and Denmark 74
2.6 Further considerations concerning the centralised model and glass trade 87
2.6.1 Revising the centralised model and new model suggestion 87
2.6.2 Summary and issues with movement of glass and production: a localised matter 91
3 Archaeological context and dataset description. 97
3.1 Introduction 97
3.2 Comacchio 97
3.2.1 Archaeological context 97
3.2.2 Comacchio glass dataset description 110
3.3 Barking Abbey 118
3.3.1 Archaeological context 118
3.3.2 Barking glass dataset 124
3.4 Ribe (8th-9th century AD) 132
3.4.1 Archaeological context 132

3.4.2 Ribe glass dataset 148
3.5 Summary and dataset limitation 151
4 Methodology 152
4.1 Introduction 152
4.2 Compositional analysis.....154
4.2.1 Sample preparation 154
4.2.2 Electron microprobe (EMPA) 155
4.3 Mass spectrometry.....166
4.3.1 Laser ablation Inductively Coupled Plasma Mass Spectrometry (LA-ICP-MS).....168
4.3.2 Isotopic analysis 175
4.4 Summary.....183
5 Results and discussion 185
5.1 Compositional analysis.....185
5.1.1 Comacchio.....188
5.1.2 Barking Abbey 226
5.1.3 Ribe 260
5.1.4 Summary compositional analysis.....283
5.2 Isotopic analysis.....293
5.2.1 Sr isotopes.....294
5.2.2 Nd isotopes.....309
5.2.3 Summary isotopic analysis. 319
6 Conclusions 325
7 Bibliography 338

List of figures

Figure 1 - Covalent bonds between silicon and oxygen atoms 14
Figure 2 - Basic Si-O tetrahedron in silicate glass……14
Figure 3 - Two-dimensional representation of hypothetical crystalline compound A_2O_3 15
Figure 4 - Simplified model of a typical Roman glass 16
Figure 5 – Western Europe and Levant map. 30
Figure 6 – Italian peninsula map. 43
Figure 7 – Southern England map. 48
Figure 8 – Southern Scandinavia map. 60
Figure 9 - CoO vs. Sb_2O_5 oxide in blue glasses from San Vincenzo al Volturno 76
Figure 10 - P_2O_5 vs. K_2O contents in Torcello glass samples. 77
Figure 11 - K_2O vs. MgO contents in Santa Maria Assunta glass samples,Torcello 78
Figure 12 - P_2O_5 vs. K_2O contents in Northern Italian glasses 80
Figure 13 - K_2O vs. MgO contents in Nogara glasses. 81
Figure 14 - Na_2O vs. K_2O contents in white, blue, and green soda-lime-silica glasses from Kaupang. 86
Figure 15 - Model suggestion for trade, mixing, and recycling or raw glass. 89
Figure 16 - Al_2O_3 vs. CaO contents in glass from Hamwic, Dorestad, and Helgo 94
Figure 17 - Na_2O vs. CaO contents in glass from Hamwic, Dorestad, and Helgo 95
Figure 18 - Comacchio, Villaggio San Francesco: hypothetical reconstruction of communications routes according to harbour location. 98
Figure 19 - Wooden waterfront structure, Villaggio San Francesco. . 101
Figure 20 - Comacchio Piazza XX Settembre: 2006-2008 excavation 103

Figure 21 - Piazza XX Settembre, workshop planimetry, phase 1..... 105
Figure 22 - Piazza XX Settembre, workshop planimetry, phase 2..... 106
Figure 23 - Hypothetical planimetry of the XI century Episcopal Church in Comacchio 108
Figure 24 - Comacchio glass dataset chronology..... 111
Figure 25 - Comacchio glass dataset arbitrary typology..... 113
Figure 26 - Comacchio glass fragments divided by colour. ……114
Figure 27 - Decorated goblet with multiple trails of opaque glass (Com96). 114
Figure 28 - Crucible with layer of green translucent and red opaque glass (Com 93 and 94)..... 115
Figure 29 - Crucible with layer of green translucent and a small area of red opaque glass (Com 30 and 31). 115
Figure 30 - Mosaic tesserae from Comacchio (Com69 and 70).. 116
Figure 31 - Barking Abbey: 1985 planimetry excavations..... 121
Figure 32 - Barking Abbey: 1990 planimetry excavations..... 123
Figure 33 - Barking Abbey, glass kiln 124
Figure 34 - Barking Abbey glass dataset arbitrary typology. 125
Figure 35 - Barking Abbey glass-working samples divided by category 126
Figure 36 - Barking Abbey samples divided by colour..... 127
Figure 37 - Deformed waster connected with vessel glass production (Ba53)..... 128
Figure 38 - Waster from millefiori rod production (Ba81) 128
Figure 39 - Residual iron layer from the gathering iron (Ba5)..... 129
Figure 40 - Waster from millefiori rod production (Ba10). 130
Figure 41 - Waster from millefiori rod production, chequered pattern (Ba01)..... 130
Figure 42 - Reticella rod deformed at its right extremity, waster from local glass-working manufacture (Ba2). 130
Figure 43 - Map of modern Ribe together with updated excavations and trial trenches up to 1976. 133
Figure 44 - Ribe, Northern side, map of 1970-76 excavations 135

Figure 45 - Reconstruction of the layout of the 8th to early 9th century plot system at the market-place in Ribe 138
Figure 46 - Comparison of the three different systems for division of the market-place layers into phases 141
Figure 47 – Ribe glass dataset typology..... 148
Figure 48 – Ribe glass chronology 149
Figure 49 - Ribe glass fragments divided by colour. 150
Figure 50 - Schematic diagram of an electron microscope with a WD-X-ray detector 156
Figure 51 - Interaction of a beam of primary electrons with a thin solid sample 157
Figure 52 - X-ray emission schematic representation..... 158
Figure 53 - Al_2O_3 contents by EMPA and LA-ICP-MS results in glass from Barking Abbey, Comacchio, ad Ribe. 164
Figure 54 - MgO contents by EMPA and LA-ICP-MS results in glass from Barking Abbey, Comacchio, and Ribe. 165
Figure 55 - SnO_2 contents by EMPA and LA-ICP-MS results in glass from Barking Abbey, Comacchio, and Ribe. 165
Figure 56 - Schematic diagram of a 60°-sector mass spectrometer .. 167
Figure 57 - Schematic diagram of a quadrupole ICP–MS 170
Figure 58 - Cluster analysis for Comacchio glass. 189
Figure 59 - PCA of Comacchio glass dataset 189
Figure 60 - Schematic representation of the contribution of each variable to the principal components (1 and 2) in Comacchio glass. 190
Figure 61 - MgO versus K_2O contents for glass from Comacchio 192
Figure 62 - SiO_2 versus Na_2O contents for glass from Comacchio.... 192
Figure 63 - Al_2O_3 versus Fe_2O_3 contents for glass from Comacchio . 193
Figure 64 – Al_2O_3 versus Fe_2O_3 contents in group 1 and 2: iron oxide content and its correlation with alumina..... 194
Figure 65 - Al_2O_3 versus CaO contents for glass from Comacchio.... 195
Figure 66 - Fe_2O_3 versus TiO_2 contents for glass from Comacchio in group 1A, 1B, 1C, 2A, 2B, and group 3. 199
Figure 67 - SiO_2 versus Na_2O contents for glass from Comacchio.... 200

Figure 68 - CaO/Al_2O3 vs. Na_2O/SiO_2 ratios in Comacchio glass dataset (comparisons),..... 203
Figure 69 - MnO vs. Sb_2O_5 contents for Comacchio translucent glass 204
Figure 70 - MnO vs. Sb_2O_5 contents for Comacchio translucent glass divided by colour..... 205
Figure 71 - Cu vs. Pb in a selected group of samples from Comacchio glass dataset 206
Figure 72 - Cu vs. Pb concentrations in a selected group of samples from Comacchio glass dataset, divided by colour..... 207
Figure 73 - Cu vs. Co concentrations in a selected group of samples from Comacchio glass dataset, divided by colour..... 208
Figure 74 –K_2O and P_2O_5 contents in glass from Comacchio..... 209
Figure 75 - Zr/SiO_2 and Ce/La ratios of Comacchio glass groups (comparisons)..... 212
Figure 76 - Zr/SiO_2 and Sr/CaO ratios of Comacchio glass groups dataset (comparisons)..... 213
Figure 77 - Concentration of trace elements normalized to the upper continental crust (Kamber et al. 2005) for a selection of elements in group 1A, 2A, and 3 of Comacchio glass..... 215
Figure 78 - Concentration of trace elements normalized to the upper continental crust (Kamber et al. 2005) for a selection of elements in group 1A, 2A, and 3 of Comacchio glass and comparison materials..... 216
Figure 79 - Concentration of trace elements normalized to the upper continental crust (Kamber et al. 2005) for a selection of elements in Comacchio group 2B and 8 and comparison materials.. 217
Figure 80 - Concentration of trace elements normalized to the upper continental crust (Kamber et al. 2005) for a selection of elements in Comacchio group Foy 2 (2B) and suggested mixed samples (group 1B, 1C, 2C). 217
Figure 81 - Concentration of trace elements normalized to the upper continental crust (Kamber et al. 2005) for a selection of elements in

Comacchio Levantine groups (1A, 2A, and 3), group Foy 2 (2B) and suggested mixed samples (group 1B, 1C, 2C). 217
Figure 82 - Fe versus Cr concentrations (mg/kg) in Comacchio group 4 – plant ash..... 218
Figure 83 - Cr/La versus 1000Zr/Ti ratios in Comacchio group 4 – plant ash (logarithmic scale). Comparison material after Henderson et al., 2016. 219
Figure 84 - Li/K versus Cs/K ratios in Comacchio group 4 – plant ash. 219
Figure 85 - Cluster analysis for Barking Abbey glass. 226
Figure 86 - PCA of Barking Abbey glass dataset. 227
Figure 87 - Schematic representation of the contribution of each variable to the principal components (1 and 2) in Barking Abbey glass. 227
Figure 88 - MgO versus K_2O contents for glass from Barking Abbey 228
Figure 89 - MgO versus K_2O contents for glass from Barking Abbey glass (no group 4, Ba24 and 27)..... 229
Figure 90 - SiO_2 versus Na_2O contents for glass from Barking Abbey glass. 230
Figure 91 - Al_2O_3 versus CaO contents for glass from Barking Abbey glass. 231
Figure 92 - Al_2O_3 versus CaO contents for glass from Barking Abbey glass (no group 4)..... 231
Figure 93 - Al_2O_3 versus Fe_2O_3 contents for glass from Barking Abbey 232
Figure 94 - Al_2O_3 versus CaO contents for glass from Barking Abbey glass (no group 4)..... 233
Figure 95 -Fe_2O_3 versus TiO_2 contents for Group 1, 2, and 3 from Barking Abbey. 237
Figure 96 - Al_2O_3 versus Fe_2O_3 contents for Barking Abbey group 1 and 3 (comparisons)..... 240
Figure 97 –SiO_2 versus Na_2O contents for Barking Abbey group 1 and 3 (comparisons)..... 241

Figure 98 - Cao/Al_2O_3 versus Na_2O/SiO_2 ratios for Barking Abbey groups based on cluster analysis. 242
Figure 99 - CaO/Al_2O_3 vs. Na_2O/SiO_2 ratios for Barking Abbey group 4 (comparisons).. 243
Figure 100 - Al_2O_3 vs. CaO contents for Barking Abbey groups (comparisons).. 244
Figure 101 - MnO vs. Sb_2O_5 contents for Barking Abbey translucent glass. 245
Figure 102 –Cu vs. Pb concentrations in a selected group of samples from Barking Abbey glass dataset, ... 246
Figure 103 - Sn vs. Pb concentrations in a selected group of samples from Barking Abbey glass dataset 248
Figure 104 –PbO vs. Sn_2O contents in Barking Abbey glass. 249
Figure 105 - Sn vs. Cu concentrations in a selected group of samples from Barking Abbey glass dataset 250
Figure 106 - Zr/SiO_2 and Ce/La ratios of Barking Abbey glass groups dataset (comparisons).. 251
Figure 107 - Zr/SiO_2 and Sr/CaO ratios of Barking Abbey glass groups dataset (comparisons). 252
Figure 108 - Concentration of trace elements normalized to the upper continental crust (Kamber et al. 2005) for a selection of elements in group 1,2,3 and 4 of Barking Abbey glass and comparison materials. 253
Figure 109 – Rb and Sr concetrations of glass from Barking Abbey (comparisons).. 254
Figure 110 - Cluster analysis for Ribe glass. 260
Figure 111 - PCA of Ribe glass dataset.. 261
Figure 112 - Schematic representation of the contribution of each variable to the principal components (1 and 2) in Ribe glass.. 261
Figure 113 - MgO versus K_2O contents for glass from Ribe 262
Figure 114 - SiO_2 versus Na_2O contents for glass from Ribe. 263
Figure 115 - Al_2O_3 versus Fe_2O_3 contents for glass from Ribe. 264
Figure 116 - Fe_2O_3 versus TiO_2 contents for glass from Ribe. 265
Figure 117 - Al_2O_3 versus CaO contents for glass from Ribe 265

Figure 118 - Al_2O_3 versus Fe_2O_3 contents for glass from Ribe (HIMT). 268
Figure 119 –CaO vs. Al_2O_3 contents for Ribe glass groups (comparisons) 269
Figure 120 –Al_2O_3 vs Fe_2O_3 contents for Ribe glass groups (comparisons)..... 270
Figure 121 - Al_2O_3 vs Fe_2O_3 contents for Ribe glass groups (comparisons)..... 271
Figure 122 - Al_2O_3 vs. CaO for Ribe glass groups (comparisons). 272
Figure 123 –CaO/Al_2O_3 vs. Na_2O/SiO_2 ratios for translucent and opaque mosaic tesserae from Ribe and Comacchio (comparisons). 272
Figure 124 - CaO/Al_2O_3 vs. Na_2O/SiO_2 ratios for translucent and opaque mosaic tesserae from Ribe and Comacchio (comparisons). 273
Figure 125 - Zr/SiO_2 and Ce/La ratios of Ribe glass groups (comparisons)..... 275
Figure 126 - Zr/SiO_2 and Sr/CaO ratios of Ribe glass groups (comparisons)..... 276
Figure 127 - Concentration of trace elements normalized to the upper continental crust (Kamber et al. 2005) for a selection of elements in Ribe glass groups and comparison materials. 277
Figure 128 - Zr/SiO_2 and Ce/La ratios of Ribe glass divided by colour (comparisons)..... 278
Figure 129 - Zr/SiO_2 and Sr/CaO ratios of Ribe glass divided by colour (comparisons)..... 278
Figure 130 - K_2O vs. MgO contents in Comacchio, Barking Abbey, and Ribe glass..... 284
Figure 131 - SiO_2 vs. Na_2O contents in Comacchio, Barking Abbey, and Ribe glass..... 284
Figure 132 - Al_2O_3 vs. Fe_2O_3 contents in Comacchio, Barking Abbey, and Ribe glass..... 285
Figure 133 - Strontium isotope results for Comacchio glass. 295
Figure 134 - Sr isotopes and strontium concentration in Comacchio group 4 and Middle Eastern plant ash.. 297

Figure 135 - Sr isotopes and strontium concentration in Comacchio glass. 299
Figure 136 - Sr mixing diagram of Comacchio glass. 300
Figure 137 - Hypothetical mixing line between Com 60 (group 3) and Com74 (group 8). 301
Figure 138 - Hypothetical mixing line between Com 44 (group 3) and Com85 (group 2B). 302
Figure 139 - Hypothetical mixing line between Com 16 (group 1A) and Com65 (group 2C). 303
Figure 140 - Sr isotopes and strontium concentration in Comacchio group 4 (comparisons).. 304
Figure 141 - Strontium isotope results for Barking Abbey glass.. 305
Figure 142 - Sr isotopes and strontium concentration in Barking Abbey glass (comparisons. 307
Figure 143 - Sr isotopes and strontium concentration in Barking Abbey glass minus group 4 (comparisons). 308
Figure 144 - Neodymium isotope results for Comacchio glass dataset. 309
Figure 145 - Neodymium isotope results for Barking abbey glass..... 311
Figure 146 - Sr isotopes vs. εNd values in Levantine and HIMT glass from Comacchio (comparisons).. 314
Figure 147 –Sr isotopes vs. Nd isotopes in plant ash group 4 from Comacchio (comparisons). 315
Figure 148 –Sr isotopes vs. εNd values in Levantine glass from Barking Abbey (comparisons). 317

List of tables

Table 1 – Typical sand impurities, after Henderson, 2000, 27; 2013, 60. 19
Table 2 - Summary of objects and samples analysed in this dissertation divided by technique. 153
Table 3 - Known and measured values for Corning B (wt.%) for the first round of analysis. 161
Table 4 - Known and measured values for Corning B (wt.%) for the second round of analysis. 162
Table 5 – Measured and expected values (mg/kg), calculated St.Dev values, RSD and Bias values (%) of trace elements for standard reference glass NIST610 by LA-ICP-MS 173
Table 6 - Measured and expected values (mg/kg), calculated St.Dev values, RSD and Bias values (%) of trace elements for standard reference glass NIST610 by LA-ICP-MS. 174
Table 7 - Mean composition for unrecycled Comacchio groups 224
Table 8 - Mean composition for selected trace elements for Comacchio groups. 225
Table 9 - Mean composition for Barking Abbey groups. 258
Table 10 - Mean composition for selected trace elements for Barking Abbey groups 259
Table 11 - Mean composition for Ribe groups 281
Table 12 - Mean composition for selected trace elements for Ribe groups. 282
Table 13 – Number of isotopic analysis for each isotope divided by site. ……293

1 Introduction

1.1 Background

It has been widely accepted how glass production during Roman and Byzantine times was organised around a centralised model involving few centres located in the Eastern Mediterranean (Levantine coast and Egypt) close to the raw materials' sourcing areas (Nenna et al., 1997; Freestone et al., 2000; Degryse, 2014), while raw glass was redistributed to secondary centres across the whole Roman Empire (Foy et al., 2003). The existence of Western primary production centres during Roman and Late Byzantine periods has also been suggested (Degryse and Schneider, 2008; Ganio et al., 2012), but no primary workshops have been discovered so far.

In the 7th - 8th century AD, Levantine I and II composition were still produced in Palestine, while HIMT formula was produced in glass-making centres in Egypt, which location is still to discover to this day (Nenna, 2014).

Analytical studies have concentrated principally in three areas of production: Northern Italy (Verità et al., 2002; Uboldi and Verità, 2003; Andreescu-Treadgold et al., 2006; Silvestri and Marcante, 2011), Southern England (Hunter and Heyworth, 1998; Freestone and Hughes, 2006; Willmott and Welham, 2015), and Scandinavia (Callmer and Henderson, 1991; Henderson, 2000, 1995a; Gaut and Skre, 2011).

The prevalence of the natron formula in the form of Levantine and HIMT compositions suggests that raw glass was traded between primary workshops and the Western Mediterranean also after the 7th century AD, but no provenance studies have been carried out on Early Medieval material dated between the late 6th and 11th century AD in Europe.

Moreover, analytical studies dedicated to secondary workshops/glass-working materials for the same time frame in the three areas are scarce (Callmer and Henderson, 1991; Henderson, 2000; Verità et al., 2002; Gaut and Skre, 2011; Paynter et al., 2014) or not fully published (Willmott and Welham, 2015).

The importance of secondary workshops lies in their being an intermediate hub between primary glass-making and the final destination area of the finished objects. Both raw glass and cullet would have been potentially gathered in these workshops to be worked and redistributed where needed. Therefore, these three datasets represent a unique chance to examine glass movement from local and long-distance trade and to investigate secondary glass-working processes (recycling and mixing) in the very same place they were occurring.

The analytical study included in this dissertation focused on Comacchio, Barking Abbey, and Ribe secondary glass workshops has the primary aim to fill these gaps.

1.2 Aims and research questions

These are the aims, objectives and research questions this project endeavours to investigate and answer:

1.2.1 Aims and objectives

- To chemically analyse glass from three Early Medieval secondary workshops in Comacchio, Barking Abbey, and Ribe and compare the results.
- To use strontium and neodymium isotopes to assess raw materials used in recycled and un-recycled glass from Comacchio

and Barking Abbey. To use the results to assess Western glass provenance and suggests potential glass production frameworks in Northern Italy and Southern England.

- To extend the use of isotopic analysis to characterise the isotopic signatures for Western European glass.

1.2.2 Research questions:

Glass production in the early medieval West deals with at least four broad research themes: composition, raw materials, production, and provenance. These themes are obviously interconnected between them, because every composition is strongly dependant from the raw materials used and the associated production process, as well as glass provenance is directly interconnected with the diagenetic processes influencing the raw materials formation and alteration. Hence, all research questions should always be considered in a broader context. However, for the purpose of this chapter I will present them separately below.

1.2.2.1 Composition and raw materials

The broad term of composition refers to all the chemical compounds characterising one recipe (such as Levantine, HIMT, and similia). The different percentage of major, minor, and trace elements creates a unique fingerprint that mirrors the use of certain raw materials. By defining Comacchio, Barking Abbey, and Ribe compositions, we will be able to make assumptions concerning of the choice of raw materials and the potential area of production of these recipes, based on the comparison with already published dataset. The area of production should not be confused with the area of provenance of such glass. The two concepts are interconnected, but they express a different concept of origin.

The definition of recipe (such as Levantine or HIMT), represents an abstract definition that helps to identify a specific group of glasses having the same compositional characteristics, but it does not reflect directly the raw materials sourcing area. On the other hand, it mirrors the primary workshop (or furnace) where the glass has been produced (production area), as a reflection of the technological choices operated by the artisans in that moment (raw materials, colourants and decolourants, opacifiers, other processes such as mixing and recycling, fritting, or purification processes). It therefore provides geographical provenance (Henderson, 2013, 327). Therefore, each batch is also unique (Henderson, 2013, 319), and it will reflect the time and place where it was produced.

Some research questions connected with composition include:

- Which compositions were produced and were circulating at the time in Comacchio, Barking, and Ribe?
- How such compositions compare to the ones already known from the published literature (HIMT, weak HIMT, and Levantine)?
- Can we assign a hypothetical area of production (Levant? Egypt? Middle East? Other?)
- Have any colourants/de-colourants been added on purpose in any of Comacchio, Barking Abbey, and Ribe recipes? If so, what colourants/de-colourants have been used?
- What about opacifiers? Is there any trace of opacifiers compounds within translucent glass? If so, what it is its significance?
- Can we register any unknown recipe? What is the significance of such composition within the other recipes?

1.2.2.2 Production

Production research questions will be based on mixing, recycling and contamination processes, and they will focus on understanding the

production of one or more specific object categories (such as rods, beads, mosaic tesserae, vessels, and others).

Some research questions connected with production processes include:

- Is there any composition directly link to a specific category object? If so, does it have any technological significance?
- Does any specific category object being produced by mixing two different compositions? Could it be a specialised production of that specific workshop?
- Does the difference in compositions mirror recycling or mixing processes?
- If mixed and recycling are present, which compositions have been affected by such practices?
- Is it possible to spot some contamination markers?

1.2.2.3 Provenance

The main aim for provenance study is to link the raw materials used to produce a specific glass composition to the area where such ingredients were originally sourced. Therefore, the main objective is to give an objective method to provenance such glass.

First and foremost, we need to clarify what the concept of provenance means in glass analysis. Wilson and Pollard (2001, 507- 8) suggest a series of six assumptions that we must take into account when approaching archaeological provenance studies. To summarise, to produce a successful provenance study using geochronology, the raw materials' characteristic fingerprint has to be related to the geographical occurrence of that raw material and such a fingerprint should mirror an inter-source variation to provide a clear geological signature of that area.

The fundamental assumption is that each piece of glass has been made from a definite set of raw materials previously sourced, but the area of

sourcing of these raw materials and the one of primary production might not necessarily match. The two concepts must remain separate. Ideally the raw materials were sourced from an area where they were easily accessible and economically advantageous to transfer them to the primary workshop.

The other basic assumption that it can be taken from Wilson and Pollard is that the recipes we are comparing should show contrasting geological signatures. If this is not the case, we would not be able to spot any variation in the geological ratios and, therefore proof of distinct provenance. Sr and Nd isotopic studies in the Levant area have proved to be diagnostic in this respect (Freestone et al., 2003; Henderson et al., 2005b, 2009; Leslie et al., 2006).

Having two different workshops like Comacchio and Barking Abbey as the objects of our study, the chance of getting materials with contrasting geological signatures potentially increase remarkably since they were able to get glass not only from other different sites and secondary workshops, but also from the re-use older material. Recycling and mixing represent a potential issue for our dataset. This issue will be discussed in chapter 2.

Some research questions connected with provenance of glass include:

- Where do the raw materials used for each specific composition come from?
- How do isotopic results compare with the compositional results and the supposed area of provenance?
- How do the hypothetical provenance results fit within the centralised model?
- Does any of the isotopic results overlap with any published results?
- Can isotopic results help with assessing the degree of recycling and mixing at the same time than provenance?

1.2.2.4 Focused research questions

1.2.2.4.1 Comacchio

Research questions concerning the Comacchio glass dataset focus around the Northern Italian context, and in particular on the early presence (7th-8th century AD) of plant ash, and recycling and mixing practices:

- How does Comacchio fit within the Northern Italy glass production context?
- Is glass from Comacchio similar to the few contemporary examples known from the South (Mirti et al., 2000, 2001; Schibille and Freestone, 2013)? Was glass travelling across Northern Italy and the whole Peninsula?
- Does Comacchio show an early presence of plant ash like Veneto (Verità et al., 2002)?
- If so, where was this plant ash was coming from? Could it have been traded from the Syria, as Raqqa is almost contemporary (8th – 9th century AD) to the Comacchio glass workshop (Henderson et al., 2004)?
- Does Comacchio show the presence of an intermediate composition between natron and plant ash like in Veneto (Verità et al., 2002; Silvestri and Marcante, 2011) and Lombardy (Uboldi and Verità, 2003)?
- Is Comacchio glass coming from the Levant?
- What impact has recycling in the Comacchio glass workshop, if there is any? Were some recipes recycled over others? And what is the significance of such experimentation?
- How did contamination from the crucibles and fuel ash impact the glass made in Comacchio?

- Were mosaic tesserae from Comacchio glass compositionally similar to the one produced in Byzantium as suggested for the one from Santa Maria Assunta (Andreescu-Treadgold et al., 2006)?

1.2.2.4.2 Barking Abbey

Research questions concerning the Barking Abbey glass dataset focus on understanding its provenance, given that no primary production has been to this day found in England. The aim is to understand if Barking glass is compositionally similar to the 1st – 3rd century Roman composition or to other contemporaneous recipes (like Levantine or HIMT). Understanding if any specialised production was occurring in Barking would also prove interesting, given the presence amongst its materials of many single rods, bi-cables, and millefiori rods. Finally, recycling and mixing practices have not yet been examined for Early Medieval material in England. The main research questions are:

- Does Barking Abbey glass show any compositional similarity with glass from the Levant and the Middle East?
- Is there any unusual composition being worked at Barking Abbey? What does this occurrence mean?
- Where do Barking glass raw materials come from?
- Does any specialised production, like monochrome rods or bi-cables, occur at Barking Abbey? If so, does such production show a different composition from the other glasses (vessel, cullet, raw glass)?
- What impact has recycling in the Barking Abbey glass workshop? Was Old Roman glass being recycled or were other contemporary recipes preferred (such as Levantine)?

1.2.2.4.3 Ribe

Research questions concerning the Ribe glass dataset focus on the provenance of its glass and in particular to understand if the “classic” Roman composition or contemporaneous recipes (like Levantine) were traded to Ribe marketplace. It has also been suggested in the past that mosaic tesserae in Ribe were traded from Northern Italy (Feveile, 2012). Comparing such tesserae with the one from Comacchio will allow us to finally address this matter. Recycling practices and the increment of certain major and trace elements significance (Henderson, 2000) also has not been explored fully in Ribe glass.

The research questions are:

- Does Ribe glass show any compositional similarity with glass from the Levant and the Middle East or is it more compositionally similar to earlier Roman glass?
- Is there any unusual composition being worked at Ribe? If so, what does this occurrence mean?
- What impact does recycling have in Ribe, if there is any? Has Old Roman glass been recycled or other contemporary recipes where preferred (such as Levantine)?
- Do mosaic tesserae from Ribe show a similar composition to the one found in Northern Italy as previously suggested? If so, what does such compositional similarity imply?

1.3 Thesis structure

This thesis is structured to give an introduction to the topic of glass production, the archaeological background, the methodology used, the analytical results produced by the three analytical methods, and finally the discussion and conclusions that can be inferred from this data.

For starters, Chapter 2 will present the framework for interpretation of Early Medieval glass production in Northern Italy, Southern England, and Scandinavia. This chapter is divided in five fundamental parts. Firstly, I will describe glass nature and its raw materials; in the second section, I will describe the nature of glass itself and the evidence for primary glass production in the Levant. I will then also discuss glass production evidence plus the previous analytical work on glass materials from the same area. In the last section, I will finally discuss the centralised mode together with some suggestions for revising the model itself.

In Chapter 3, the first section is dedicated to the archaeological context of Comacchio, Barking Abbey, and Ribe (excavation, history, and chronology). In the second section, I will describe the three datasets included in this thesis separately for each site. I will also discuss the limitation pertinent to this thesis.

The description of the basic methodology followed in this project such as sampling, the three different analytical techniques used, and reviews of previous work of trace elements and isotopic analysis will be described in chapter 4.

Chapter 5 is divided in two sections. The first is dedicated to compositional analysis (EMPA and LA-ICP-MS), while the second part instead focuses on Sr and Nd isotopic analysis. In the first section, results will be presented and discussed separately: basic glass compositions, comparison with known published data and recycling practices, together with their interpretation. In the second section, each isotope and a discussion of their meaning will be discussed separately.

Finally, chapter 6 will be dedicated to conclusions and further work.

2 Frameworks of interpretation for secondary glass production and trade of glass as raw materials and finished vessels in Western Europe between the late 6th and the 11th century AD.

2.1 Introduction

Archaeological and compositional evidence suggests that betweenthe Late Byzantine and Early Medieval periods primary production is only limited to the Levant coast (Gorin-Rosen, 1995;Freestone, 2002; Freestone et al., 2000; Oren Tal et al., 2004), Syria (Henderson, 1995b, 1999), and Lebanon (Aldsworth et al., 2002). This centralised model of production implies that Western Europe was dependent on glass from these major primary production areas. Fresh raw glass was shipped from the primary production area to be re-worked in secondary workshops throughout Western Europe (Nenna et al., 1997; Freestone et al., 2000; Foy et al., 2003).

Any potential reconstruction of this glass production network is inevitably biased by the scarce number of workshops and manufacture debris evidence existing to this day. This is particularly true for Late Byzantine and Early Medieval Western Europe, where evidence for secondary production sites are limited to only certain areas, such as the UK (MacGowan, 1996; Bayley, 2000a, 2000b; Cramp, 2006; Willmott and Welham, 2007, 2015), Northern Italy (Leciejewicz et al., 1977; Leciejewicz, 2000; Gelichi, 2009; Gelichi et al., 2012), Southern Scandinavia (Sode, 2004; Feveile, 2006; Andersen and Sode, 2010), and Germany (Wedepohl and Baumann, 2000).

In addition, even though glass-making and working activities would have produced visible traces in the archaeological record (such as furnaces, annealing chambers, and ovens), unearthing these structures is a very

fortuitous event and, therefore, most of our knowledge on glass-working still relays on the study (typological and analytical) of the material itself.

Secondly, until recent years glass was often overlooked in favour of other materials, potentially because of its intrinsic fragmentary in the first place. Most of archaeologically-recovered glass will be in the form of tiny and fragile fragments (such raw glass, cullet, or pieces of vessels), which will make difficult not only to find the actual evidence, but also to reconstruct its typology in comparison to other materials (such as ceramic and metal for example) if no diagnostic element is present.

In addition, the context of recovery will influence the vision of its distribution and consumption: settlements, graves, and churches will provide different categories (usually better quality) of vitreous materials compared to a workshop's context.Therefore, most of the time the latter was overlooked by scholars because of its scarce aesthetic and diagnostic value. Glass also has been greatly recycled in antiquity. It easy to assume that glassmakers would have presumably worked in a clean environment (Henderson, 2000, 40), and even though materials evidence such as raw glass/chunks, glass cullet, moulds, crucibles, dribbles, pulls of glass (in addition to fuel deposits and frit dedicated to making glass from scratch) would be still present in the archaeological layers of the possible workshop, but most of that debris would have been re-used in future melts to not waste any raw material.

Considering these premises, not only our vision of consumption and distribution of glass during the Early Medieval period in Western Europe is biased from the start, but also tracing back glass' journey from its primary production workshop to its place of distribution becomes an arduous task.

The main aim for this chapter is to give an interpretative framework to understand the nature of the research questions introduced in chapter 1. I will first describe glass' raw materials (section 2.2). Secondly, I will introduce the concept of glass production by introducing a definition of

primary and secondary production and workshops, together with glass-making and working materials evidence. I will then describe the existing evidence for primary production between the late 6th and 11th century AD, together with evidence for glass trade and current theories supporting the centralised model of production in contrast to the localised one (section 2.3).

I will then move to focus on the main evidence for secondary glass production in the three key areas in which the three workshops materials are located: Northern Italy, Southern England, and Southern Scandinavia (section 2.4). In addition, I will focus on previous analytical work carried out on Late Byzantine and Early Medieval glass, with a focus on these three areas (section 2.5).

Finally, I will revisit the structure of the centralised model : the pivotal role of secondary workshops in manipulating the glass' recipes and the importance of chemical analysis in conjunction with typological studies to gather information about the potential glass production network will be remarked (section 2.6).

2.2 Glass as a material

The silicate tetrahedron (Figure 2) represents the basic network former in ancient glass for all silicate glasses. The single silicon atom, which has a valence of four, shares a covalent bond[1] with four other neighbouring atoms of silica. Each silica atom is joined to four oxygen atoms (Figure 1), with a connection that tends to be a fixed directional relationship[2] (Askeland et al., 2010, 36).

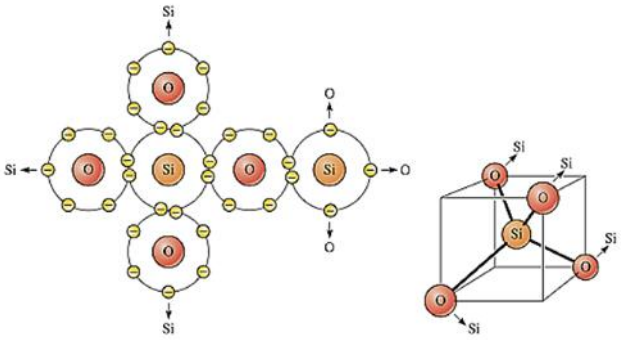


Figure 1 - Silica (SiO_2), in which covalent bonds between silicon and oxygen atoms (left) will allow silicon and oxygen molecules to arrange themselves into a tetrahedral structure (right), from Askeland et al., 2010, fig. 2.13, 37.

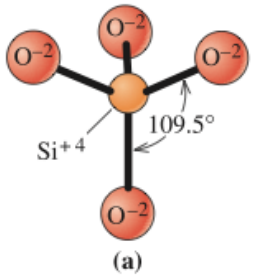


Figure 2 - Basic Si-O tetrahedron in silicate glass, after Askeland et al., 2010, fig. 3-2, 57.

The order manifested in the short-range between silica and oxygen atoms does not equally repeat itself throughout glass structure (long-term order), but the oxides will be arranged in an open network, such as the one shown in Figure 3 (Zachariasen 1932, 3547-8).

[1] Materials with covalent bonding are characterized by bonds that are formed by sharing of valence electrons among two or more atoms (Askeland et al., 2010, 37). Valence is defined as the number of electrons in an atom that participate in bonding or chemical reactions (Askeland et al., 2010, 51)

[2] In the case of silicon, this arrangement produces a tetrahedron, with angles of 109.5° between the covalent bonds (Figure 2).

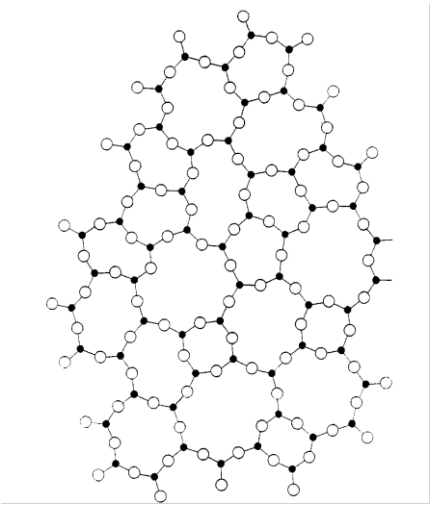


Figure 3 - Two-dimensional representation of hypothetical crystalline compound A_2O_3, after Zachariasen 1932, fig. 1b, 3548.

The tetrahedra of silica and oxygen atoms constitute the basis of glass networks. Glass network also includes components that interact with glass physical and chemical properties, its translucency and, finally, colour: such components are called network modifiers (Figure 4). For example, reaching silica melting temperature (1710 - 1730C°) in antiquity was not possible with the furnaces that were built at that time; therefore, to make proper glass, artisans needed to add a component (a flux) that would dissolve sand or quartz grains, thus lowering the melting temperature from 1710° to the absolute melting point (Henderson, 1988, 271)[3].

By adding soda, the glass will take longer to solidify, thus increasing the amount of time during which it can be worked (Moretti and Hreglich, 2013, 28). Since the beginning of glass-making history, soda (NaO_2) was added to the recipe in the form of plant ash or trona ($Na_2CO_3NaHCO_3\ 2H_2O$, commonly known as natron). More recently, potash wood ash was used in Western glass-making as alkali source.

[3] Henderson (1982) estimates the working temperature for most soda-lime-silica European prehistoric glasses with a composition of c. 18-20% Na2O, 6-9% CaO, and 68-72% SiO2 being between 1000°C and 1100°C.

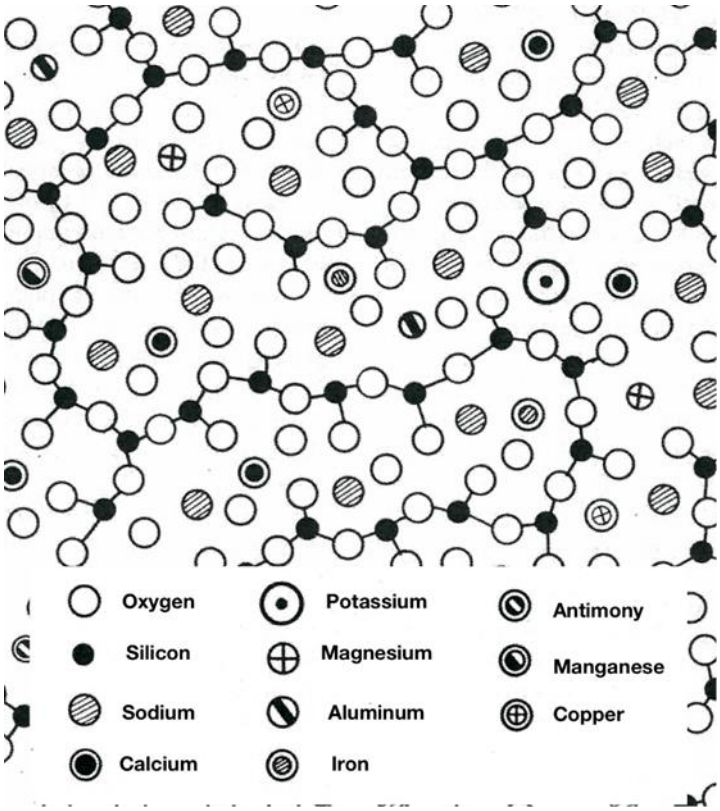


Figure 4 - Simplified model of a typical Roman glass, after (Brill, 1962, fig. 6, 135). The short-range order is clearly illustrated in this drawing: silica and oxygen atoms constitute the matrix, while other elements (the so called “modifiers”) fill in the free space in-between the structure, and therefore altering glass’s final properties (sodium, calcium, potassium, magnesium, aluminium) and appearance (Iron, copper, antimony, manganese).

Without any additive to the original structure, the basic glass matrix would have dissolved when in contact with water. Thus, a stabiliser component was added to the melt to make it water-resistant. Alumina and alkaline-earth oxides are basic stabilizers that make glass water-resistant (Moretti and Hreglich, 2013, 28): alumina is provided by the sand source as an impurity, while the most common alkaline-earth oxide recognised as stabiliser is calcium oxide, which would have entered in the melt through the alkali source plant ash, or by adding it on purpose to the recipe. Known additive sources of lime in antiquity were shells (Wedepohl and Baumann, 2000) and bones (Henderson et al., 2004).

Other elements that help to remove impurities were introduced unknowingly into the recipe. Fining agents serve to facilitate the removal of gas bubbles from molten glass, formed by the reaction and decomposition of raw materials, and to homogenise glass during the melting process (Moretti and Hreglich, 2013, 31). Finally, some components, like colourants and opacifiers, where added on purpose to change the glass matrix and therefore its appearance.

2.2.1 Glass raw materials

The basic recipe of glass in antiquity included two or three components: natron or plant ashes supplied the necessary soda content; sand (rich in quartz) for natron-based glass (Freestone et al., 2000) and quartz (or some other purer source) to make plant ash glass (Henderson et al., 2004) provided the silica content. If the sand source or plant ash did not contain enough calcium to produce a stable glass, an extra source of lime was added as a separate third component.

Raw materials and their ratios represent the first choice of a series that glass-makers make to shape the final glass (Jackson et al., 2005, 782-3). Other choices include any pre-treatment taking place before the melting process (such as fritting[4]), the melting schedule, and the time and temperature chosen for that particular recipe. These choices are linked to the knowledge and experience possessed by the artisans themselves, which in antiquity were based mostly on empirical experience of the material. For example, change in colour when the glass was ready to be

[4] During the process of fritting, the raw materials undergo a solid-state reaction to drive off any unwanted gases and reduce the volume of the batch (Turner, 1956, 293).

worked, or choosing a plant according to its colour and smell (Henderson, 2013, 24)[5].

The availability and the quality of raw materials close to the area of the primary workshop would have greatly influenced the glassmakers' choices and the quality of the resulting glass, since trading the same materials from far away must have been a complex and, above all, costly operation.

Wedepohl suggests that 3000 tons of wood were necessary each year to supply one single glass house producing wood ash glass (1997, 254). Also, the decision of undertaking manufacture and trade would have been influenced by the capacity of artisans and the local community to deal with such a complex organisation and overall workload that glass-making/working would have had required to be cost-effective and functional.

2.2.1.1 Silica

Silica (SiO_2) is the principal glass-former in ancient soda-lime glasses, usually included in the final glass at levels of c. 60 to 70wt%. Sand is the principal source of silica in ancient glass-making, but not all sands were suitable. A suitable sand to produce natron-based glass would first have lacked in impurities (like a low iron oxide content of c. 0.5wt%). Secondly, it should have contained a good amount of calcium carbonate, to mix with the alkali source: this would have produced a stable and workable glass with 8-9%wt of CaO content (Turner, 1956; Freestone 2006). The purity of sand is greatly influenced by the type of rock from which it is derived and the distance over which the material has been transported before deposition (Henderson, 2013, 57), such as weathering or sedimentary

[5] Henderson refers to Abu'l Qasim passage (Allan, 1973) where he describes how to choose the suitable plant ash to make a proper glaze *"… the best shakhar* [ash made by burning plants*] is that which has a red-coloured centre when broken, with a strong smell …*".

processes, the latter containing a higher proportion of heavier mineral and feldspar contents (and therefore less pure). The depositional environment (aeolian sands or fluvio-glacial sands for example) also plays a part in determining the characteristics of the grain and the degree of sorting of such sand (round, well sorted and clay free or angular, poorly sorted and varied in composition).

Typical sand impurities include (Henderson, 2000, 27; 2013, 60):

Table 1 – Typical sand impurities, after Henderson, 2000, 27; 2013, 60.

Impurities	***Inclusions***
Feldspars (plagioclase or alkali)	Al_2O_3, CaO, Na_2O, K_2O
Titanite or sphene - $CaTiSiO_5$	CrO, TiO_2
Chromite - $FeCr_2O_4$	Fe_2O_3
Epidote - $Ca_2(Al, Fe)_3 (SiO_4)_3$ OH	CaO, Al_2O_3, Fe_2O_3
Shell fragments	CaO

Controlling the amount of such impurities would not only determine the quality of the final glass but also influence its appearance. For example, the amount of iron present in the recipe could potentially colour the glass a typical blue-green. To counteract the blue-green tinge and produce colourless glass, MnO or $Sb2O_5$ would have been added to the original recipe as decolouriser.

Strabo around the 1st century AD states that three regions would have produced sand suitable for glass-making: Syrio-Palestine, Egypt, and Italy (Geographica XVI Chap. 2.25; Hamilton and Falconer, 1889). The suitability of Syrio-Palestine sand, and in particular the one from the River Belus (present-day Nahr Na'aman, which flows into the Bay of Haifa between Haifa and Acre, Israel), has been reviewed by multiple authors (Turner, 1956; Brill, 1988; Vallotto and Verità, 2002).

The use of such sands has been confirmed by many classic authors in antiquity. Pliny in his *Naturalis Historia* refers to glass-making had depended on a mixture of soda with the sand from a beach near the mouth of the River Belus, on the coast of Syria (Freestone, 2009, 81). Tacitus also refers to the use of Belus sand for glass-making (Hist., V, 7,2). The use of Belus sand has been confirmed by Brill's study on Jalame glass (1988, 268-9), and by Freestone and et al. study on primary glass-working workshops in the Syrio-Palestine region (Freestone et al., 2000, 70), both primary production centres between the 4th to 7th- 8th century AD. Belus sand, high in both CaO and SiO_2, would have not required to add a separate lime-bearing ingredient (such as shells) to produce a stable natron-based glass.

Sand from River Volturno (Italy) is also mentioned by Pliny the Elder in the context of glass production (Nat. Hist. XXXVI Chap. 65-66; Bostock and Riley, 1857), but several works (Turner, 1956, 300; Silvestri et al., 2006, 416, Brems et al., 2013, 2094) proved that such sand is not suited to produce glass in its original state, given insufficient SiO_2 and because they would introduce into the final glass high ratios of Al_2O_3, Fe_2O_3, CaO, and K_2O due to the abundant augite, feldspar and volcanic lithic fragments in the sand.

Both Strabo and Pliny mention France and Spain as potential sand-sourcing areas together with Italy. Degryse and colleagues Sr and Nd isotopic analyses on Roman glass for 27 vessel glass samples together with samples from silica raw materials throughout the Roman Empire[6] hints at the existence of a Western primary production between the 1st and 3rd century AD (Degryse and Schneider, 1999, 2008). Eastern Mediterranean primary glass has a Nile-dominated Mediterranean Nd isotopic composition (ε Nd higher than -6.0), while glass with a primary

[6] Glass from Bocholtz (Netherlands), Maastricht (Netherlands), Tienen (Belgium), Kelemantia (Slovakia), Sagalassos (Turkey): sand from Antwerp (Belgium), Tienen, river Belus (Israel), Wadi-el-Natrun (Egypt), and river Volturno (Italy), after Degryse and Schneider, 2008, fig. 1, 1995.

production location in the Western Mediterranean or North-Western Europe should have a different Nd isotope signature (ε Nd lower than -7.0). The area of production has not been yet located.

More recently, Brems and colleagues (Brems et al., 2012) discuss the suitability of sand from different Mediterranean locations, including the three areas suggested by Pliny (Italy, Gaul, and Spain). Based on compositional analysis for major and minor elements of sand samples around the Mediterranean, very few areas were found with sand suitable for glass-making. According to Brems and colleagues (Brems et al., 2012, 2902), sand sourced between the mouths of the Basento and the Bradano Rivers and the north-eastern side of the Salentina peninsula (SE Italy) and sand from the west part of the Follonica Gulf would make a glass very similar to the typical Roman glass, without any need to add additional lime-bearing component.

Other sands instead from Central Italy, Southern Spain, and Southern France would have required an additional lime-bearing content to their recipe to produce a stable natron-based glass (Brems et al., 2012, 2903).

As an alternative source of silica, quartz pebbles were often used. Quartz has been preferred in combination with plant ash since it constitutes a purer source of silica (less impurities) when compared to sand, especially in the late bronze age. The shift in composition from sand to quartz marks the technological transition from natron to plant ash glasses. At Raqqa, the same shift in composition in the 8th - 9th century AD marks the use of a purer source of silica, from sand to quartz. Such transition became necessary because a purer source of silica was needed to pair with a plant ash-alkali source, since the latter would have carried with them the necessary content of lime to produce a stable glass. On the contrary, an impure silica sand source paired with plant ash as alkali would have resulted in a failed composition (made with two lime components), similar to the failed slab of Bet She'arim (Freestone and Gorin-Rosen, 1999).

2.2.1.2 Alkali and lime

Two major shifts in the source of alkali in glass production occurred in the Roman and Post-Roman period. At the beginning of glass production, ashes of plants were used as major alkali source until approximately 1000 B.C. After this date, plant ashes were replaced by a new source of alkali, an evaporitic mineral called natron. The second shift occurred around the 9th century AD: when natron became scarce due to some environmental and climatic factors (Shortland et al., 2006, 527), glass-makers reintroduced plant ash as a raw material for the second time.

The primary source of Natron in antiquity is the evaporites deposits (mostly made of layers of evaporitic minerals) of the Wadi Natrun in Egypt. Wadi Natrun's major water intake derives from percolating ground waters from local springs and the lake itself: throughout their underground journey, percolating water accumulates salts from the rocks they travel within. Accumulated evaporitic minerals precipitate during the warmer period of the year (when water evaporation is at its peak) and form deposits rich in carbonates, and sulphates known as "natron" (Shortland, 2004, 502), which have been exploited by humanity for millennia to provide salt and sodium carbonate minerals to use in a variety of different crafts and industries.

Recent studies clarify the concept of natron itself (Shortland, 2004; Shortland et al., 2006). Strictly speaking, natron is the mineral name for the sodium carbonate 10-hydrate, one of the many carbonates and compounds presents in the evaporitic Wadi Natrun deposits[7]. Natron provides a purer source of alkali (relatively free of chlorides and sulphates) compared to plant ash. Hence, the final product will have a far more predictable, stable (and therefore desirable) composition. Such

[7]The dominant carbonate in these deposits is trona, sodium carbonate bicarbonate 2-hydrate (Shortland, 2004, 499).

characteristics must have been considered crucial if we consider the large quantity of glass produced during the Roman period after the invention of glass-blowing manufacture in the 1st century AD.

Work by Shortland and colleagues (Shortland, 2004; Shortland et al., 2006; 2011) discusses the potential sources of Natron in antiquity. Wadi Natrun and Al-Barnuj in Egypt are considered the best potential primary sources of natron in antiquity in Egypt based on medieval and modern accounts (Shortland and Eremin, 2006, 523). Recently, modern evaporitic deposits from Lake Fazda has also been evaluated for its suitability as natron source in Roman times, but its suitability to glass production is still debated. Even though modern deposits cannot be used, Shortland and colleagues suggest that overexploitation might have altered the original chemical profile of such deposits and therefore might have been used in antiquity, provided that sulphate mineral phases would have been converted to carbonates (Shortland et al., 2011). Other sources outside Egypt are again inferred from ancient written sources: al-Jabbul (Northern Syria), Lake Van (Turkey), and Lake Pikrolimni (Greece). Both Lake Van and Lake Pikrolimni evaporitic deposits have been recently object of chemical analysis, which has confirmed for both the presence of elevated contents of carbonates in their water (Dotsika et al., 2009), and therefore their suitability for natron formation. The increase in demand for natron during the Byzantine and Islamic periods combined with its finite natural reservoir forced glass-makers to find a new source of alkali. According to Shortland (Shortland et al., 2006, 527-8) the decline in natron supplies needs to be ascribed to both environmental and political events in the Nile Delta and adjacent regions, which both might have contributed to reduce natron circulation across the Mediterranean (Shortland, et al., 2006, table 3, 527).

The shortage of natron led to the reintroduction of plant ash as a primary source of alkali. Traces of the transition are reflected in mixing and experimental practices in 8th - 9th century Raqqa, Syria (Henderson et al., 2004) that together with Tyre are the only primary known production

centres for the Early Islamic period. Mixing glass-working practices in Northern Italy also attest a similar transition between the 7th and 8th century AD (Verità et al., 2002; Uboldi and Verità, 2003; Silvestri and Marcante, 2011 Bertini et al., 2017).

Halophytic plant ash from the *Chenopodiaceae* family can tolerate highly alkaline environments and collect alkaline salts (sodium carbonate) in their tissues by photosynthesis (Heller et al., 1998; Barkoudah and Henderson, 2006, 297). In soda-lime-silica glasses, the breakdown of sodium-rich salts, mainly sodium carbonate (Na_2CO_3), in the ashes produced the flux (Barkoudah and Henderson, 2006, 298).

The amount of reactive alkali, which is controlled by the plant physiognomies (Henderson, 2013, 44), contained in the plant will influence the final glass melt (Barkoudah and Henderson, 2006, 298). The best glass-making plants contained sufficient levels of sodium carbonate in their ashes to reduce the melting temperature to a suitable working range (Henderson, 2013, 23).

Salicornia is also cited in ancient glass-making written text sources of alkali as one of the two *genera* of *Chenopodiaceae* abounding in soda (Turner, 1956, 281). A recent study by Barkoudah and Henderson showed how *Salicornia* and *Salsola* genera were potentially used in 8th-9th century AD primary glass-making centre in Raqqa, Syria because of the constant positive correlation between potassium, calcium, and magnesium oxide observed (Henderson, et al., 2004, 311-13; Barkoudah and Henderson, 2006). The latter, which strictly depends on the limestone environments in which the plants grow, is also shared with plant ash glasses from Raqqa, and therefore it highly probable that *Salicornia* plants have been used to produce 8th-9th century AD glass in Syria.

Lime reduces glass solubility in water. In ancient times, the lime content in soda-silica-lime glass is between 5% and 10%. Plant ash can contain a high lime content, so theoretically no additional lime source is required

in the sand (Freestone and Gorin-Rosen, 1999, 111). The principal source of calcium in plants is in the form of $CaCO_3$ (calcium carbonate), and its levels depend from both the choice of plant used to make the glass (Henderson, 2013, 46), but also from the location in which the plant grew (Barkoudah and Henderson, 2006, 320). *Salsola sp.* from Balikh valley shows adequate levels of CaO (around 10.5%), but about 200 kilometres away the same species register a variation in CaO up to a factor of 3.5 (Barkoudah and Henderson, 2006, 320). If the collection location greatly influences the amount of lime-content in that specific plant (and therefore in their ashes), it was crucial to choose the richest area in CaO if you did not want to add a separate lime source to the melt. Other plants, such *A. strobilaceum*, *S. vermiculata* and *S. jordanicola*, even though they were soda-rich, still needed a supplementary addition of calcium (Henderson, 2013, 38), since their ashes do not contain enough calcium to be suitable for glass-making.

The weak positive correlation between phosphorus and calcium oxides in some samples from Raqqa (Syria) shows that a separated calcium-rich raw material was added to the basic plant ash composition (Henderson et al. 2004, 459; fig. 6, 456): Henderson and colleagues suggest that bone could have been that component[8].

Calcium carbonate is also the major lime source in natron glass. Because a relatively pure source of soda was used, the lime must come from elsewhere to produce a glass with consistent properties. Two models have been suggested to explain how lime enters the melt in natron glass (Freestone, 2006, 12): the first hypothesis is that lime may have been added deliberately to the batch by the glassmakers to a fixed recipe, in the form of shells. The addition of shells as source of lime is also mentioned by ancient sources, and in particular by Pliny (Freestone, 2009, 91). Some authors (Turner, 1956; Brill, 1988; Vallotto and Verità,

[8] Hydroxyapatite, the main inorganic constituent of bone, is rich in calcium and phosphorus (Turek, 1984), and would transfer such components to the melt (Henderson et al., 2004, 459).

2002) suggested that the ancient glassmakers were not aware of the stabiliser property of lime. This suggestion would support the second hypothesis, which implies that the lime-content was not added consciously within the sand component. If this latter hypothesis is correct, natron glass was made essentially mixing two components (sand and natron), and lime was incorporated within the sand source as an impurity (Freestone, 2008, 90). Sand from Bay of Haifa (close to the mouth of the River Belus) sits well within this model since the content of calcium carbonate is close to 15%, which would have produced a soda-lime-silica glass with about 8.4% of CaO (Freestone, 2008, 87).

Sand from the river Belus (Bay of Haifa, Israel) was used in Levantine I glass from Apollonia and Dor (Freestone et al., 2000, 72). An experiment in glass-making mixing sand from River Belus and natron from Wadi Natrun resulted in fresh glass matching closely the one made in Jalame, which suggests that the same sand could have been used at Jalame workshop to produce fresh glass (Brill, 1988, 266-68).

Freestone (2006, 12), even though he prefers the second hypothesis, remarks interestingly that these two models "*are not mutually exclusive*", since different sands (with different lime contents) might have been used in natron glass-making production at the same time, with each primary workshop adding the required lime source when needed (based on using a lime-bearing sand or not).

2.3 Basic framework for interpretation of glass production's network

2.3.1 Definition of primary and secondary production

A centralised production model has been used to explain glass production and circulation between the 6th and 11th century AD (Brill, 1967; Henderson, 1989; Freestone et al., 2002). This model revolves around the idea that glass production is the result of two main operations (Brill and Wosinski, 1988, 283-4):

- **An engineering stage**. The material (raw glass) is produced from its ingredients (primary production).
- **A handcrafting stage**. The material is shaped into objects (secondary production).

The first stage would have included (Henderson, 2000, 38):

- The selection and preparation of raw materials.
- Making the glass (including fritting process).
- Mixing the batch and melting the glass.
- Working the glass to make the desired objects.
- Annealing the objects.

The last two points would have also been included in the final phased of the handcrafting stage.

The second stage of production would have included those operations dealing with modifying the basic raw glass formula and its external appearance, such as changing its appearance by adding colourants and opacifying agents, by adding decoration, or by implementing the original basic recipe by mixing different types of glass (recycling practices). The

last stage would have included shaping the new glass into the final product.

Sadly, the discovery of complete furnaces (or even partial remains) pertinent to both primary and secondary production are a rare event, and the whole production process is rarely reflected by the archaeological record.

2.3.2 Glass-making and working material evidence

The presence of glass-working debris will always identify some sort of secondary activity, even though at different degrees of technological complexity. On the other hand, the presence of primary production needs to be assessed by the presence of both furnace, sub-products, raw materials, and debris from the first stages of production in the immediate vicinity of the workshop.

Fenzi and colleagues (481-6) define a comprehensive overview of both glass-making and glass-working indicators based on the 13th and 15th century AD primary glass-working centres evidence in Tuscany (Italy).

Four stages between glass-making and working are identified, such as (Fenzi et al., 2013, table 6.1.9., 509):

1) Glass-making:

Step 1 – **Fritting of raw materials**: raw materials (ashes, Ca-Mg carbonates and Si-rich –sands) are involved in the setting of the batch.

Step 2 – **Melting and refining**: frits and cullet are melted. Archaeological evidence will include: glass fragments (cullet[9]), opaque heterogeneous vitreous masses [10](overheated frit), skims[11], and crucibles.

2) Glass-working:

- **Step 3** – Modelling artefacts. Archaeological evidence will include: cuttings[12], drops[13] and drippings[14], moils[15], filaments[16], opaque and transparent glass masses, masses with tweezers marks, glass fragments (cullet), and crucibles.
- **Step 4** – Annealing. Archaeological evidence will include mostly fragments of artefacts.

[9] Raw glass or pieces of broken glass from a cooled melt, intended for use as an ingredient of batch or scrap glass intended for recycling (Whitehouse, 2006, 27).

[10] Greenish or whitish hard, coherent masses with a granular vitreous appearance, generally with a polyhedric shape of different dimensions often are characterized by bubbles and inclusions as well as by a concoidal surface fracturing (Fenzi et al., 2013, 481-2).

[11] Heterogeneous spongy opaque finds in a variety of sizes and with an irregular, plastic-like, outer aspect and an inner vitrified mass which is partially crystalline (Fenzi et al., 2013, 483).

[12] Thin glass curls or plain curved trails often containing a lot of air bubbles, in different shapes and dimensions according to working techniques (Fenzi et al., 2013, 485).

[13] Pear-shaped opaque or transparent glass blobs with a diameter between 6 and 8 mm, usually with a plain surface and no macroscopic inclusions or earthy concretions or signs of pressure or impact. Drops forms from glass dripping from the crucible during the glass-making phase as well as during the glass-working as the result of solidification process (Fenzi et al., 2013, 482).

[14] Drippings of glass forms as the results of glass dripping in the glass-making as well as in the glass-working phase (Fenzi et al., 2013, 483).

[15] The remnants (usually broken) of the glassy rings wrapping the blowing pipe (Fenzi et al., 2013, 485)

[16] Thin glass threads with diameters ranging between 0.5 and 1.5 cm (Fenzi et al., 2013) which can be formed both during the glass-making and -working phases. In the latter case, they can be related to the decoration of the artefacts, and they are mostly likely to be made with a different colour in comparison to the base artefact glass.

2.3.3 Evidence for primary production between 7th and 11th century AD.

To this day, we have little evidence concerning primary production for the period between the 6th and 11th century AD, and all of them have been discovered in the Near East.

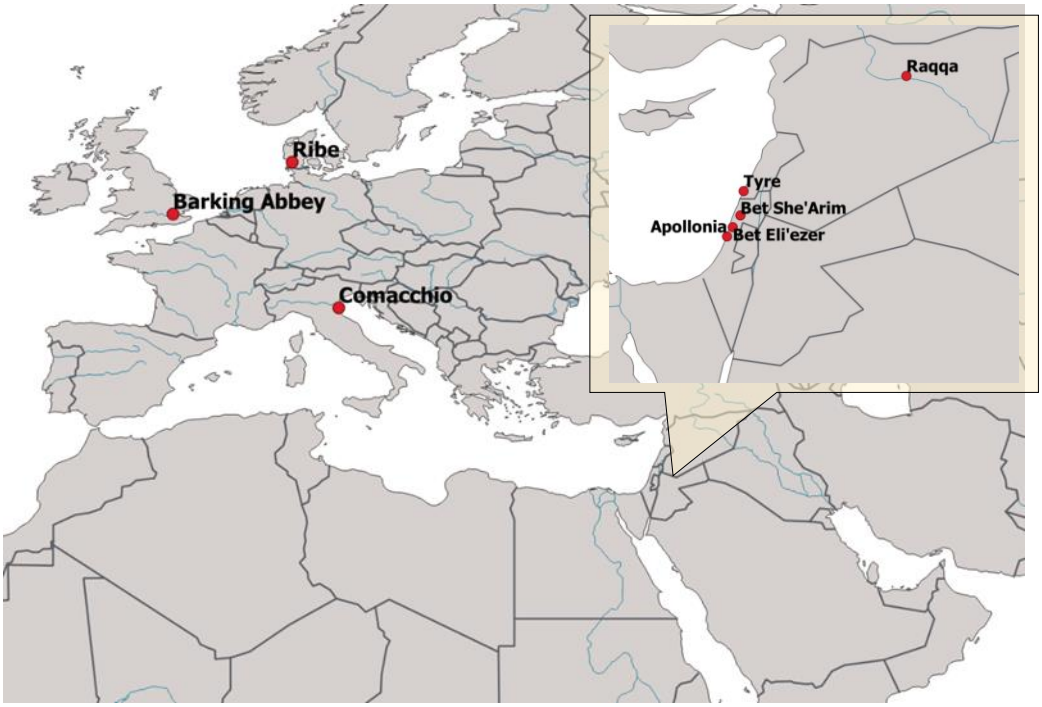


Figure 5 - Western Europe and Levant map. In addition to Comacchio, Barking Abbey, and RIbe, site with primary glass-making evidence have also been included.

In the following sections, a total of four maps have been included to show the position of the mentioned sites. Maps were made in Quantum GIS (QGIS) v3 Bonn using base maps from www.naturalearthdata.com. Both the GIS and base maps are open source software and their use is acknowledged. The maps are made using the coordinate reference system: EPSG:4326 - WGS 84 – Geographic.

Bet She'arim (Brill and Wosinski, 1965; Brill, 1967; Gorin-Rosen, 2000). The Bet She'arim glass slab (Israel) was found firstly in 1958 inside a cave. Since the slab was too big to be removed, the excavators decided

to leave it in situ. Brill suggested that the slab, measuring 3.80m x 1.95m x 0.45m (Brill 1967, 91), had been melted in a tank built of limestone and was left in place because the result of a failed production process: chemical analysis revealed an unusually high content in lime for Roman glass, over 16% (Brill and Wosinski, 1965, 5). Brill and Wosinski cannot explain if the high content of calcium oxide has been added voluntary, but they suggest that in any case it was a poor manufacture choice, since no physical or chemical properties (*in primis* transparency or malleably) would have benefitted from this preference. For these reasons, the slab was left in situ untouched, and probably abandoned. Brill (1967, 95) assigned a date to the slab between the 4th and the 7th century AD for Brill, but Freestone and Gorin-Rosen (1999) are inclined to suggest a 9th century AD date based on comparative analytical studies.

Apollonia (Gorin-Rosen, 2000; Tal et al., 2004). Two furnaces were discovered in the early 1950s during salvage excavation in Apollonia/Arsuf (Israel) in 1950s. Unfortunately, the study of Apollonia's glass industry has not been published (Dor and Kahane, unpublished) but their notes report structures very similar to the one built at Bet Eli'ezer in Area D of the excavated site (Gorin-Rosen, 2000, 54; Tal et al., 2004, fig. 2, 53; 54-56). The two furnaces, dated to the 6th – 7th century AD (Tal et al., 2004, 58) based on one pottery fragment found below the firing area[17], were found in the southern-eastern corner of a courtyard adjacent to a rectangular building, with one of the installation (possibly a melting chamber with some floor remains covered with a thick layer of glass) being 5.5 m long. The furnace was located east to the first, in area D (Tal et al., 2004, fig. 2, 53; 55). A large deposit of raw materials (ashes, sand, and glass debris) was found near the two structures, validating further

[17] The same chronological frame has been confirmed for the more recent excavated furnace, based on the recovery below furnace level of a bag-shaped Palestinian jar type dated to the 6th – 7th century AD (Tal et al., 2004, 58).

their use as primary production workshops (Gorin-Rosen, 2000, 55). In 2002, a new furnace was discovered in area N (Oren Tal et al., 2004, fig. 2, 53; 56) which included a badly preserved firing area (external dimensions, about 3.8 m x 1.6 m) and a melting chamber (external dimensions 5 x 3.8 m) located at the east end; two conical firing chambers that opened onto the same melting chamber, and a layer of glass covered the floor of the furnace. The furnace contained a large glass slab (about 4.45 m x 2.95 m) similar to the Bet She'arim one; after the slab solidified and cooled down, the roof had to be dismantled to remove it. The furnace's filling material includes lumps of melted glass, burned *harma* (red loam), small chunks of charcoal, and several ribbed potsherds, stones, and bones.

Bet Eli'ezer (Freestone et al., 2000; Gorin-Rosen, 2000, 1995). Other evidence for 6th - 7th AD centres glass production was revealed at the site of Bet Eli'ezer, near Hadera (Israel) where seventeen tank furnaces, including firing and melting chambers, were excavated. Each furnace would have produced several tons of glass per firing (Gorin-Rosen, 2000, 53). The only finds in the area were the remains associated with the furnaces and the remaining pieces and waste of previous melting, with no workshop attached, which points to a single melting event: the furnace must have been destroyed each time to remove all the glass produced, even the remains attached to the wall. Remains of a Byzantine settlement were discovered a few hundred metres north-east of the factory.

Raqqa - Primary production in Raqqa has been recognised from the beginning of the 8th century AD (Henderson et al., 2004, 440-41). Three sites, which belong to a greater industrial complex associated with Al-Raqqa twin town Al-Rafika, in particular showed evidence for glass production in Al-Raqqa (Henderson, 1999; Henderson et al., 2004): Tell

Zujaj, Tell Fukhkhar, and Tell Bellor (respectively dated to the 8th – 9th, 11th, and 12th centuries AD).

The site of Tell Zujaj shows relevant evidence for glass production, where the remains of two three-chambered, beehive-shaped glass furnaces (1.3 m tall) were discovered. In association with these workshops, not only glass vessels, but also raw chunks of glass, debris (from glass working), and most of all frit (Henderson et al., 2004, 441) were found in association with these furnaces.

Tyre - Four reverberatory-type furnaces for raw glass of different sizes were found at the Island Site in Tyre: the largest one, furnace 1, shows a melting chamber of 6.90 by 3.90 m (Aldsworth et al., 2002, 53). According Aldsworth and co-workers, the overall glass complex should not be earlier than the 8th century AD, and the evidence suggests that the factory could possibly operate between the 10th-11th century AD (Aldsworth et al., 2002, 65-66). Together with Al-Raqqa, Tyre is the only other site during the Early Medieval Islamic period that shows evidence for primary production. Nonetheless, Tyre does not show evidence for fritting *per se* (Aldsworth et al., 2002, 64) as Al-Raqqa does (Henderson et al., 2004, 441-2; 455), but it is likely that glass was made in one stage melt from raw materials, as it suggested by Gratuze for Bet Eli'ezer tank furnaces (Gorin-Rosen, 2000, note 10, 52).

2.3.4 Glass trade evidence during Roman and Early Medieval period.

Trade can be defined as movement and exchange of raw glass, raw materials, and cullet between primary and secondary production workshops and consumption areas. Several confirmations, both written

and archaeological, point to the fact that glass was indeed “a thing that travelled”[18] in Early Medieval times, but evidence is still scarce[19].

It is certain that raw glass was traded across the Mediterranean at least from the second century AD (Foy et al., 2000; Foy and Nenna, 2001).

The only existing evidence for cullet trade has been documented 6 miles from Grado (North Western Italy) where the *Iulia Felix* cargo ship (dated to the first half of the 3rd century AD) was discovered (Tortorici, 1994; Dell’Amico, 2001). Amongst other trade goods transported by the 22 ton ship, the cargo contained 11.000 fragments of glass vessels, for a total weight of 140 Kg: the most common were blue-green, pale blue and pale green coloured, but the load also contained many colourless examples (Silvestri, 2008; Silvestri et al., 2008). Not only the compositional variability among both coloured and colourless glass supports the hypothesis that different sand sources were used to make these glasses, but the evidence for a clear separation between pure/non-pure sand sources and the use of decolourisers demonstrate a selective choice of raw materials together with a strict control over recycled processes by glass-makers since the 3rd century AD.

Glass ingots from the Serçe Limani shipwreck reveal that natron glass was still circulating in the 11th century AD (Bass and Van Doorninck, 1978; Bass, 1984; Bass et al., 2009): results for ingots fragments from the Serçe Limani wreck have been included in Brill’s work (Brill, 1999, 178-179). XFR analysis made by Verità and Toninato (Verita and Toninato, 1990, tab. III, 173) on glass materials from the Venetian area reveal also that six samples from Ferrara and two from San Arian (Venice) dated to the 8th to 12th century AD show a similar chemical composition (major

[18] I am referring to Whitehouse’s work (2003) in which glass is described as a means to understand evidence for long-distance trade.

[19] First evidence of long-distance trade of raw ingots has been recognised in the Uluburun shipwreck (Bass, 1986; Pulak, 1988, 2005; Nicholson et al., 1997; Jackson, 2010) discovered off the coast of Turkey and dating to 1300 BC.

elements) as two of the Serçe Limani ingots. Bass (2009, 503) suggests that Serçe Limani boat was returning to a home port near Constantinople.

During a later period, evidence for trade of raw materials, raw glass, and cullet from the Levant to the Mediterranean area can be found in the written sources. Antonio Neri in the 16th century (Cable, 2001, 1) considers a type of plant ash imported from Syria, *Rochetta*, the best soda source to produce the best quality ashes, even better that the one imported from Spain, the so-called *Barilla* plant.

In their analysis of the evolution of Venetian glass composition, Verità and Zecchin (2009 table 1, 603) summarise the known written sources for the main glass-making raw materials imported in Venice. It is known that Venice was importing raw glass from at least the 13th century AD, together with soda and beech sand: Zecchin (1990, 173) mentions the trade of *vitreum* and *vitrum in massa* from the Levant in the 13th century AD (from 1233 and 1255 respectively). He also mentions *verre brizé* (broken glass) imported from Tripoli (in 1277 AD). In addition, Carboni (1998, 101-02) mentions that the same *verre brizé* (also called *vitrum deslaboratum*) was subject to taxation together with *alumen album* (soda used in glass-making) and beech sand[20] from the late 13th century AD.

Jacoby (1993, 69) mentions that in the 14th century AD glassmakers from Genoa and Altare were acquiring ashes respectively in the 14th century AD from Syria[21]. The same *Rochetta* plant mentioned by Neri (Cable, 2001, 1-2) was also imported from Syria to France through Marseilles (Foy and Sennequier, 1989, 33).

Even though these sources are dated to a later period than Comacchio 7th – 11th century AD materials, the fact that a fluent movement of glass (including both raw glass and cullet) was occurring at least since the 13th

[20] Concerning the first mention of this treatise, please refer to Carboni 1998, note 12.

[21] About the bibliography concerning the trade Altare and Genovese glass made with traded Syrian soda, please refer to Jacoby, 1993, note 17, 69.

century AD from the Levant to Venice as a preferential destination cannot be underestimated when thinking about potential connections between Northern Italy and Middle East primary production areas, especially concerning the significance of plant ash in Veneto from the 8th–9th century AD (Verità et al., 2002).

2.3.5 Some considerations on glass recycling

Any discussion concerning production cannot be debated at its best without mentioning the possibility of recycling. The practice of reintroducing already-worked material into the productive cycle represents not only a great economic advantage but also has a profound impact on the material's recipe.

The general practice of recycling can be defined as:

> *"…an activity whereby a secondary material [usually cullet] is introduced as a raw material into an industrial process in which it is transformed into a new product in such a manner that its original identity is lost …" (Degryse et al., 2006).*

Glass is the perfect material to recycle: fragile by nature, it breaks easily into small chunks, and therefore, it is easy to move and re-melt into new artefacts. Also, the use of cullet has a technological advantage as a certain amount of it mixed together with raw glass lowers the melting temperature (Vose, 1980, 67). In antiquity, the earliest archaeological evidence for cullet is a pit deposit from Watling House, London, which is dated to the Neronian-early Flavian period (Shepherd, 1987, 143). Early Imperial Roman written sources confirm also that glass was indeed recycled in antiquity (Whitehouse, 1999; Keller, 2004).

Since recycling can endure many stages of re-melting, it becomes more difficult (or impossible) to reconstruct its full technological history step by

step. Moreover, cullet is often absent from the archaeological record because it would have rather been used to increase the amount of material available to produce fresh “new” glass or traded than been preserved and stored away.

Is it therefore possible to distinguish recycled from non-recycled glass?

Colour is not a good indicator for spotting recycling. Both fresh and recycled materials come in both colourless and blue-green shades, making impossible to distinguish their true nature with a naked-eye examination. Some indication might come from circumstantial data pertinent to the archaeological record or the material itself, such as place of deposition and from the archaeological context. Keller (2004) describes deposits of cullet from Roman military camps and civil settlements, where the nature of the material has been deduced because found in waste pits.

If we observe the same topic from the analytical point of view, how can we spot recycling with the help of scientific analysis?

Potentially, there are three criteria that allow to recognise if a glass has been recycled. First, recycling is usually seen compositionally through measuring the contents of specific indicators (such as CuO, CoO, PbO, and SnO_2) or decolourisers compounds (such as Sb_2O_5 and MnO). The former compounds are also responsible for glass colouring/opacifying in intense coloured and opaque glass, while antimony and manganese oxides are also used as decolourisers[22] . Measuring such compounds in intense coloured/opaque glass in order to assess recycling would simply prove ineffective, since these elements would be naturally present in a

[22] Antimony and manganese oxides decolorize glass by oxidizing the iron. The efficacy of such decolouring compounds will depend on how effective they will be in counteracting impurities (such as FeO, responsible for the blue-green colour in most natron glass for example) naturally present in the glass melt and on the atmosphere present in the furnace (oxidising or reducing) when the glass was originally made.

relatively high amount. Therefore, the first limitation of this criteria, is that is applicable only to blue-green or colourless glasses.

In such samples, the high amounts of the same components have no functional purpose[23]. The same can be said to the concurrent presence of both antimony and manganese oxides in elevated amounts, since the presence of both in the same recipe would be superfluous (they both fulfil to the same function).

In the current literature there is no known fixed threshold for colourant markers values acquired through EMPA analysis to detect recycling practices. The recognised threshold for LA-ICP-MS analysis is 100 ppm (Foster and Jackson, 2009), but is considered always arbitrary. The separation between non-recycled and recycled samples needs to be evaluated in each dataset according to the nature of the glass itself (colour and opacity).

Secondly, recycling can also be spotted in the form of mixing lines. When two non-recycled glasses (A and B) are mixed together, a third recipe is created (A + B). The same A + B recipe will appear on a bi-plot as samples falling along a so-called “mixed line” between recipe A and recipe B (see for example section 5.2.1). A partial limitation of this method is the fact that it is strictly connected with the presence in the assemblage of supposedly unrecycled material, which constitute a sort of benchmark for the mixed recipe. If A and B untainted glass are not recognisable in the assemblage, the recycled nature of the mixed recipe might anyway manifest as a blurred recipe (having in-between values between the two original raw glasses).

Another approach implies assessing the effect of contamination on glass (Paynter, 2008; Freestone, 2015), caused by the deterioration in composition (such as of alkali flux) over consecutive reheating, incorporation of contaminants from the workshop’s equipment (such as

[23]Such elevated values add up through repetitive cycles of recycling.

iron from the blowpipe and pontil or absorbed from the pot walls), and incorporation of elements derived from the fuel ash (increment of potassium, magnesium, and phosphorus oxides). A final limitation of these analytical criterias is connected with the definition itself of recycling: when does raw glass “original identity” is lost? After one re-melt? After two or more?

In my opinion, faintly coloured and colourless glass can be considered recycled when has gone through repetitive re-melting cycles, which will be reflected in its composition by the heavy accumulation of impurities and recycled/decolourants elements. Unless in the presence of raw glass from primary production site, we should always be careful when assigning the label of non-recycled glass. The associated non-recycled glass will still contain a small percentage of impurities, but in relatively lower quantities when compared with supposedly recycled glass.

2.3.6 Models for glass production: centralised vs. local

Aside the previously mentioned workshops (section 2.3.3), no further evidence of primary production exist. The lack of archaeological evidence has inspired a debate concerning glass production models.

Based on primary production evidence, we can make two simple considerations. The first is that primary production seems to occur only in the Near East. Secondly, glass was produced in large tank furnaces, apart from Raqqa where glass was instead produced in beehive-shaped three-chambered furnaces (Henderson et al. 2004, 441). It is fair to suggest therefore that these furnaces would have been producing a massive amount of glass for each firing, which would have been proportional in some way to the actual demand for glass at the time.

While discussing the 9-tonns Bet She’Arim glass slab, Brill (1967, 95) discuss the idea that glass could have been produced in great quantity

all in one stage: the huge slab would have been made to be broken-off later and then its pieces shipped where needed to be re-softened at lower temperature. Such practice would have therefore allowed to make glass from its primary raw materials locally but only in certain “specialised” furnaces, given that not all workshops would have been close to the right raw materials and would have had the necessary structure to attain such elevated temperature to produce glass in the first place. The hypothesis that glass was made in big tank furnaces in few workshops close to the raw materials and then redistributed to secondary glass-working workshops is at the base for the so-called centralised model.

Freestone and colleagues (Freestone et al., 2000, 66) apply the idea suggested by Brill (1967) to the Levant area (few primary centres, many secondary workshops): the presence of furnaces, chunks of raw glass, the closeness to raw materials’ sources, and the striking similarities between glass made in Apollonia, Dor, and Bet Eli’ezer would suggest a strict control over the recipes and their raw materials and therefore the result of a centralised and organised network from the 6th century AD onwards.

Henderson (1989, 39), while discussing conservatism in glass chemical composition, previously suggested the idea that centralised production might not be the only model to consider in glass manufacture, when chemical composition is considered. According to him, the model of production will influence the final glass composition for raw (soda-lime) glass in two possible ways:

- In the centralised model, a limited number of glass centres is involved in the production of glass. The chemical composition therefore remains strictly regulated. The raw glass produced is then traded to other centres, where it is worked and modified according to local necessities.

- The local model would have possibly required glass artisans to travel around local glass centres, sharing their technological knowledge to produce glass where needed.

The idea that artisans travelled around local glass centres embodies one intriguing possibility. However, Freestone and colleagues (Freestone et al., 2002) describe further both frameworks by focusing on the relation between workshops and recipe modification. In the first centralised model, few primary workshops made glass from imported natron and local sands. Each primary centre would have then traded its produced raw glass to the many secondary workshops across the Mediterranean where the glass was shaped or compositionally modified according the local taste. The localised model would have instead involved the existence of many primary workshops distributed across the Roman Empire, each one of them potentially producing their own glass of different compositions by mixing local sands with imported natron.

Both models are theoretically valid, even though archaeological and analytical evidence strongly indicate that the first model based on few primary workshops and many dispersed secondary ones is the most probable.

The local model lays its foundation on the idea that primary production would have been carried out also in the Western Europe. Wedepohl and Baumann (2000) have argued on compositional grounds that 4th century AD glass from Gellep cemeteries and Hambach factories (West Germany) was made locally using local raw materials (Wedepohl and Baumann, 2000, 130- 32): intermediate lead and high barium concentrations together with lead isotopes composition would suggest that quartz sand from the Eifel River has been used to produce glass in these Roman factories. Moreover, the mean $^{87}Sr/^{86}Sr$ ratios of the six Roman glasses is 0.70887 (below present seawater, indicating an isotopically lighter strontium as the result of diagenetic alteration), which might indicate the deliberate addition of shells (typically local) to the glass

recipe (Wedepohl and Baumann, 2000, 130). This hypothesis is not immune from criticism. First, lead isotopes are not exclusively reliable when used as a means to provenance glass materials: such issues have been described in different occasions (Brill et al., 1974; Brill, 2006, 1970).

In second instance, in terms of their $^{87}Sr/^{86}Sr$ ratios and Sr contents, later Freestone and colleagues (Freestone et al., 2003, table 2, 29) remark "*that it is equally probable that the strontium in the German glasses was the result of the use of beach sand, containing shell and some limestone, as a raw material, without the deliberate addition of shell*".

Therefore, glass from Gellep and Hambach might have been also made from coastal sands similar to Bet Eli'ezer and Bet She'an glasses analysed by Freestone and colleagues (Freestone et al., 2003). These criticisms together with the lack of other evidence of production from raw materials in Western Europe have contributed to reinforce the validity of the centralised model.

2.4 Glass working evidence in Western Europe: Italy, England, and Southern Scandinavia.

The only other glass-working site for which it has been suggested primary production is the site of Torcello, near Venice (Italy), because of the large structures present (see below). Unfortunately, the same site lacks some basic starting materials (such as frit) to validate this hypothesis. Evidence for secondary glass-working in the West are scarce too. Given that this dissertation's purpose is to analyse glass from the sites of Comacchio, Barking Abbey, and Ribe, I will focus on major secondary glass-working archaeological evidence published for Italy, Southern Scandinavia, and the UK area.

2.4.1 Italy

Even though Italian glass-working evidence are scarce between the 6th and the 11th century, analytical evidence show a much more lively context, which arises from the duality between the Centre and the South of Italy relying on Old Roman glass (Mirti et al., 2000, 2001; Schibille and Freestone, 2013) and Northern Italy's choice to base its production not only on recycling practices, but also on fuelling experimentation such as mixing different recipes.



Figure 6 - Italian peninsula map. Site with secondary glass-making evidence cited in the text have been highlighted.

The latter has been proved already by different publications (Verita and Toninato, 1990; Verità et al., 2002; Verità and Zecchin, 2009; Silvestri and Marcante, 2011).

I will discuss this specific aspect in the next section (2.5) dedicated to the analytical issues connected with Western glass production, while the next sub-section is instead dedicated to describe briefly glass-working archaeological evidence published to this day for the Italian peninsula.

2.4.1.1 Torcello

At Torcello Island in Venice, the nature and significance of Early Medieval glass production is still debated. Between 1961 and 62 excavations campaigns, in the area defined as *area della Cattedrale* (Cathedral area), the remains of a glass workshop were discovered in *stratum IV*, *V*, *VI*, with the actual workshop remains embedded in *stratum* V (Leciejewicz et al., 1977, 89). Overall, the workshop area included four structures, spread over an area of 13 x 18 m^2 (Leciejewicz et al., 1977, 63-73; 140; 144-147), with the remains of one circular furnace (*costruzione* 2) associated to other structures (*costruzione* 3 and 4).

Unfortunately, the upper structures were demolished when the production activities ceased, so only the main perimeter is preserved. In addition, the entire workshop plan is yet unknown, since both the north eastern and south-eastern areas were not entirely excavated (Leciejewicz et al., 1977, 89). A great variety of glass artefacts were found in *stratum V*, as well as in *IV* and *VI*, which were respectively dated earlier and later to the workshop itself: vitreous mass/raw glass (in shape of a bar o droplets), crucibles with glass layer attached (mainly associated with *costruzione* 2), tumblers, cups, bottles, and mosaic tesserae of different colours (Leciejewicz et al., 1977, 47-48; 57; 74).

The Torcello workshop was originally thought to be active between the beginning of the 7th and the end of the 8th centuries AD (Leciejewicz et al., 1977, 145). Later on, its chronology was adjusted between the 9th and 10th centuries AD, once a burned wood sample coming from the circular furnace (*costruzione 2*) was carbon-dated (Leciejewicz, 2000, 91; Pazdur, 2000, 86).

The existence of primary production at Torcello is then still debated, since no primary production indicators were found in the glass workshop. Leciejewicz and co-workers consider two main hypotheses concerning

the function of the different structures in relation to glass production (1977, 140). Considering *costruzione 1* as a proper glass-making furnace (primary production), *costruzione 2 and 3* as glass-working furnaces, and *costruzione 4* as an annealing oven (secondary production), it is plausible that both primary and secondary production could have occurred here.

On the other hand, it is also plausible that the four furnaces were used just as glass-making kilns save the last (*costruzione 4*), which would have been still used as an annealing oven.

2.4.1.2 San Vincenzo al Volturno.

During the first decades of the 9th century AD, four different industrial productions (tile-making, copper-smelting, glass-working, and bell-casting) were episodically active in San Vincenzo al Volturno (Hodges et al., 2011, 141). These workshops activities were concomitant to the construction of San Vincenzo church and the extensive refurbishment planned by Abbot Joshua in the first decades of the 9th century AD. According to Hodges and colleagues (Hodges et al., 2011, 141), all workshop activities and their associated structures were replaced at the end of each productive phase with new ones directly above the destruction levels. After the temporary workshops were demolished, the new ones were transferred 20 metres to the south, and an *Atrium* was allocated in the same area. The new collective workshops were connected to the actual monastery structure by a vaulted passageway (Hodges et al., 2011, 129).

The glass workshop belongs to the so-called 4A4 phase (Hodges et al., 2011, 141-7) and it was built on top of the levelled remains of a copper-working workspace. Its exact perimeter is yet unknown: the north-west part of the temporary workshops was obliterated below the *Atrium* foundations. The glass workshop includes two kilns: a semi-circular one (5717) constructed with tiles, plus a larger central furnace (5711). The

latter had a tripartite structure with a central firing chamber and adjacent firing ash-pits. A smaller pit (5782) could have functioned as additional firing chamber (Hodges et al., 2011, 144). As Hodges and co-workers point out (2011, 143), it is possible that the smallest kiln (5711) would have functioned as subsidiary furnace to melt cullet, and therefore, to make new glass.

The type of glass production carried out at San Vincenzo is still debated. Glass was indeed recovered in a great variety of colour (purple, dark red, green, cobalt blue, turquoise, and streaked red in green-blue background), decoration techniques (flashing, festooning), and shapes (bottles, flasks, bowls, jars, dishes, lamps), but compositional and trace elements analyses have excluded that primary production has occurred at San Vincenzo. Schibille and Freestone (2013, 11), by analysing a mix of mosaic tesserae, reticella rods, vessels, and sheets of glass, proved that the core material used in San Vincenzo has been almost exclusively old Roman glass, mainly colourless and opaque, made about 500 years before the construction of the church. The presence of glass-making debris, including droplets, cullet, clippings and trimmings of glass, and reticella rods, in association with mosaic tesserae strongly suggests that secondary production was carried out instead at the site to support the construction of San Vincenzo's Church.

2.4.1.3 Crypta Balbi

Despite the significant glass deposit discovered inside the Crypta Balbi *exedra* dated to the 7th century AD, the actual workshop location associated to secondary production of glass is still missing: scholars believe that it was in some way connected with the nearby monastery of S. Lorenzo in Pallacinis (Saguì, 2002). Analytical work on materials from the Crypta (Mirti et al. 2000; 2001) demonstrates the use of recycling of Old Roman glass as raw materials as late as the 8th century AD.

A lot of attention has been recently paid to analytical studies concerning Roman and late Roman glass (Silvestri, 2008; Silvestri et al., 2008; Boschetti et al., 2008, 2016; Gallo et al., 2014, 2015,; Maltoni et al., 2015) and less attention has been given to Early Medieval glass dataset. Nonetheless, major and minor compositional data from previous analytical studies reflect a lively experimental context in Northern Italy (more specifically, mixing of natron and plant ash recipes and recycling practices), which clash with the evident lack of structural and material glass-working evidence: the association between experimental mixing and recycling practices and furnaces (like for example in Torcello), might indicate that there is a chance that an experimental recipe might have been made in the same workshop, and not imported as already made glass ready to be melted.

Other archaeological evidence of glass-working is scarce. Uboldi recognised the presence of reticella rods in Santa Giulia da Brescia context, possibly ready to be remelted (Uboldi 2000). The same presence of reticella rods possibly ready to be remelted has been recognised at San Vincenzo al Volturno (Schibille and Freestone, 2013). More than 200 hundred glass-working fragments, including glazed crucibles, droplets, and chunks of glass have been found in Brescia, Monastero di Santa Giulia (Uboldi, 1999, 305-7)[24]. At Torcello, remains of twenty-two soap-stone melting pots were found (Leciejewicz et al., 1977, 101; Verità et al., 2002, 263) together with thirty-five chunks of glass, waste, and droplets (Leciejewicz et al., 1977, 104- 112) three melting pots from San Marco and one from Malibran excavations (Verità et al., 2002, 263) with most of them covered with layers of green and yellow glass. These evidence all suggests the presence of some sort of secondary glass-working workshop/activity at the fore-mentioned sites. Comacchio furnace and its

[24] No structures have been recovered in connection with a possible secondary workshop in Santa Giulia da Brescia (Uboldi, 1999, 307); nonetheless, Uboldi believes the existence of a secondary workshop most probable, given the concentration of glass-working remains concentration in IIIB period onwards ("Lombard" phase, 568-680 AD), mostly in "W3" (buildings XXVIII and XXIX and connected activities) and "Y2" areas.

crucibles lined with blue-green glass, glass-working debris, and chunks of glass also points towards glass-working at least during the period of activity of the furnace (late 7th to early 8th century AD).

2.4.2 Britain



Figure 7 - Southern England map. Site with secondary glass-making evidence cited in the text have been highlighted.

To this day, no evidence for primary production has been found in Eastern England, nor there is not much evidence of glass-working in Anglo Saxon times (Bayley, 2000a, 137). Cool (1995) reports glass-working in Roman Britain up until the late 4th century AD, but we have no further evidence for Period I (400-550 AD) and Period II (550-700 AD). The earliest evidence (6th century AD) in Post-Roman England were found at Buckden (Cambridgeshire) in the form of eleven crucibles (Wilson and Hurst, 1962, 307-08; Rye and Bayley, 1996)with pots lined in different glass colour according to their dimensions: the larger crucibles (c. 120mm) have inside an opaque pale yellow glassy layer. The smaller diameter crucibles (c. 90 mm) are instead covered with a layer of white opaque glass.

Typological similarities between Eastern England and contemporaneous vessel glass production on the Continent have been underlined recently (Evison, 2000; Feveileb, 2006, 253; Evison et al., 2008, 7), and more specifically with the Rhineland region, Northern France, and Belgian glass production[25]: such typological similarities have been interpreted as sign of trade between the Continent and Eastern England.

According to Campbell's analysis (2007, 55), imported glass in Western Britain between 400 and 800 AD shows typological difference in shape, colour, quality of glass, and decoration that could suggest a different area of production, also on the Continent. So-called Atlantic glass vessel groups (group C and D in Campbell's work) dated mainly to the later 6th and 7th century AD on the basis of associations with imported continental pottery such as Classes D and E ware (Campbell, 2007, 73) could theoretically have been produced in different continental centres than the one producing Eastern English material, even though they have been not yet identified. Other imports (group B in Campbell's work) better resemble Anglo-Saxon English production, albeit with some difference in shape, quality of glass, colour, and decoration which, according to Campbell, could also imply a different source from group C and D (possibly England or parts of the Continent). Such imports would have reached Western Britain though a variety of overland routes from Anglo-Saxon England (Campbell, 2007, fig. 48, 73).

Even though I would be personally careful to suggest production differences based only on typological features, it would be incredibly stimulating to compare analytical results from both Western and Eastern England glass to see if this difference in typological features translates into a difference in raw materials, hence suggesting the possible existence of distinct glass production Continental centres. I will describe

[25] Evison (2000a; 2008, 7-8) goes into a very detailed description of typological vessels distribution and comparison with the European Continent.

now the existing evidence (direct and indirect) for glass-working in Middle and Late Anglo-Saxon period, contemporary of Barking Abbey.

2.4.2.1 Glastonbury

Excavated between 1955 and 1957 firstly by Radford and then later by Harden, the latter never published the result of his work. The material evidence was later examined and published by Bayley (2000b)[26] and Evison (2000b)[27] together with a brief catalogue of the materials recovered. Unfortunately, part of the excavated materials has been lost (Evison, 2000b, 189); and for these materials, no measures or drawings remain.

Willmott and Welham (2007; 2015) recently reconsidered Harden's work and finally published the furnaces, together with a new brief summary of evidence connected with glass-making (Willmott and Welham 2007; 2015, 219). Three glass-making areas were excavated, each of them showing remains of some glass-making activity (Willmott and Welham 2015, 219-32; fig. 7.1, 220; fig. 7.2, 221):

- **Glass-making area A**: discovered in 1955, during the same campaign when Furnace 1 and 2 were found. Furnace 1 included an oval structure (the furnace itself, 1.8 m x 1.2 external) with east to west orientation, the remains of the wall of the furnace (13cm wide) which it has been labelled as "kerb", remains for a furnace floor made with re-used Roman tiles and red clay (burnt by the heat of the furnace). Recorded and surviving elements also

[26] Concerning the complete catalogue of glass-making evidence drafted by Harden and edited later by Bayley, see Bayley, 2000b, 176-86. This catalogue includes also the glass that did not survived to this day.
[27] The surviving glass was further catalogued by Evison (2000b, 195-99), including a more specific colour and shape characterisation.

allowed excavators to reconstruct the superstructure, which Willmott and Welham (2015, 231; fig. 7.12; 232) compare closely with the so-called Roman circular “pot furnace” type experimentally reproduced by Taylor and Hill (2008).

Furnace 2 was recorded by Harden himself south of Furnace 1, with the same size and orientation (SW-NE) as the latter. Discussing furnace 2 written notes and plan (LA35) left by Harden, Willmott and Welham (2015) question the actual existence of the furnace 2, given that the section draw by Harden does not show effectively any notable feature connected to glass-making (Willmott and Welham, 2015, fig. 7.2, 221). On the other hand, furnace 2 might pre-date furnace 1, with furnace 2 being demolished before furnace 1 was built and the removal of most glass-making debris (Willmott and Welham, 2015, 224). Also, the concentration of glass-working debris south towards furnace 2 support the existence of furnace 2 in the first place.

Evison (Evison, 2000b, 189; 196-9) describes the association of 28 fragments with furnace 2, including glass-working debris (16 pieces), while Willmott and Welham (2015, 224) remark how 28 crucibles out of 29 fragments were recovered in this area.

- **Glass-making B:** located 5m West of glass-making area A, this area was excavated between 1956 and 1957. One furnace was recovered in this area (furnace 3): one oval chamber (2 m by 1.4 m, externally), north-west to south-east orientation, together with a stokehole and a stoking pit (Willmott and Welham, 2015, fig. 7.6, 226). Since the structure was built directly on natural clay, it appeared that no earlier structure was built before furnace 3, unlike to furnace 2. Sadly, no finds survive from this area to this

day (Willmott and Welham, 2015, 228)[28], therefore it is impossible to comment of the kind of glass was worked here.

- **Glass-making area C**: this area was heavily disturbed by later activities, and the recordings of the relative findings were relatively sparse (Willmott and Welham, 2015, 228). Two furnaces were recorded. Furnace 4 is identified by Willmott and Welham (2015, 229) as directly beneath between CLE1 and CLF4 areas, with a large burnt clay mixed with glass and slags is associated with the same furnace. When the furnace was out of production, the whole area has been levelled by a redeposited level of clay. A semi-circular portion of burned clay suggest the existence of another furnace (number 5) in north section of CLE1 in area C (Willmott and Welham, 2015, 229; fig. 7.1, 220).

Only a few finds (19 out of 33 reported previously) originally reported has been found. Evison (2000b, 189) reports only one fragment (now lost) out of the ones not associated with furnace debris. Finds in area C include also glass-working tools: a curved iron tube, possibly a portion of a blowing iron. Other artefacts discussed by Evison (2000b, 195-99) include 22 undiagnostic vessels glass, windows, glass making debris (such as moils, coloured pieces used probably to make trail decoration, rods, and wasters), one tessera (debated, opaque light blue-green), a bead (one light blue-green barrel shaped) Even though it was initially suggested that furnace 1 and 3 were annealing ovens, Willmott and Welham consider them as melting furnaces (2015, 229). The furnaces' activity period has been long debated: initially dated between the 9th and the 10th centuries AD, an earlier chronology (7th - 8th century AD) has also

[28] Harden noted of a single fragment of green glass above the furnace, but it is now lost (Bayley 2000, 166).

been considered by Evison (Evison, 2000b, 193-4) based on the typological analysis of the artefacts.

2.4.2.2 Jarrow

The monastic site of Jarrow is located in the coastal region of the historic County of Durham, inland on the south bank of the Tyne, in low-lying marshy land at the eastern end of the Tyne Gap (Cramp, 2005, 5-8). Its foundation must be placed eight years after the foundation of the twin monastic complex of Wearmouth (respectively founded in 681 and in 673 AD).

No glass-making evidence has been connected with the Jarrow-Wearmouth monastic complex, but some evidence suggest that glass-working might have instead occurred. Glass consumption in both sites included window and vessels fragments. More so, it comprises also original shapes and decoration patterns when compared to other known British contexts.

Three monastic buildings (Building A, B, and D) at the Anglo-Saxon monastery of Jarrow lay to the south of the cemetery and extended down the slope to the river (Cramp, 2005, 187): the same buildings have been connected with fragments of window glass. Based on the quality of manufacture and on the internal detail of the structure itself, building A is dated around the first Saxon building phase, c. 683-700 AD (Cramp, 2005, 201). Building B seems to belong to the same first monastic plan given their small constructional differences, and possibly built sequentially before building A (Cramp, 2005, 207). Industrial use (glass-working, copper-alloy, and lead melting) of building D has been attributed

to a later phase of the 9th century AD based on the presence of two coins (Cramp, 2005, 226)[29].

In total, 1756 fragments of window glass have been found at Jarrow, and 298 at Wearmouth, overall dated between 7th and 8th century AD (Cramp 2006, 56), in a wide range of colours (Cramp, 2006, fig. 27.1.11, 69). These range from the series of blues, greens and blue-green to colourless, to amber, yellow, and opaque red glass; the latter is quite common in Jarrow-Wearmouth, to the contrary of other English glass dataset[30]. Interestingly enough, Bede (Cramp, 2006,56) mentions that in 674 Benedict sent for continental glaziers to glaze the window of the church, *porticus* and refectories or upper stories, because this particular skill was the time unknown in Britain. The 7th century AD presence of artisans at Jarrow does not necessarily exclude that a later local production could have been established in Jarrow, this time with the help of local artisans and not from the Continent.

As for vessel glass, 51 are associated with Jarrow and 6 with Wearmouth. The most common types present on sites were globular beakers, palm cups, and funnel beakers, which suggests a date for the same fragments around 700-900 AD. Vessel fragments do not seem to be a random collection of cullet: it is more plausible to consider them as the results of breakage after normal domestic use, and then possibly have been gathered to be re-used in the future as cullet.

Jarrow is also connected to manufacture of glass, with both direct and indirect evidence. Riverside buildings, located east to building D, hold remains of presumed workshops phase: phase 3a (first workshop) and

[29] The first coin is one of Eanred (AD 810–41), while the second belongs to Athelred II (AD 841–50).
[30] Cramp remarks that red opaque glass is quite rare in other 7th century AD British context, but that in Jarrow-Wearmouth is more common, with red-streaked glass concentrated in particular in Jarrow's building D (Cramp, 2006, 63); other red opaque glass used in windows has been found only at Glastonbury monastic complex.

phase 4a and b (second workshop) have both been associated with glass-working production.

Phase 4a, dated after mid-9th century AD (Cramp, 2005, 241)[31], includes a hearth filled with layers of mixed ash, charcoals and clays have been found (Cramp, 2005, 235), while phase 4b shows evidence for another hearth associated to glass fragments (Cramp, 2005, 235-6).

Concerning glass-working, in building A, the end part of a millefiori rod was found (Cramp 2006, 263-4), while two portions of millefiori rod were found in phase 2 of building D (Cramp, 2005, 224). Finally, east to building D, Riverside buildings also shows the occurrence of millefiori rods (Cramp, 2006, 470), hinting at the hypothesis that this specific production could have occurred at least in these three close areas at Jarrow.

The millefiori rod at Riverside buildings is also associated to so-called "dish-type" crucibles fragment in phase 4a and 4b, which would support the idea of some glass-working/craft activities were occurring in the area. Analytical results performed on crucibles glass layers revealed that they were made using two different types of clay, one rich and one poor in iron. The latter type shows a uniform layer high lead yellow glaze[32] distributed to the whole surface of the crucibles: it has been therefore suggested that these crucibles could have a specific use, as containers of some sort of specific substance resins, unguents, or oil (hence the protective and impermeable layer). On the other hand they might have been connected to the glazing process itself in the first place (Cramp, 2006, 273).

---

[31] Phase 4a and 4b chronology's (and therefore the workshop's) is defined by the association with *stycas* coins dated indeed to the 9th century AD (Cramp, 2006, 470) building A was also associated with the same type *stycas* (Mills and Cramps 2006, 470) and therefore share the same chronology.

[32] Although chronologically more recent (late Anglo-Saxon) when compared to Jarrow, Bayley also describes other crucibles fragments with yellow glass layers: at Gloucester, Lincoln (Flaxengate), York (Coppergate); only Gloucester and York show evidence for high lead glass though (Bayley, 2000a).

Window glass production has been connected to a different crucible shape, and in particular to a two-piece jar crucible found in workshop phase 4a of Riverside buildings: analysis of a superficial layer of glass from the same crucible show similar high Na_2O composition to the window glass from Jarrow (Cramp, 2006, 470).

Finally, other fragments of crucibles have also been found associated with fuel ashes and parts of tuyères at Jarrow (Cramp, 2006, 470; fig. 35.1.1, 471) in the south-east corner of the site, south to building A, within the medieval cloister (trench 7006), and finally south-west of the church (trenches 7001 and 6501).

It seems therefore that at least window glass, millefiori, and high-lead yellow glass could have been worked at Jarrow in the 9th century AD in different areas of the monastery.

Hamwic:

No furnace or any other similar structure connected to a glass workshop have been found to Middle Saxon Hamwic (modern Southampton, Hampshire). Nonetheless, two excavations have given one of the most important and largest Anglo-Saxon glass datasets: c. 100 fragment from “Melbourne street excavations” (Hunter and Holdsworth, 1980) and c. 1700 fragments of glass were recovered in an overall number of 32 sites excavated since 1946 in Saxon Southampton (Hunter and Heyworth, 1998, fig. 2.5).

The importance of Hamwic glass dataset resides in not only in the substantial number of fragments, but also in the well-known typological comparison mostly with the Continent (more specifically with the Rhineland region and Northern France production and Scandinavia suggested in various publications). Hunter and Heyworth (Hunter and Heyworth, 1998, xi; 56) state that 90% of the total Hamwic glass includes

vessels: both datasets (Melbourne street and later Hamwic excavation) are typologically dominated by palm cups and funnel beakers. Hence, the typological range would suggests a chronology for glass from Hamwic predominantly between the 8th and the 9th century AD (Hunter and Holdsworth, 1980, 71; Hunter and Heyworth, 1998, 56). Across the 32 sites presented in Hunter and Heyworth's work, only 4% of would be window fragments, beads, wasters (Hunter and Heyworth, 1998, 4; 26), of which 17 wasters (such as droplets/globules and a partially formed trail) would indicate that some sort of glass-working activities was occurring, such as bead-making.

Even if such evidence might be considered scarce, the presence of some droplets cannot be ignored together with a small number of ceramic sherds and stones with some glass droplets adhering on the surface (Hunter and Heyworth, 1998, 61). A concentration of the latter has been found in SOU 169 area, together with two "hearths of furnace features", but none of which could be identified as glass-making or working structure, neither any working debris was found in place. Indicators of glass-working practices in Melbourne excavations are also limited: just one dark blue rod cut at both ends, which suggests the possibility of local glass-working (Hunter and Holdsworth, 1980, 71).

2.4.2.3 Flixborough

90 sherds of glass are associated with the Anglo-Saxon site of Flixborough, of which seventeen are window glass fragments, sixty-nine vessels, one bead, one tessera, and the remaining is melted waste. Based mostly on rim, base fragments, and wall fragments with distinctive features, Evison (2009, 103) suggests that Flixborough shows original Anglo-Saxon forms, with few examples of drinking vessels in use between 700-900 AD (such as palm cups and funnel beakers), and several vessel fragments (at least seven different vessels) decorated with

reticella rods of different colours (Evison, 2009, 105ff.), such as yellow and white trails.

Aside from vessels and window glasses, two other objects were recovered in Flixborough: one streaky blue tessera (Evison, 2009, 108), which Evison connects to glass-working (such as trail decoration or provide colour to melted glass), plus one multi-coloured bead (Evison, 2009, 109; fig. 2.3, 108), which Evison describes as "*a light and dark green reticella background and an elongated "ring-a-dot" motif on each side*". The latter bead figures as n° J001 in Callmer's system (Callmer 1970, 99) and its occurrence is dated from 790 to 845 AD. Interestingly, this type of bead occurs in Scandinavia, Europe, and also in the Middle East, where it was probably produced (Callmer, 1977, 99).

The tessera and the melted waste suggest the existence of glass-making practices to some degree, even though limited (Evison 2009, 109).

2.4.2.4 Kirkdale (North Yorkshire)

During 1994 excavations, trench II on the North side of the present churchyard, a structure together with several large postholes were located. Associated to these, a layer of dark soil (possibly connected with the destruction phase of the same building) showed evidence for several craft debris (charcoal, slag, and other debris), including glass-working. In the same layer, one piece of glass rod was found.

Paynter (2014, 33) remarks the association of the same rod with a metal strip with an inscription in Old English (Waltz et al. 1997; fig. 2, 55), which Rahtz and Watts (2003, 300) date to the 8th- 9th century AD. The same rod, 5.75mm long and 2.9mm in diameter, is of a pale blue-green/colourless colour, broken at both ends: 2 applied trails of glass, one opaque white and one opaque yellow, decorate the object.

2.4.2.5 Whitby Abbey

The first abbey was founded after the battle of Winwead in 655 AD (Jennings 2005, 207). After being destroyed by the Danes and a period of abandonment, it was later turned into a Benedictine monastery around 1078 AD (Hunter et al. 2005; Jennings 2005, 207). Two small plaques were recovered during the first period of excavation in the 1920s made from coloured twisted canes decorated with white and yellow opaque glass fused to a clear glass backing (Jennings 2005, fig. 1, 207).

Recent excavation campaigns between 1993 and 2007 were carried out on the Headland outside the Monastic area. Two trenches (U1 and U2) near the cliff edge and to the north east of the Abbey ruins (Hunter et al. 2005, fig. 1.c, appendix 2; Paynter 2014, 32) revealed evidence for a large timber building (9.2 m wide and at least 15 m long), with four large pits 4.5 m (evidence for central postholes) from the side walls and heading down to the centre of the building. The structure has been given a possible date around the mid-9th century AD.

Probably after abandoning the structure, the large postholes were filled with craft work debris from high temperature industries, such as iron-smiting and lead working, including glass-working. Seventeen fragments in total, such as chips, dribbles, rounded chunks of deep blue glass, and finally two pieces of reticella rod found associated with these pits: one reticella piece was blue-green and the other was instead made with blue glass, both with opaque white trails (Paynter and Dungworth 2011, 11; Paynter 2014, 32).

2.4.3 Northern Europe

Looking at sites such as Ribe (chapter 3) or Kaupang, both archaeological evidence and glass materials leave no doubt that glass was worked there, but evidence for glass-working in Northern Europe in the Early Medieval period is still scarce considering not only the vast area investigated but also the amount of material that has been recovered.

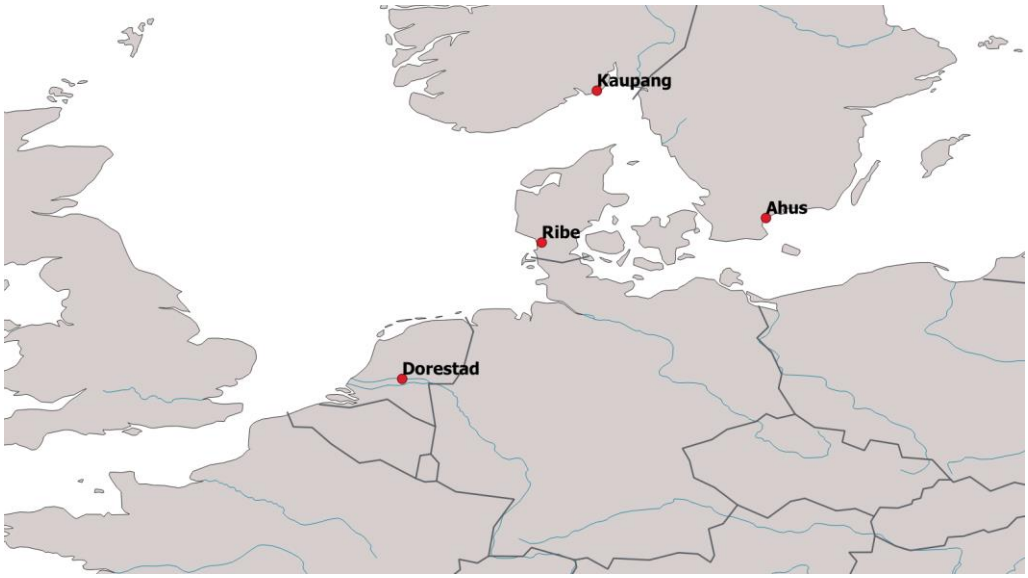


Figure 8 – Southern Scandinavia map. Site with secondary glass-making evidence cited in the text have been highlighted.

2.4.3.1 Dorestad (Netherlands)

The early Medieval occupation of the Harbour area in Dorestad was studied through five different archaeological campaigns between 1971 and 1975 (Van Es and Verwers, 2009, table 1,9): each campaign, labelled respectively *Hoogstraat 0*, *I*, *II*, *III*, and *IV*, correspond to five complexes of excavation trenches in the left bank of the river Rhine (west to east direction). The results of *Hoogstraat I* were published in 1980 (Van

Es and Verwers, 1980); the remaining 4 campaigns (0-II-III-IV) in 2009 instead (Van Es and Verwers, 2009).

An extensive catalogue of all glass fragment found in *Hoogstraat* excavation has been published by Isings (Isings, 2009, 1980). In summary, most of the glass can be ascribed to palm cups or funnel beakers types; bowls and squat jars are also represented, some with *in calmo*[33] rim decoration. In addition, some bowls show reticella trails as decorations on their body.

Most of mosaic tesserae have been discussed in Preiß's work (2010), but a couple more (white and cobalt blue, possibly Roman origin) have been found in Hoogstraat IV (Isings, 2009, 277-78). Beads have also been found in Dorestad: Isings (Isings, 1980, 264-5; 2009, 233-5) mentioned them in *Hoogstraat I* (n= 17, mostly monochrome), *Hoogstraat III* (n=4), and *Hoogstraat IV* (n=2). Concerning glass-working, other finds[34] (n=85) possibly connected with glass-working are discussed by Preiß, such as tesserae (n=36) glass lumps, drops/threads and deformed glass fragments (2010, 123). Bead-making might have occurring (Willemsen, 2009; Isings, 2010) and the same suggestion has been made regarding vessels' production. Even though this is definitely a possibility, no furnace or glass-working workshop evidence has been mentioned in these reports. Isings (2009, 277) also remarks that no proof of glass working is directly connected with mosaic tesserae used as scrap material in Dorestad. Hence, for now Dorestad should be seen as a centre of glass consumption and distribution rather than production[35].

[33] *Incalmo* or *in calmo* (Italian): technique of constructing an object (usually a vessel) by fusing two or more blown glass elements (Whitehouse 2006, 45).

[34] Reports concerning these new finds can be found in Van Es et al. 1993, 45; 1994, 45.

[35] It is also altogether possible that more diagnostic evidence for glass-working might be located in not-yet excavated areas.

2.4.3.2 Ähus (Sweden)

The site of Ähus (Southern Sweden) is located on the lower Helge River in North-eastern Scania (Callmer, 2002, 126). Two excavation areas, respectively named as *Ähus I* and *II* were excavated between the late 1970s and mid 1980s and dated to the early 8th century (700-750 AD and 750-800 AD respectively). Both sites have revealed glass materials (Callmer, 2002, 136-7). The distribution of glass is quite uneven between the two sites: on the whole, more than 70000 pieces of glass were recovered at the earlier site of *Ähus I* (Callmer, 2002, 141). On the other hand, at *Ähus II* the fragments' number is relatively lower, with only 124 units including lumps, drops, slag, tesserae, and various undetermined pieces.

No primary production evidence has been recognized at Ähus (Callmer and Henderson, 1991, 144). On the other hand, according to Callmer (2002, 138) beads were probably made at both sites. In addition to *Ähus I* impressive number of glass fragments, other evidence would point out to the occurring of bead-making such as presence of glass debris, pits, hearts, and the remains of two damaged ovens plus the pieces of other destroyed ones (Callmer and Henderson 1911, 143; fig. 1, 144). At *Ähus II*, even though most glass debris associated to bead-making[36] is concentrated only in the riverine part and on a few plots in the eastern part (Callmer 2002, fig. 8, 142), the nature of the finds does not allow us to restrict glass-working to a precise area of the site.

Glass-working at both sites has been possible through glass import, which is discussed by Callmer and Henderson (1991), in particular referring to some category of glass. First, most of Ähus glass is blue coloured, 47 % of which is made by sherds or flakes, which bigger flakes could have possibly come from some sort of imported glass cakes/ingots

[36] Interestingly enough, many beads found in Ähus II are defective, suggesting a local production (Callmer 2002, 141).

(Callmer and Henderson, 1991, 144; fig. 2, 146)[37]. Secondly, Callmer suggested that some mosaic tesserae could have been imported from the West or Southern Mediterranean area (Callmer and Henderson, 1991, 146)[38]. Finally, millefiori rods (commonly the blue and yellow chequer pattern framed with red opaque glass variant) must have been imported already made to Ähus.

2.4.3.3 Kaupang (Norway)

The site of Kaupang is located in county Vestfold at the mouth of the Oslofjord, near present-day town of Larvik (South-East Norway). Since the 1950s, three major survey and excavation campaigns unearthed the remains of a Viking Age specialised production and market site of roughly 54,000 m^2 with activity from about 9th - mid-10th century (Skre, 2007, 2008; Pilø and Skre, 2011).

In addition to the market place, in the surrounding the settlement area several large cemeteries have been discovered, some of which have been studied since the 19th century[39]. The Kaupang Excavation Project recent work (1998 – 2003) led to the publication of an impressive report concerning Kaupang materials, including glass artefacts (Gaut, 2007; 2011)[40].

Th most recent report on glass materials published by Gaut (2011, 170) reveals that nearly five thousand individual pieces of glass have been

[37] Caller and Henderson (1991, 144) report that c. 78% of glass is made only by transparent blue glass or where the latter constitute the main constituent.

[38] Callmer describes how some tesserae would still show traces of mortar attached, which would be the proof that these tesserae originally belong to a floor pavement or wall.

[39] More specifically, Nicolay Nicolaysen's work on Nordre Kaupang cemetery (Pilø and Skre 2011, 17-18) and later Charlotte Blindheim's 1950-57 excavation of Bikjholberget cemetery (Blindheim, C et al. 1975; Stylegar 2007).

[40] Glass materials have also been published in previous reports; please refer to Gaut 2011, 176 and relative bibliography.

recovered from the settlement area at Kaupang from the archaeological excavations and surveys of 1998–2003[41], and 1103 fragments of vessel and window glass, raw materials and waste from glass-working (such as rods), and other miscellaneous glass objects (tesserae) have been described in the same study. From Kaupang glass, 40% of the glass evidence is associated with stratified Viking-period deposits, the majority of which belongs to three phases (SP I to II) in the main research excavation (MRE) area dated between c. 800 and c. 900 AD (Gaut 2011, 176). Even though most of Kaupang vessel glass is fragmented in very thin pieces, it has been possible to recognise some major shapes based on diagnostic features such as rims. Among the identified vessels (n=148), funnel beakers are the most represented, followed by squat jars and tall palm cups (Gaut 2011, fig. 9.59, 249).

Glass appears to have been deposited throughout the whole settlement area, but no large deposit has been recovered so far during excavations, neither any furnace or semi-fused material (such as frit), which could suggest that primary production was indeed occurring. Nonetheless, aside from vessel glass, the other major category of artefacts is production waste associated mostly with local bead-making but found sporadically across the whole site[42]. The most conclusive evidence for local bead production seems to come in the form of rods and rod ends together with finished and failed annular beads in corresponding colours (Gaut 2011, 234).

[41] A total number of 322 pieces of glass according to the overview of glass Kaupang finds (excluding beads) recovered in the 1998–2003 campaign (Gaut 2011, table 9.1, 176).

[42] Glass-working is concentrated in phase SP I and (mostly) in SP II:1 (Gaut 2011, fig. 926, 201), respectively in phase SP I (plot 1A), SP II:1 (Plot 1A and 3A), and finally SP II:2 (3A and B), after Gaut 2011, 202; 204; 207.

2.5 Previous analytical work

2.5.1 Recent trends in Byzantine and Early Medieval glass studies

In the past fifty years, glass research has come a long way from the original distinction between natron (LMG, or low magnesia glass) and plant ash (HMG, or high magnesia) glass by Sayre and Smith (1961). For natron glass, a major difference in composition has come forward in the last 20 years, namely between the so-called Levantine and HIMT (high iron, manganese, and titanium oxide) recipes. Levantine glass is a blue-green coloured with no added manganese (less than 0.4%), low Fe_2O_3 contents (low impurity, around c. 0.4wt%) and high alumina (c. 3wt%) made with coastal sands of the Syro-Palestinian region, most probably with sand from the River Belus (Brill, 1988; Freestone et al., 2000).

As the acronym implies, “HIMT” definition includes glass with relatively higher contents of iron, manganese, and titanium oxide, respectively around >0.7wt%, c. 1-2wt%, and >0.1wt%: high impurity levels are accompanied by higher soda (>18-19 wt%) and lower lime contents (around 6wt%). High levels of iron and titanium oxides suggests an impure source of silica. Recent Sr isotopic results (low $^{87}Sr/^{86}Sr$ ratio) has suggested not only that HIMT could be the result of mixing two different sands (one beach or marine sand and the other enriched in non-marine materials, such as limestone or volcanic rocks), but also that the silica source might have been sourced in the Middle East, possibly Egypt (Freestone et al., 2005; Leslie et al., 2006). HIMT was manufactured from at least the 4th century in North Sinai until the middle of the 7th century (Nenna, 2014), when primary workshops in Egypt took up its production, but their exact location is still unknown.

Levantine and HIMT have become through the years “umbrella” terms to be used in most of Roman and Post-Roman studies. If on one side, most compositional recipes fall within these two macro-categories, on the other

hand we inevitably witness the multiplying of compositional subgroups. HIMT compositional groups illustrate this situation perfectly. Since the term HIMT was firstly introduced by Freestone (1994), many new subgroups of HIMT have been recognised, but two main groups emerged and have been discussed over the years. One group with relatively higher Fe_2O_3, MnO, TiO_2, and Na_2O levels compared to Levantine, stronger correlation between the same oxides, and lower CaO: Foy 1 (Foy et al., 2003), HIMT1 (Foster and Jackson, 2009), and Maroni 2 (Freestone et al., 2002). The second group on the other hand, presents the same fore-mentioned HIMT characteristics, but in lower amounts, a "weaker HIMT recipe": Foy 2 (Foy et al., 2003); HIMT2 (Foster and Jackson, 2009); Saxon 1 (Freestone and Hughes 2008); weak HIMT (Rosenow and Rehren, 2014); HLIMT (Ceglia et al., 2015), HIMT from Italy (Mirti et al., 2000, 2001).

Two questions that still needs to be answered are first how should this compositional division be interpreted? Secondly, what does it mean in terms of raw materials provenance and recycling?

If, as previously suggested (Freestone, 2005, 154), HIMT sand component is made by mixing two sand sources (a beach/marine sand and one enriched in non-marine material), what is the significance of this raw material mixing? Freestone and colleagues (2005, 154-55) explain this mixture in two ways: first, it could be the result of using one naturally mixed sand. On the other hand, it could also reflect the combination of two different raw glasses (therefore, HIMT would be the result of recycling). Foy and colleagues (Foy et al., 2003; Freestone et al., 2005) suggest an Egyptian source for these glasses based on their high titanium content (common to Egyptian glasses), and their lead, neodymium, oxygen and strontium isotope signatures (Freestone et al., 2005; Leslie et al., 2006): the high soda content and a sand source with mixed geological signatures would indicate a location close to a natron source, potentially around the Nile delta.

In light of the Egyptian provenance hypothesis, what does a division between strong and weak HIMT mean? Does it mirror a different provenance or an expected variation in the same area? And how useful it is to define so many subgroups?

Recent work of Foster and Jackson (2009, 193) on Romano-British glasses interpret the division between their groups (HIMT1 and HIMT2) from Foy and colleagues (2003) work (Foy1- HIMTstrong and Foy 2 - HIMTweak) in light of not only a compositional difference but also a chronological one. HIMT1 and HIMT2 not only differ in major oxide contents from Foy's materials but also chronologically: Foster and Jackson's materials are in fact 4th - 5th century AD glasses, but HIMT1 is slightly later than HIMT2, while Foy 1 and Foy 2 date respectively 5th century AD and 6th - 8th century AD. According to Foster and Jackson the compositional difference between these two HIMT recipes could also reflect changes in production and supply: HIMT2 would be the result of HIMT diluted with other glass compositions (therefore being recycled), while later HIMT1, dominating now the trade markets, would have been made by mixing only HIMT recipes, with the result of a final composition richer in impurities ("stronger").

This approach reminds us how differences in composition should be considered by multiple chronological, technological and manufacturing perspective: HIMT glass is the perfect example of what is sometimes perceived as a unique composition should also being potentially considered as the result of dilution of two or more recipes, as a response in the chain of raw glass supplies or trade. This inevitably complicates the centralised model as presented by Freestone and colleagues (Freestone et al., 2002).

In recent years, very few analytical works have been published concerning Post Roman glass, especially dated between 7th and 9th century AD. The key studies with focus on major and minor elements belonging to primary production areas in the Palestine coast and Syria (Freestone et al., 2000; Tal et al., 2004; Henderson et al., 2004, 2016;

Phelps et al., 2016). Such focus on primary production areas is understandable, because it fulfils the need to examine glass without intermediaries, directly where it was made. However, if researchers of Early Medieval glass focus on just one area, it does not allow research to progress in new directions. The causes may be various: from simply not being willing to do extra analysis, or lack of funding, or not having access to new samples, or possibly not having an interest in publishing materials from peripheral areas.

If the centralised model is accepted as the one in place for Early Medieval glass production, it is imperative to gather more comparative analyses from areas distant from primary production, in order to understand the type of raw glass that was traded, and the impact of mixing and recycling practices and therefore start to fill the gaps in our conceptual glass trade network model: secondary workshops like Ribe for example, show an extraordinary amount of glass but the provenance of such material is still unclear. The same could be said for the other areas explored by this dissertation, Northern Italy or Southern England.

Trace element contributions to the glass recipe have also been explored, in particular concerning their application in understanding recycling practices and silica sources. Enhanced colourant elements, such as Co, Cu, Pb, Sb, and Sn, have been identified as markers for recycling practices in faintly coloured/colourless glasses (Freestone et al., 2002; Henderson, 1995a; Jackson, 2005; Mirti et al., 2000, 2001; Schibille and Freestone, 2013): their presence in a discrete amount cannot be explained in faintly coloured glass if not by through repetitive cycle of recycling or addition of mosaic tesserae to already made glass. As a general rule, 100 ppm has been recognised as possible marker for recycled materials for Cu, Co, Pb, and Sn as 0.1wt% for Sb_2O_5, though as Foster and Jackson (2009, 196) comment on the arbitrary nature of such classifications, which inevitably becomes an obstacle in establishing the recycled nature of glass materials.

The best approach to recycling is to consider the colourant markers contents as well as other elements which mirror recycling and contamination processes. Paynter (2008) in her recent exploration of the effects of contamination through re-melting, proved the contribution of potassium and phosphorus to the recipe, together with iron, alumina, and titanium oxides enrichment from glass-working instruments, pots used as crucibles, and furnace lining. Firstly, the alkali-rich waste gases in wood-fired glass-working furnaces can affect the composition of the glass when heated over prolonged periods: this will result in increased concentration of potash and phosphorus in particular, but also lesser amounts of calcium and magnesium oxides. In addition, all glass would eventually acquire a blue-green tinge (even the colourless one) by absorbing iron, aluminium, and titanium oxides from iron instruments used during glass manufacture (such as pontil rods), clay crucibles, or furnace linings, together with enrichment of such oxides in their composition. Therefore, excess of potash and phosphorus are considered contamination markers in faintly coloured and colourless glass, while the same can be said for excess of aluminium, iron, and titanium oxides in the same glasses.

Recent work of Freestone (2015) and Schibille and colleagues (2016) explore also the effect of contamination associated with recycling by plotting the fraction of Mn in the total concentration of decolourants [$MnO/(MnO+Sb_2O_5)$] together with potassium phosphorus, and iron. This multi-layered approach is potentially able not only to isolate the two end-members from which the recycled materials have been made, but it will also show a component deriving from the primary sand source (not influenced by any manufacturing processes and therefore mirroring the original primary composition), providing a much stronger evidence that the intermediate glass has been formed by mixing the two end-members. Unfortunately, such an approach can be applied only to faintly coloured or colourless glasses, therefore limiting the number of samples to be

analysed[43]. Nonetheless, I think that whenever possible, it would be extremely beneficial to approach our material with such a multi-layered approach, in order to maximise our chances of spotting recycling and contamination based on primary raw materials.

Zr, Ti, La, and Cr proved to help discriminating different silica sources[44]. In particular, Shortland and colleagues (2007) showed how the covariation of Zr/Ti and Cr/La can discriminate blue and colourless Late Bronze age glass made in Egypt and Middle East. This ratios combination proved to be effective for two main reasons (Shortland, et al. 2007, 787): firstly, because all four elements show a great variation between the two fore mentioned regions. In second instance, because all four are refractory, non-volatile and their inter-element ratios are not affected by the high temperatures involved in either manufacture or subsequent reprocessing. In other words, these elements are not influenced by primary or secondary manufacture processes, and therefore their concentration in the final glass mirrors the original one from the raw materials sand source. Not only Egyptian material has higher absolute concentration of all elements, but also relatively higher contents of some trace elements when ratios are plotted together (Zr/Ti; Cr/La); for example, Zr/Ti ratios in Egyptian glass is relatively higher compared to the Near East material (Shortland et al., 2007, 788).

Comparing ratios rather than a couple of single components proves to be a more effective way of discriminating recipes, because it emphasises differences already present in the raw materials. A similar approach has been also applied to major elements whenever the singular compositional groups show enough heterogeneity in their raw materials (Ceglia et al., 2015, fig. 3, 219; Cholakova et al., 2016, fig. 5, 630; fig. 7, 631; Phelps et al., 2016, fig. 7, 64; Schibille et al., 2016, fig. 9, 1237).

---

[43] In strongly coloured samples, the presence of colourant markers (such as CuO, PbO, SnO_2, and Sb_2O_5) might also being interpreted as the result of their colouring process.

[44] An excellent summary of their potential in assessing provenance glass raw materials has been done recently by Brems and colleagues (2014).

Unfortunately, the majority of other Roman or Post Roman natron glass compositions does not differ greatly at a major elements' component level because natron source is more constant in its basic components' sourcing area.

Trace elements can also be used to discriminate areas of provenance. Henderson and colleagues (2016) used trace elements mainly connected to both silica sources (Fe and Cr) and plant ash source (Li, Cs, and K)[45] to provide provenance definitions for regional centres of production of 8th - 15th century AD plant ash glass from the Levant, northern Syria and in Iraq and Iran. On one hand there is an increment of both Fe and Cr from West to East, from the Levant and Egypt to Northern Syria, Iraq, and Iran (Henderson et al., 2016, fig. 4, 140). The same geographical distinction is showed when of Cs/k and Li/K ratios are plotted together, with Eastern glasses tend to have higher Li/K ratios, particularly those from Nishapur and Samarra (Henderson et al., 2016, fig. 6, 143). These variations in trace elements vary according to the local geochemistry (Henderson et al., 2016, 139)[46], and such variability is the basic principle according on which such discrimination is possible.

Finally, I cannot finish this brief summary without mentioning the application of isotopes to glass research. Being able to provenance raw materials has always being the ultimate objective in any glass research, but only recently this matter has been started to be explored using isotopic techniques. Sr and Nd have been considered until now the most promising isotopes, respectively $^{87}Sr/^{86}Sr$ mirroring the lime-bearing constituents in the glass (Wedepohl and Baumann, 2000), and $^{143}Nd/^{144}Nd$ ratio reflecting the heavy or non-quartz mineral fraction of the

[45] Henderson and colleagues (2016, 139) explain such an oversimplification might be a problem, since both groups of elements might have been introduced into the recipe by contamination through other sources (silica or plant ashes).

[46] For the Western production area, these variations are ultimately determined by the geochemistry of the mountain ranges such as the Anti-Lebanon, Taurus, Zagros and Elburz from which the principal rivers such as the Barada, Euphrates and Tigris flow. In the East, the Nile in Egypt is a principle contributor to the geo-chemical characteristics of the southern part of the Levantine coast (Henderson et al., 2016, 139).

silica raw material (Degryse and Schneider, 1995, 2008), therefore helping to distinguish the different sand sources[47]. The potential of this technique is still to be explored fully with the identification of lime-bearing sources (coastal sand, limestone, or plant ash) (Freestone et al., 2003; Henderson et al., 2005b, 2009; Leslie et al., 2006; Brems et al., 2013a). Concerning sand sources, the most recent research highlights a contraposition of East vs. West production in Roman times (Degryse and Schneider, 2008; Ganio et al., 2012; Brems et al., 2013b). If glass was indeed produced in the West Mediterranean in Roman times (as both the suitability of sands and Nd signature imply) we should start re-thinking the whole model of centralised production based solely on the Levantine coast from a broader perspective (if not entirely).

In addition, in a recent study, Brems and colleagues (2013b, 461) have pointed out how εNd values in suitable glass-making sand sources from Basilicata and Apulia (Italy) overlap with Middle East values from different suppliers (Degryse and Schneider, 2008): this finding suggests that neodymium isotopic results should be considered more carefully in the future when suggesting provenance.

When considering the Early Medieval period, the amount of isotopic analyses is still not sufficient to trace a satisfying picture of where the glass in Western Europe was traded from: in fact, most of the isotopic work so far is concentrating on Levantine (Freestone et al., 2003; Leslie et al., 2006) and Middle Eastern (Henderson et al., 2005b, 2009) material. The hypothesis of a Western Mediterranean production is directly connected with the recent work of Wedepohl (2.3.6) and the "localised model" of primary production: Wedepohl and Baumann (2000) discuss the "Eifel river area" distinct lead isotopic signature ratios as proof of potential Western primary production located in late 4th century Hambach and Gellep (West Germany), though this result might be

[47] The concentration of Nd within glass can also help to indicate the type of silica used, since the purer the silica the lower its concentration (Henderson et al. 2009).

considered controversial as well, because of the risk of overlapping lead sources (Brill, 2006)[48]. Moreover, Freestone and colleagues (2003, 29) also criticise how Wedepohl and Baumann's (2000) interpret the lower $^{87}Sr/^{86}Sr$ ratios from Hambach and Gellep: being the latter signatures close to Levantine materials of Freestone and colleagues, it is equally probable that the strontium in the German glasses was the result of the use of beach sand, containing shell and some limestone, as a raw material, without the deliberate addition of shell (Freestone et al., 2003, 29).

Finally, a recent investigation of sand, flux, and samples from the Western Mediterranean area (Italy, Gaul, Spain) and North-Africa have been investigated by Sr, Nd, and B isotopes (Degryse, 2014) to reconstruct potential trade routes of both glass and raw materials used in glass-making and therefore creating a database of mineralogical and chemical compositions of possible raw materials (sand and flux) for primary glass making.

To my knowledge, Wedepohl and Baumann's work (2000) remains an isolated case within the isotopic studies. In fact, this PhD project is the first attempt in this direction, since no work has been done so far on material dated between the 7th century and 9th century AD in the three areas pertinent to this dissertation.

[48] Lead isotopes has also been used concurrently with strontium ones to assess the degree of recycling in Sagalassos glass samples (Degryse et al., 2006).

2.5.2 Early Medieval glass analysis in Northern Italy, UK, and Denmark

2.5.2.1 Northern Italy

To this day, no primary production centre is known in Italy. The first question therefore would be what kind of glass was traded to Italy if no glass was made locally? And, did the natron shortage affect the Italian peninsula?

Recent studies were carried out on the Late Byzantine and Early Medieval Italian glass dataset lead to two possible scenarios for the Italian Peninsula. On one hand, Italian glass manufacture in the Late Byzantine period seemed to depend entirely on recycling of old natron glass, mostly mosaic tesserae: since no more natron glass was produced, it was much easier to recycle the old material. This practice seems to suggest not only continuity with the Roman glass-making tradition, but also agrees with the overall contraction in trade for this period (Wickham, 2000, 345).

The 8th century AD glass found in an archaeological deposit in the *exedra* of the Crypta Balbi is a clear example of natron formula persistence in Late Byzantine times. Mirti and colleagues (2001, 492) explain the deposit as result of using the *exedra* as a dump by the nearby monastery of San Lorenzo in Pallacinis. According to electron microprobe analysis, all the samples are sodalime-silica glasses with low contents of both potassium and magnesium (below 1.5wt%), as expected for Roman glass produced with natron as an alkali. The presence of unusual high quantities of elements, like copper, lead and antimony, in mostly of eight-century Crypta Balbi transparent glasses has led the authors to believe that the production was mostly relying on recycled glass (Mirti et al., 2001, 501): coloured mostly in blue, blue/green, green or yellow/green, the presence of the fore-mentioned trace elements is not justified by their

colour outcome. It is indeed possible that these trace elements instead entered the glass by the addition of recycled glass mixed with the original ingot/vessel in the melt, resulting in transparent glass that was mostly iron-coloured (Mirti et al., 2001, 499).

At San Vincenzo al Volturno (Italy), recycled glass represented the only source for glassmakers. Schibille and Freestone carried out electron microprobe analysis on a variety of samples, mostly associated with secondary glass-working (mosaic tesserae, window sheets, etc): the results showed that they were all soda-lime-silica natron glasses, similar to 1st and 3rd century AD Roman material (Schibille and Freestone, 2013, 10).

San Vincenzo production revolved around three different manufacturing phases:

- Glass entirely made from mosaic tesserae (group 1).
- Weakly coloured glass (group 2).
- Colourless glass (group 3).

Group 3 was entirely made from old Roman colourless glass and used to make vessels and windows. The other two groups are more difficult to interpret. In particular, group 1 is formed almost exclusively by mosaic tesserae, which were melted to decorate other glass (mostly vessels), but also to produce transparent glass belonging to group 2. Group 2 is formed instead by weakly coloured glass made by mixing and melting together opaque and transparent glass.

The same group shows unusual high levels of CuO, PbO and Sb_2O_5 that did not influence their colour outcome: therefore, these unusual levels had to come from another source, possibly recycling. The positive correlation between levels of antimony and cobalt oxides in tesserae with different blue finishes proves how blue transparent glass at San Vincenzo was produced by remelting of different hues of blue tesserae (Figure 9).

Since the overall glass compositions seems tightly homogeneous, the authors suggest that all the glass found at San Vincenzo was taken from the same source, possibly a single old Roman building (Schibille and Freestone, 2013, 11).

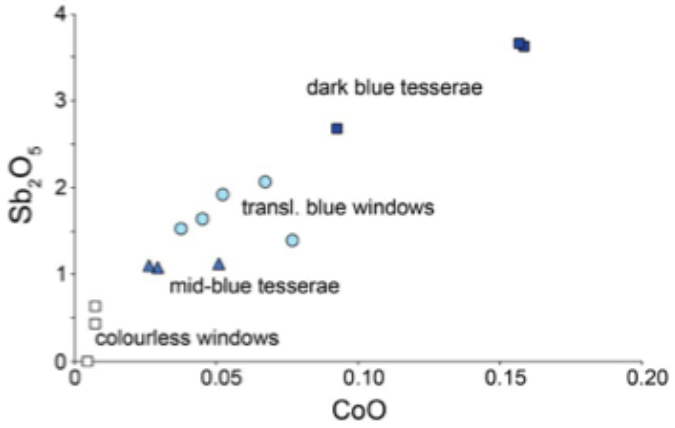


Figure 9 - CoO vs. Sb_2O_5 oxide in blue glasses from San Vincenzo al Volturno, after Schibille and Freestone, 2013, fig. 4, 8.

Although at San Vincenzo's workshop continuity is observed with the Roman glassmaking tradition, in other areas of the Italian peninsula glass chemical compositions start to show more variability, as observed in the same period in the Levant. Staring with the Early Medieval period in Northern Italy there is evidence for both plant ash and mixing of plant ash and natron.

It is still debated if primary production was occurring on the island of Torcello, since no frit has been found on the site (Andreescu-Treadgold et al., 2006, 120). The presence of the furnaces and vessels (goblets and beakers), associated with other bi-products of secondary production like waste (droplets and test pieces), flat glass (probably window glass), and finally mosaic tesserae suggest that without a doubt secondary production was carried out. Moreover, the chemical composition of the residual glass layers adhering to the inner surface of the crucible associated with the inner part of the furnaces indicates that only natron glass was melted in Torcello (Verità et al., 2002).

Natron glass was not the only chemical group found in the Veneto. Verità and colleagues report the presence of a plant ash group samples in material from the Venetian lagoon (2002): the high content of both K_2O and P_2O_5 (Figure 10) in glass found in layer IV (10th - 12th century) suggests that a different alkali source (plant ash) has been used.

Different hypotheses can be suggested for an early presence of plant ash glass in this territory: it could have been primarily manufactured in Torcello, or ingots of plant ash could have been imported directly from the Levant. According to Verità and colleagues the latter hypothesis (2002, 264) is the most probable, as no plant ash glass has been found on the bottom of crucibles used to carry out secondary production in Torcello workshop (Verità et al., 2002, 269), and plant ash is dated to a more recent period than the Torcello workshop (9th - 10th century AD)[49].

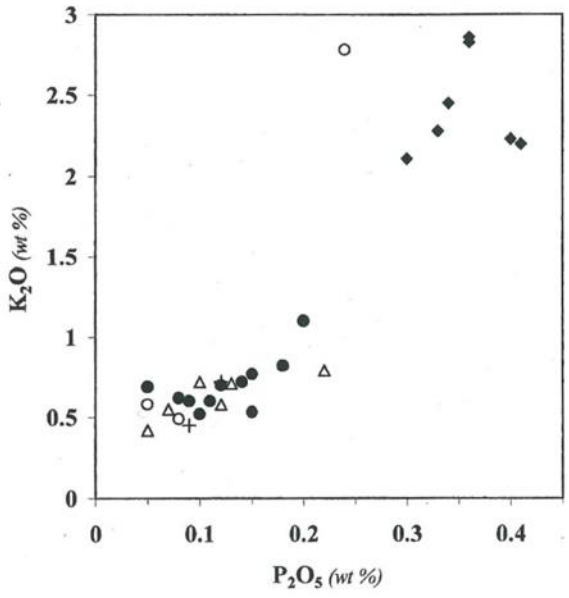


Figure 10 – P_2O_5 vs. K_2O contents in Torcello glass samples dated from the 7th to 12th century AD, after (Verità et al., 2002, fig. 1, 264). Black diamonds (top right) highlight the plant ash glass compositional, opposite to the natron one (white circles and triangles, black triangles).

[49] Mostly of these plant ash samples are tesserae, together with only two vessels and one piece of scrap glass (Verità et al. 2002, tab. 1, 263).

To this day, the provenance of a conspicuous group of mosaic tesserae belonging to the Santa Assunta Basilica in Torcello west wall has not yet been explained. Analysis of some mosaic tesserae samples belonging to the 11th and 12th century AD was carried out by Andreescu and Henderson (2006). A total of three different chemical compositions were underlined in the original 11th century construction phase (Andreescu-Treadgold et al. 2006, 121): the first expected natron group is accompanied by a plant ash and an intermediate one (Figure 11), this latter composition being predominant (c. 48.5 %).

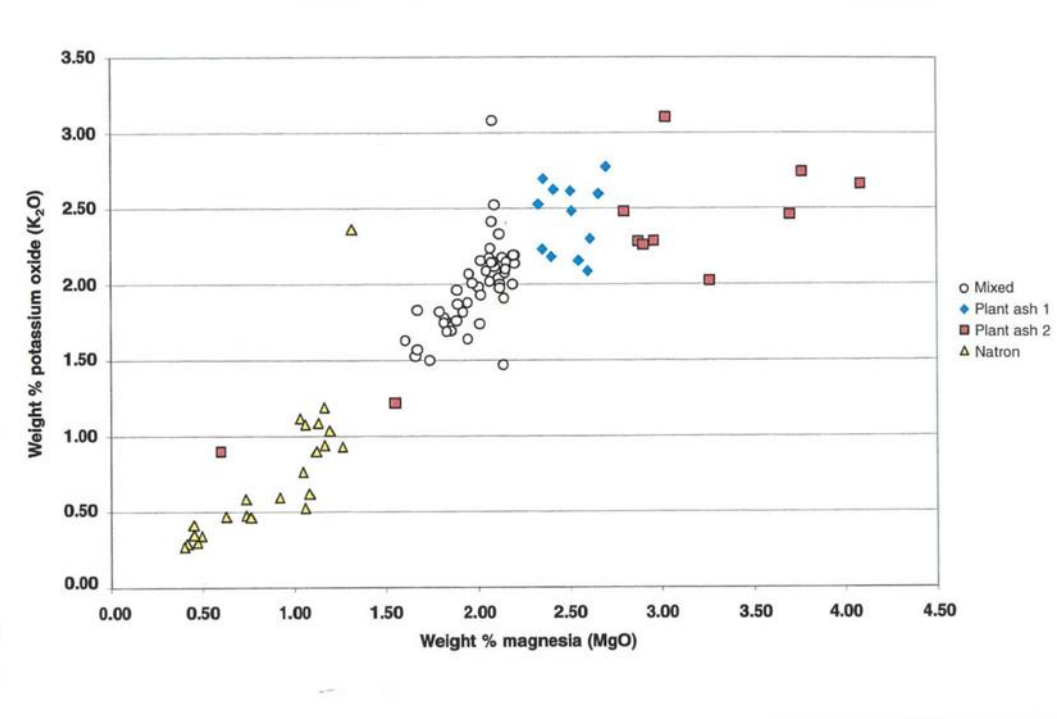


Figure 11 – K_2O vs. MgO contents in Santa Maria Assunta glass samples, Torcello, after Andreescu-Treadgold et al., 2006, fig. 3, 125. Three compositional groups are underlined: natron, plant ash, and a mixed group.

According to the authors, this latter is the result of experimentation by mixing natron and plant ash compositions: plant ash would have been used to dilute the remaining amounts of natron glass (Andreescu-Treadgold et al. 2006, 137). The same consideration made about plant ash analysed by Verita' and colleagues (see above) could be suggested for plant ash in Santa Maria Assunta.

Andreescu and Henderson suggests that the tesserae where manufactured somewhere else, more specifically in Byzantium, and then imported to Torcello in a finished state (Andreescu-Treadgold et al., 2006, 137).

The trade hypothesis is also potentially confirmed by a group of glass dated between the 8th and the 12th century AD (group 2) analysed by Verità' and Toninato (1990, tab. III, 73)[50]. A group of these samples belonging to second group (Ferrara and St. Arian Island samples) shows a similar chemical composition with two cullet fragments found at the Serçe Limani shipwreck, dated to the 11th century AD (Verita and Toninato, 1990, 173). The similarities with Serçe Limani glass open a new scenario of trade and exchange with the East Mediterranean area which has definitely to be considered.

Other Northern Italian glass datasets recall compositions similar to primary workshops. Glass from Lombardy (4th to 12th century) analysed by Uboldi and Verità shows a gradual passage from natron to plant ash composition (2003, 136), reflecting in a way the same transition that was occurring at the primary workshop of Al Raqqa (Syria). A low-potash, low phosphorous group (natron); a high-potash and high-phosphorous (plant ash); and finally, an intermediate group can be distinguished (Figure 12). Uboldi and Verità considered the intermediate composition as the result of melting natron and plant ash together (2003, 132). Based on minor and trace elements, Uboldi and Verità divided the natron group in three distinct sub-groups (N1, N2, and NR).

NR group shows evidence of recycling previously made natron glass: the unusual content of antimony, copper, lead, and tin oxides in their composition has no technological significance (their percentage is too

[50] In the same group of glass, the same intermediate mixing between natron and plant ash as registered in the Torcello materials can also be observed (Verità and Toninato, 1990).

low to have been intentionally added to the recipe), and therefore has to come from another source (Uboldi and Verità, 2003, 127).

Plant ash glasses continue to occur in later glasses (10th-11th century AD) found at the site of Nogara, located thirty-five km south of Verona (Silvestri and Marcante, 2011).

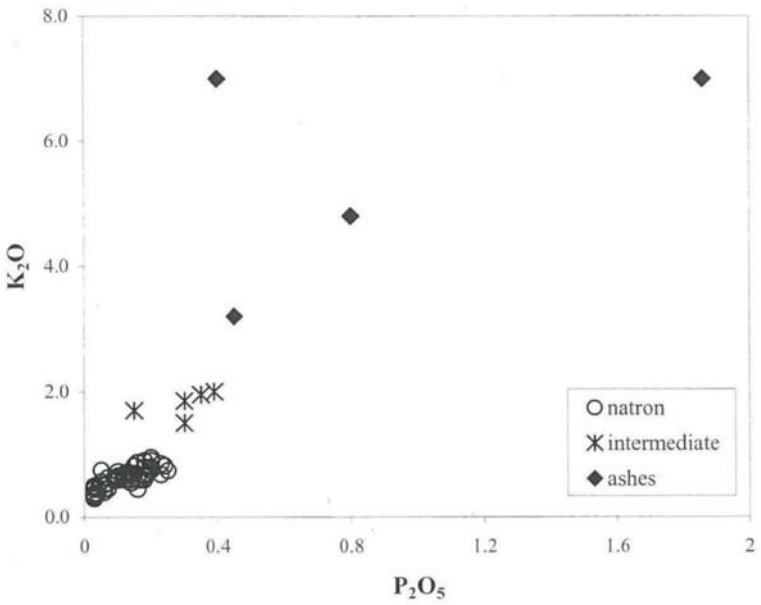


Figure 12 - P_2O_5 vs. K_2O contents in Northern Italian glasses, after Verità' and Uboldi 2003, fig. 10, 125.

Electron microprobe analysis for Nogara samples identifies three different compositions of soda-lime-silica glass: most of Nogara samples have a natron composition, but a small percentage of plant ash is recorded (Figure 13). The same mixing of plant ash and natron displayed at Santa Maria Assunta and Lombardy occurs in Nogara too. According to Silvestri and Marcante, natron glasses from Nogara have a composition similar to 1st - 3rd century AD glass, but at the same they show a higher content of Fe_2O_3, TiO_2, MnO, MgO and Zr. Authors suggest that Nogara natron glass is a mixture of early Roman glass with small quantity of later compositions, like for example Levantine or HIMT types: the continuous recycling cycles would have caused the high trace

elements values and the homogenous final compositional outcome (2011, 2517).

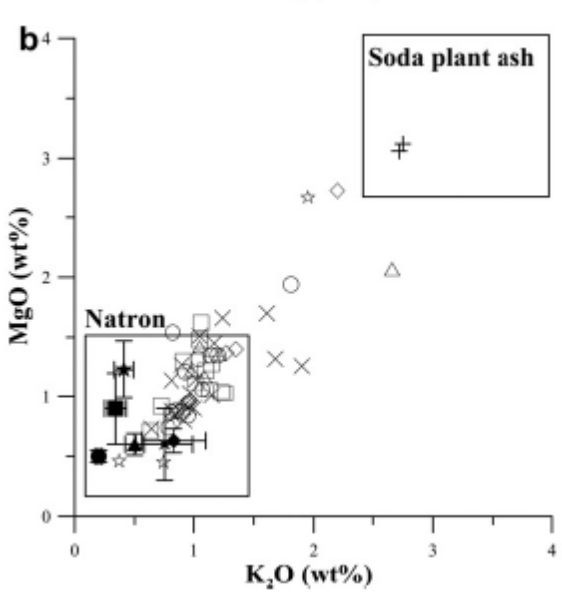


Figure 13 - K_2O vs. MgO contents in Nogara glasses compared with other chemical compositions (Levantine I, Levantine II, Egypt I, Egypt II, and HITM), after Silvestri and Marcante 2011, fig. 4, 2517.

2.5.2.2 UK

Few analytical studies have been published so far concerning glass materials from England dated to the Early Medieval period. The majority of analytical work has instead concentrated on Romano-British glasses (Jackson, 1997, 2005; Jackson et al., 2003; Baxter et al., 2005; Foster and Jackson, 2009; Jackson and Paynter, 2016). Sanderson and colleagues (Sanderson et al., 1984, 65-66) discussing Early Medieval funnel beakers composition from Hamwic and from Dorestad (The Netherlands) and Helgo (Sweden), noticed a significant compositional difference in major elements between Hamwic and the other two sites, in particular with sodium, magnesium, calcium, and manganese contents. Therefore, glass from Hamwic could have been made with different raw materials from glass from the Continent, potentially even locally.

Unfortunately, to this day there is no evidence that would support glass production for Saxon Britain, even though at least two centres, Glastonbury and Barking Abbey, show evidence of furnaces that potentially were able to bear glass-working activities. Hamwic at that time was port of trade for many goods, and therefore glass from the Continent could have been traded easily from the place of production.

Recently, Freestone et al. have interpreted new data that could point in a new direction (Freestone, and Hughes, 2006; Freestone et al. 2008). Discussing the results of major and minor element analysis, Freestone and Hughes show the similarity of Jarrow glass with the one produced in the Syrio-Palestine region (Levantine I), in particular with CaO and Al_2O_3 contents: Anglo-Saxon Britain could have received glass directly or through intermediaries from the Levantine coast and Britain is in some way included in the centralised model as consumer of glass from the Near East. Fascinating enough, Jarrow glass does not match precisely with the southern compositions (Freestone and Hughes, 2006, 153): as a matter of fact, iron and aluminium oxide values falls in-between Levantine and HIMT compositions (Freestone and Hughes, 2006, fig. 27.3.4, 153), which could reflect contamination or Jarrow glass being the result of mixing two different types of raw glass. These values agree with Freestone et al. other hypothesis (Freestone et al. 2008, 31) that Anglo-Saxon glass in Britain might have originated from recycling old Roman glass by British glass-makers after the departure of Rome. Also, plant ash recipe was found in 6th and 7th century AD period II group of Freestone et al. material from the British Museum (Freestone et al., 2008). Even though this group is not “pure” plant ash, it might be the result of mixing of a natron-rich material with a plant-rich material (Freestone et al., 2008, 37), as suggested by its positive correlation between potassium and phosphorus oxides.

This observation paints a much more lively context compared to the one that was considered before, and two questions come to mind: is this

mixed glass imported or is it mixed locally? And as a result, where was this plant ash sourced from?

Both examples reflect how little information we still possess on Saxon glass and how we lack comparable results. Further analytical work, including the one presented in this dissertation will contribute to glass-making and working in Britain during the Early Medieval period knowledge.

2.5.2.3 Scandinavia

There is no structural evidence of workshops or furnaces in Scandinavia from the 8th – 9th century AD (Feveile, 2006b, 253), nor evidence for primary production in Early Medieval Scandinavia before the 16th century AD (Ingemark, 1995, 241). On the other hand, evidence for by-products from glass-making industry (potentially bead-making) such as glass vessels, glass cakes, glass tesserae, glass cables, millefiori rods, plus beads and wasters, leave no doubt that some sort of glass industry was occurring at Ribe (Denmark). No analytical data have been published so far on Ribe glass. Henderson (2000, 72-5) dedicates part of his chapter on glass materials to describe some major and minor elements analysis on part of Ribe materials, but no data are included in his text. Even though such data must be considered as preliminary, it is possible to consider them in light of the most recent glass studies. Major and minor analysis (EMPA) showed that most of glass from Ribe is low alkali, natron-based glass (Henderson, 2000, 72).

Ribe glass falls within two major categories: the first group resembles in its basic components Roman glass with the exception of translucent blue and green glass, characterised by impurities of lead, tin, antimony, and copper oxides (Henderson, 2000, 72-73). According to Henderson, such impurities in blue and green glass will be the reflection of the consistent

use of an antimony-rich cobalt source to colour the glass or the use of as base of a glass with higher antimony impurity.

Such formula finds parallels in 8th century AD Ähus glass dataset, in the blue more specifically (Callmer and Henderson, 1991; Henderson, 2000). Callmer and Henderson suggest that such distinctive pattern sets apart such glasses from the “usual” Roman formula, representing therefore a new Medieval recipe made with a different mix of raw materials (Henderson, 2000, 73). On the other hand, the remaining translucent glass would instead be closer in composition to the Roman production and it represents continuity of production with the Roman glass-making recipe.

The same can be said for all mosaic tesserae, which show an almost identical compositions with Roman opaque enamels (Henderson, 1991). According to Henderson, such composition is possible if such glass was made entirely from Roman mosaic tesserae, therefore the result of a recycling process (2000, 74). Henderson suggests therefore that Ribe glass production is characterised by both continuity on one side (mosaic tesserae) with the Roman glass-making tradition and innovation on the other with the new medieval recipe (blue and green glasses).

In my opinion, if we consider the levels Pb Sn Sb and Cu oxides in Ribe blue and green translucent glasses, the presence of such elements associated with colourant in a relatively higher content in translucent glass might also reflect that it has undergone through extensive recycling, most probably by the addition of Roman tesserae to the basic natron recipe. The same has been noticed for natron glass from 7th- 8th century AD Dorestad (Henderson, 1995, 53) and can be said for translucent natron glass from Ähus with its high trace levels of lead, tin and antimony (Callmer and Henderson, 1991, 152): this means that possibly the new “Medieval” recipe discriminated by Henderson might instead be itself another sign of continuity with the Roman glass-making, being the product of repeated cycles of re-melting processes, Unfortunately, I

cannot verify this hypothesis first hand on Ribe glass since no major, minor, or trace elements data have been published.

If indeed glass was not produced in Scandinavia, recent work by Gaut (2011) on the market site of Kaupang (Norway) shows the compositional diversity of glass traded to this area. Compared to Ribe, Ähus, and Dorestad, 8th -10th century AD Kaupang glass includes a compositionally variegated set of materials, the majority of which were natron-based soda- lime-silica glass, which indicates continuity with the Roman tradition. Overall, six different compositional groups (Figure 14) were identified: a natron based low-alkali Levantine group, an Early Islamic high potash high magnesia plant ash-based, one high potassium type, one high lime low alkali type (HLLA), and some lead-potassium glass, all three potassium-fluxed glass, and finally, two samples belongs to an alkali-mixed group (Gaut, 2011, 269; fig. 9.57 and fig. 9.58, 245.).

If the Levantine glass indicates that some sort of contact trade with the Syrian-Coast could have been possible, Gaut suggests that the potash-fluxed glass, because it is compositionally similar to the material analysed by Wedepohl (2003) and Krueger (Krueger and Wedepohl, 2003), could have a Carolingian origin[51]. The presence of such compositions not only suggests glass similar to the one circulating in Continental Europe was definitely reaching Norway, but also that the Scandinavian market was open to new recipes like the high-potassium ones from Continental Europe.

[51] Glass analysed by Krueger and Wedepohl (2003) includes the Carolingian monasteries of Corvey, Brunshausen and Lorsch, the Viking trading site of Haithabu and the settlements of Hoexter, Drudewenshusen (Germany), Rouen (France), Beverley (England) and Borg (North Norway).

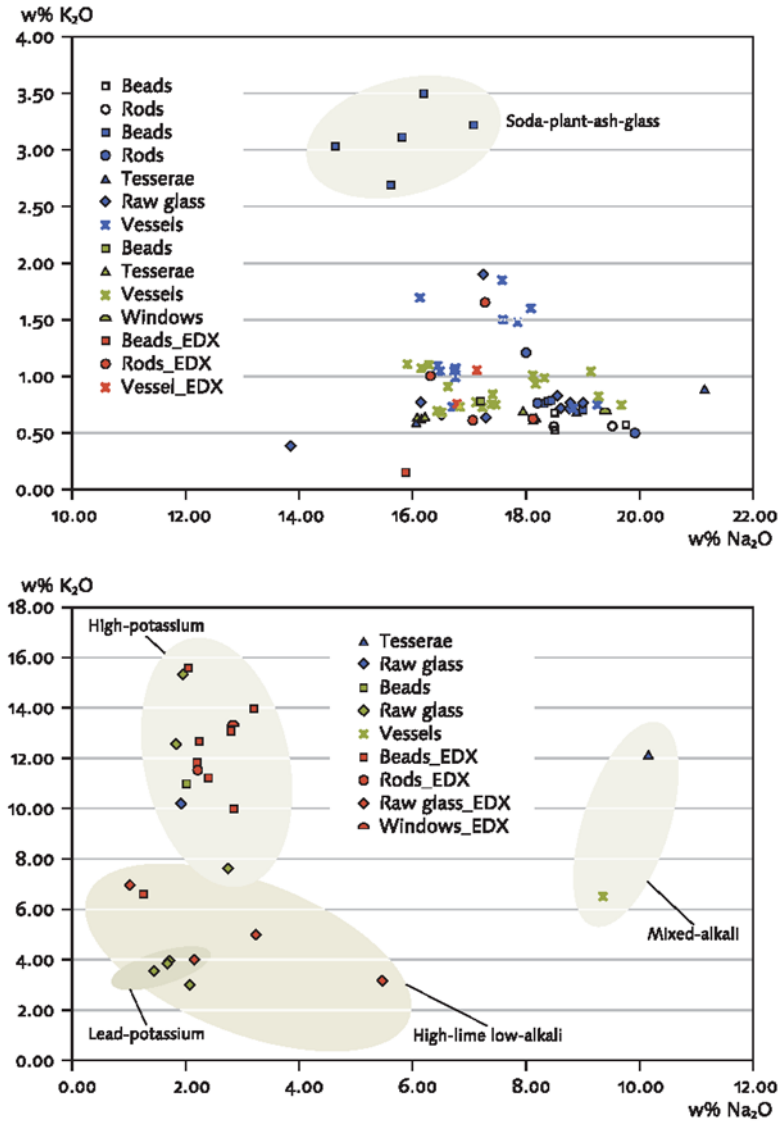


Figure 14 - Na_2O vs. K_2O contents in white, blue, and green soda-lime-silica glasses from Kaupang sorted by artefact type, after Gaut, 2011, fig. 9.57 and fig. 9.58, 245. Six compositional groups: a soda plant ash (top), a high-lime low alkali (bottom, natron glass), a lead potassium, a mixed-alkali, and finally three high-potassium groups.

Gaut (2011, 270) also mentions an intermediate composition in blue glass made by mixing natron and plant ash, which hints that similar mixing and experimenting processes occurring in Northern Italy might have occurred in Scandinavia too. Recycling is also detected in high levels of colouring agents, as well as antimony and tin oxides in the glasses (Gaut, 2011, 269).

2.6 Further considerations concerning the centralised model and glass trade

2.6.1 Revising the centralised model and new model suggestion

The model suggested by Freestone and colleagues reflects the existing relationship between glass composition, workshops, and the raw materials (section 2.3.6), and it deals, with glass recipe in its purest form (raw glass), straight from its primary production area. Unfortunately, it does not offer a realistic model of glass production and trade in Western Europe.

First, the model suggested by Freestone and colleagues does not include recycling from multiple sources[52]. A final glass object has potentially undergone through many different recycling and mixing cycle, which will inevitably influence the its final composition, and this aspect has not been included in the graphic model representation. Freestone and colleagues themselves acknowledge the same limitation (Freestone et al., 2002, 258).

In my opinion, the importance of secondary workshops as recycling and experimenting hubs needs to be acknowledged in a potential new model, without forgetting that, on a less abstract level, it might prove undoubtedly an arduous task (if not impossible) to match the final recipe directly to the secondary workshop that re-worked (by mixing or recycling) the same formula. Considering this issue, it becomes even more urgent to analyse untainted glass found on-site at secondary workshops if we want to recognise any compositional dissimilarities with the final re-worked (and recycled) product.

[52] This is not a real issue *per se*, since their primary intent was not to describe the whole complexity network of connections, but it needs to be considered in a potential new model.

The second issue with the suggested model is that it does not involve the concept of final product destination, or what I would define as “distribution area”. By considering the range in which the final object will be distributed and consumed, it will help not only to trace the circulation of a specific chemical recipe[53], but also to consider the impact of recycling and mixing practices. The same distribution area potentially embodies the basin where glass will be selected and transported to the secondary workshop to be re-worked, and later on (potentially) re-introduced in same distribution market[54].

I want to suggest a revised model to discuss the many potential scenarios that would originate from considering movement of glass and recipe between their primary production centre, to the secondary workshop, and finally to their distribution area[55]. This would be described by the passage through three stages: stage 1 (primary production), stage 2 (secondary production), and finally stage 3 (distribution/consumption stage).

Two hypothetical primary workshops (P1, section a, b, and c; P2, section c) produce raw glass to be traded to two distribution areas, respectively D1 and D2 (section a, b, and c). The location of D1 and D2 is not relevant in this model: they might be close or far from both primary workshops (P1 and P2). In addition, both P1 and P2 will source their raw materials (sand, natron and plant ash, and potentially shells) from contrasting geological areas, and therefore chemical signatures will be specific for their production area[56]. S1 and S2 represent two different secondary production centres.

---

[53] Every object is tied up to a specific chemical recipe, and therefore the distribution of such object will reveal the circulation of the recipe itself.

[54] For the sake of the argument, I will assume that a closed model

[55] In this model, I am not considering the difference in production between natron and plant ash because the first aim is to describe different stages of production through which a single artefact might have undergone through its consumption cycle independently from its specific chemical composition.

[56] Success in differentiating glass recipe depends on comparing raw materials that have been sourced in contrasting geological areas. If this is not the case, it will be more difficult to differentiate one production area from the other; it might therefore only identify the nature of raw materials (sand and alkali).

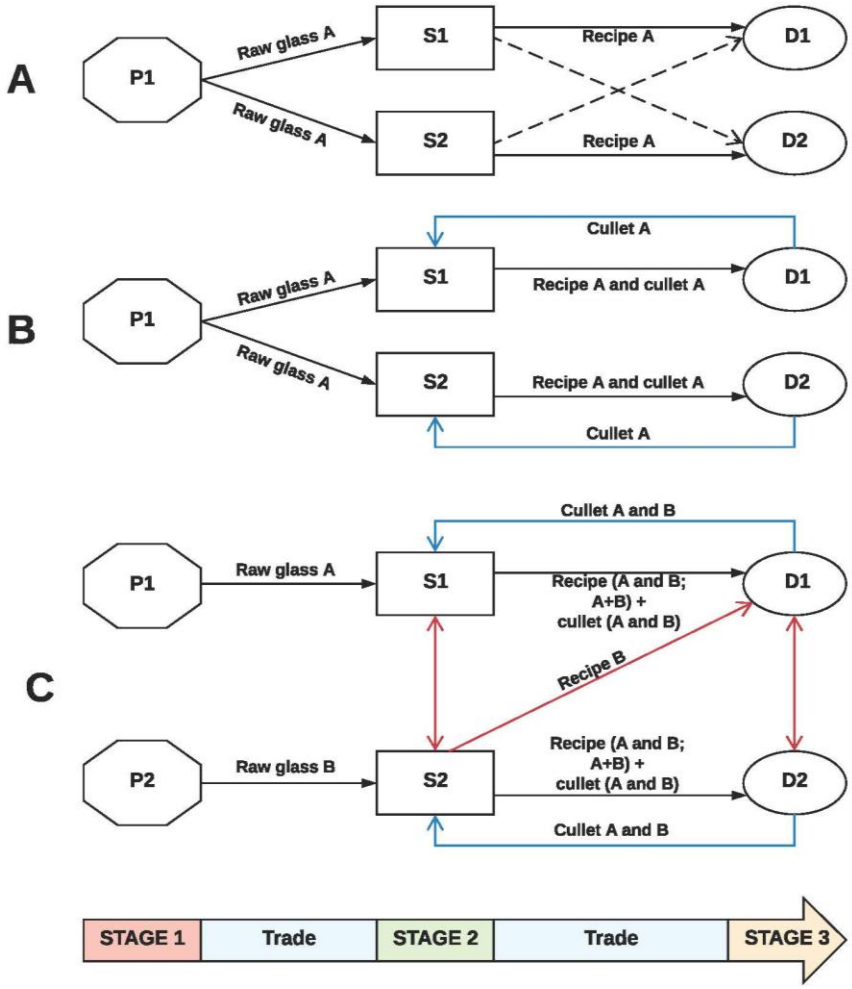


Figure 15 - Model suggestion for trade, mixing, and recycling or raw glass. Primary production centres (P1 and P2); secondary production centres (S1 and S2); distribution centres (D1 and D2). Stage 1 primary production stage; stage 2 secondary production stage; stage 3 distribution/consumption stage. Dotted arrow: movement of glass to different distribution areas; Red arrows represent movement of glass out of its original sourcing area; blue arrow identifies reintroduction of cullet into the production cycle.

In the **first scenario** (section A, Figure 15), primary workshop (P1) trades its freshly made raw glass (recipe A) to two secondary production workshops (S1 and S2); the product of both workshops will trade glass to either distribution centres (D1 and D2). In this setup, the chemical composition (indicated here as recipe “A”) will reflect the raw materials originally sourced by P1. Therefore, the original raw materials’ fingerprint is intact.

A **second scenario** (scenario B, Figure 15) involves recycling and mixing the same recipe (recipe A)[57]. Primary workshop (P1) trades its freshly made raw glass (recipe A) to two secondary production workshops (S1 and S2). The product of both secondary workshops will trade glass to either distribution centres (D1 and D2). In this scenario, even if glass from destination site 1 and 2 will mix, the resulting glass from recycling will still retain its primary workshop fingerprint: movement of glass (artefacts and cullet[58]) between the two destination centres will not alter the base recipe (A). On the contrary, if glass made from recipe A is reintroduced into the manufacture cycle, the original fingerprint will not be changed, but some alteration in the formula will be noted. For example, trace elements, such as copper (Cu), cobalt (Co), antimony (Sb), tin (Sn), and lead (Pb) will be present in considerable amount in the modified recipe (A rec, section B, Figure 15) in blue-green or faintly coloured glass after repetitive recycling cycles (Freestone et al., 2002; Jackson, 2005, 1997).

In the **last scenario** (scenario C, Figure 15), the trade of glass and its influence on the glass final recipe between two primary production areas sourcing different raw materials is explored. Two primary workshops (P1 and P2) trade their freshly made raw glasses (respectively recipe A from P1 and recipe B from P2) to two secondary production workshops (S1 and S2). The product of both secondary workshops could have been traded glass to either distribution centres (D1 and D2). P1 and P2 source their raw materials from contrasting geological areas.

If recipe A and recipe B are not mixed, it will be possible not only to distinguish them according to their chemical fingerprints, but also to

[57] To this day, there is no common agreement over the distinction between mixing and recycling process. In this model, mixing of two glass recipes (see section C, stage 2) occurs when raw glass A is blended with raw glass B to produce a new glass artefact. On the other hand, recycling occurs when one glass recipe is re-melted over and over again during a certain period of time (section B and C, stage 2 and 3). In the latter case, mixing might have been occurred during recycling process.

[58] In this case, the word cullet has been used in this case to describe glass (entire object or fragments) that has lost its original function but is going to be used as recycling material.

associate each one of them to their area of production[59]. If, on the other hand, recipe A and B have been mixed, the resulting glass (A+B) will present a blurred fingerprint, which will not be matching its original one, hence, it would harder to trace it back to its primary sources. Recipes A and B could also have been traded between distribution centres (D1 and D2) and from secondary centre to another (S1 and S2): both movements will be chemically traceable provided that the presence of both pure recipes at the same site[60].

2.6.2 Summary and issues with movement of glass and production: a localised matter

The purpose of this chapter is to first present the basic framework for interpreting glass production network in Late Byzantine and Early Medieval period, and secondly to emphasise the impact that recycling, mixing practices, and movement of glass might have had on the final artefact recipe, later discovered in the archaeological record. In my opinion, the current literature does not emphasise enough the crucial role that secondary centres have in influence and distributing glass through the centralised network, being dynamic production hubs influencing not just the external appearance of the final product, but also deeply modifying the original recipe by mixing primary recipes (potentially from contrasting geological areas) and, later-on, re-introducing artefact in the production cycle through recycling practices. The way we consider secondary production centres needs to shift from passive receivers of raw glass from the Levant to active contributors to such a centralised model.

---

[59] Or better, it will be possible to associate recipe A and B chemical composition to the area where their raw materials have been sourced.

[60]Hence it will be possible to compare both original recipes with the mixed one and then make some hypothesis concerning the origin of the latter.

Unfortunately, as I remarked in section 2.4, very few secondary centres have recognised as certain, and even fewer are properly excavated and published together with their glass material. Also, the state of research today allow us to recognise recycling practises only on colourless and blue-green glass, and current publications have focused mostly Roman materials (Jackson, 2005; Foster and Jackson, 2009; Silvestri, 2008; Silvestri et al., 2008; Jackson and Paynter, 2016). Another issue is that we still lack in comparative between studies different production areas rather than focus on finite archaeological contexts. I hope that this dissertation will help in partially filling such gap and taking our comprehension of Western network one step further.

Another crucial step must be taken when considering typological data in combination with compositional analysis when suggesting hypotheses of glass trade theories within the Early Medieval glass production network. Indisputably, typological (shape and decoration) similarities between separate group of artefacts found at different archaeological sites might indicate that both datasets could have been produced in the same workshop, or possibly by the same artisanal group[61]. If, on the other hand, such production's assumption is taken for granted without testing its validity through compositional analysis, partial and incomplete assumptions concerning the local trading network might be made. A clear example of such problem can be found in Western glass typology studies, when 7th – 9th century glass artefacts from the UK, Scandinavia, and the Continent are compared.

Typological similarities for materials dated between the 7th to the 9th century AD between these regions has been remarked recently by several authors (Nasman 1986; 2000; Evison 2000, 78-79; 91-93; Feveile 2006b, 253; Evison 2008, 7). Feveile (2006b, 253) comments on

[61] In the first case, we assume that such glass objects might have been traded on different markets or possibly moved later on, as personal belongings or gifts. In the second, the artisans' group might have travelled from site to site to share their knowledge.

how the material from ASR 9 Posthuset in Ribe almost all "*have a west European- Anglo-Saxon distribution area*". Out of 54 palm cups in the collection studied by Evison in her study for the British Museum Anglo-Saxon glass collection in 2008, a considerable proportion "*are not distinguishable in form and colour from contemporary products in Rhineland, northern France, and Belgium*" (Evison 2008, 7), which led to the hypothesis that such cups must have a common area of origin (possibly the Continent) or that a group of artisans must have travelled across the Channel and made them locally.

If we consider the scarce evidence for secondary production, the hypothesis that both Eastern England and Scandinavia were depending for their glass vessel supplies from Continent could be therefore a possibility. At best, given their striking typological similarities, we could suppose a common production area. On the other hand, the few compositional data we do have allude to a more complex picture.

To this day, few scientific analyses have been performed on well dated and typologically significant artefacts pertinent to 7th to 9th century in such territories. Funnel beakers represent not only a well dated and distributed more or less evenly over the Continent, Scandinavia, and the UK (Näsman, 2000, fig.1, 39; fig, 2, 41), and a common production on the Continent in Frankish glass-works has been indeed suggested for this class of artefact.

On the other hand, Nasman (2000, 38) cannot exclude a local funnel British production based on the nature of Hamwic materials. In addition, Hunter and Heyworth (Hunter 1980, 69) agree on the basis of the existence of an intermediate form between palm-cups and funnel beakers with features and decoration virtually unknown in Scandinavia and with very few parallels with the Continent (Hunter, 1980, 69).

Compositional analysis paints a more complex picture. Major and trace elements compositional data performed on Helgo, Dorestad, and Hamwic materials (Sanderson et al. 1984) show a difference in major and

trace elements between Hamwic glass and Scandinavian samples, which indicates a difference in sourcing materials (at least between these three glasses dataset). If both alumina, calcium, sodium oxides are plotted against each other (Figure 16Figure 17), while they all have similar alkali values, Hamwic glass show different percentages of lime and alumina contents.

Excluding a small group with relatively lower sodium oxides, Dorestad, Helgo, and part of Hamwic samples compositions show similar values (over 8%wt CaO; between c. 3.40 – 4.30%wt of Al_2O_3; 12.60 - 18.45%wt of Na_2O[62]). The remaining Hamwic samples show substantial lower values in CaO (<8wt%), and higher alumina if compared with both Helgo and Dorestad, and lower Na_2O if compared only with Dorestad samples. This variance in key major components likely indicates a difference not only in alkali, but also sand source, which therefore points out to different workshops.

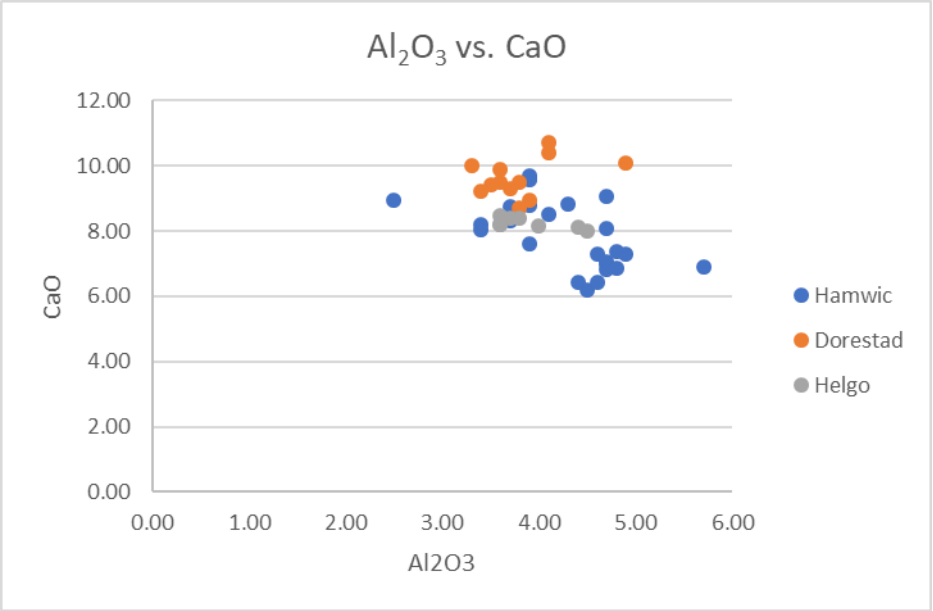


Figure 16 – Al_2O_3 vs. CaO contents in glass from Hamwic, Dorestad, and Helgo, after Sanderson et al. 1984, replotted by the author, showing difference in sand and lime sources.

[62] I would like to argue that such difference in sodium oxide possibly deserves further investigation.

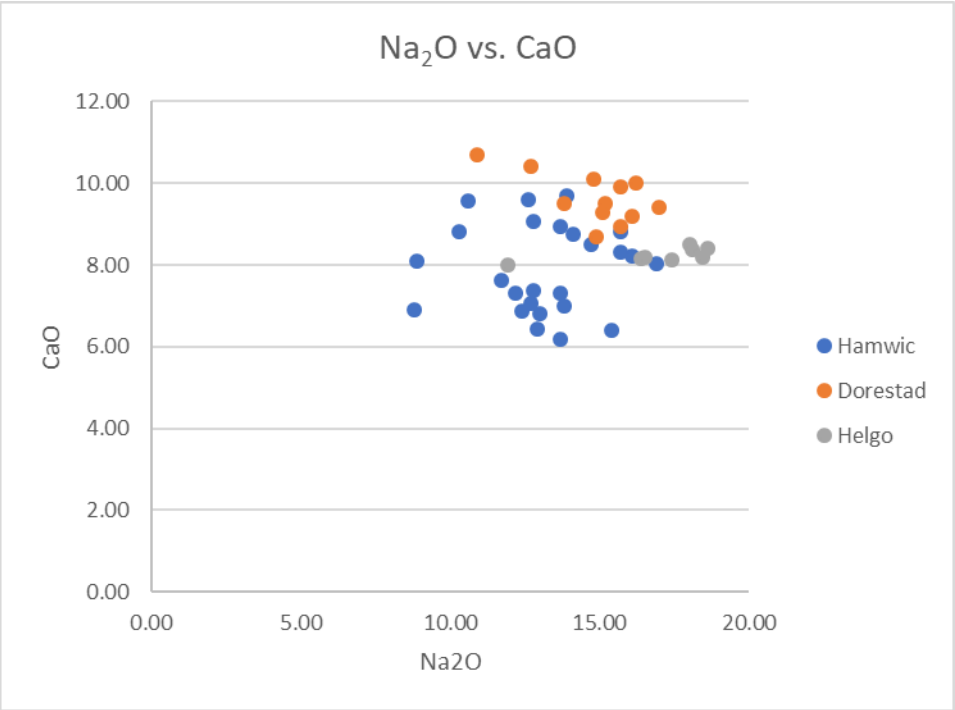


Figure 17 – Na_2O vs. CaO contents in glass from Hamwic, Dorestad, and Helgo, after Sanderson et al. 1984, replotted by the author, showing difference in sand and alkali (natron) sources.

If we consider Sanderson and colleagues' compositional data from a broader compositional level, two possible scenarios: the funnel beakers could have been made in the same glass-working centres (either in the UK, Scandinavia, or the Continent) with raw glass from different sources. On the other hand, this variation in lime and alkali needs to be interpreted as the presence of two distinct glass-working centres using different raw glass, which could easily be located in the UK and Scandinavia or on the Continent.

Even though in my opinion we need to be careful to come to a hasty conclusion, this example reinforces the idea that we cannot base our idea of network production studies just on typological data (even if chronologically and stylistic), but we need to integrate when possible with compositional and comparative analysis to assess the degree of variance of such data in a broader context. The primary aim of this dissertation is to recognise the power that secondary centres hold over the glass recipe (as essential production hubs first and recycling centres later) in the fore

mentioned three key areas in Western Europe, in order use the compositional data to fill several gaps in the Western European glass network map and to suggest potential network trade routes and test previous assumptions based on typological data.

3 Archaeological context and dataset description.

3.1 Introduction

In this chapter, I will describe the archaeological context pertinent to the three sites from where the glass for this dissertation has been sampled from: Comacchio (section 3.2) Barking Abbey (section 3.3), and Ribe (section 0). Each section will differ from each other since not only the sites have faced a different archaeological development, but also because the nature and amount of data published concerning them is strikingly different. I will then move on to describe briefly each dataset by mentioning samples chronology and typology, together with some brief comparisons where possible.

3.2 Comacchio

3.2.1

3.2.2 Archaeological context

The site of Comacchio is located in the Northern part of the Italian Peninsula: its territory faces the Adriatic Sea on one side, while on the other it connects to the Po Plain by a widespread river network (Figure 18). Its geographical position was certainly one of the principal reasons which inspired Byzantines to build a *castrum* in this territory around the beginning of the 7th century AD. By being close to the Lombard territory, it could have served to control the boundary, and also to manage the exchange of different types of goods along the Po Delta: salt, *garum*, oil, wine, textiles, glass vessels, globular amphorae, and white painted wares are only some of the products being traded through Comacchio emporium.

Unfortunately, most of these materials have not left any trace in the archaeological record. What it is known is based mostly on written sources and on the remains of Villaggio San Francesco harbour area and San Cassiano cathedral excavations.

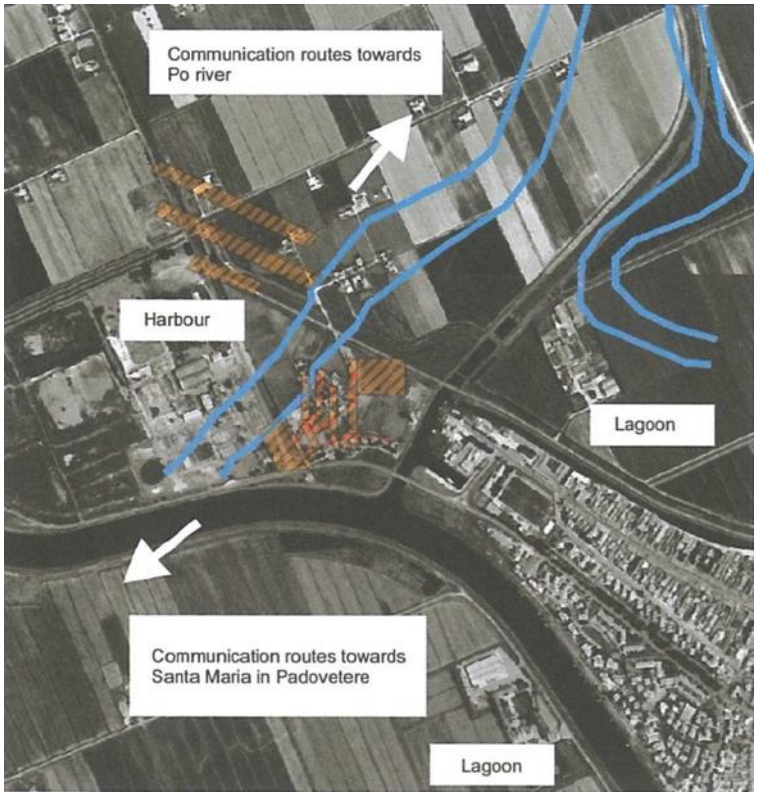


Figure 18 - Comacchio, Villaggio San Francesco: hypothetical reconstruction of communications routes according to harbour location, after (Gelichi et al., 2012). Captions from the original illustration have been translated in English from Italian. No other features have been modified in any way from the author.

3.2.2.1 Written sources

In the written sources, Comacchio is recognised as an important part of the Northern Italian exchange network. In the Liutprand Capitulary, the entire Lombard community ("*a cunctis fidelibus Longobardorum*") addresses directly Comacchio authorities (the *magister militum,* a *presbyter*, and two *comites*): the entire community ("*cunctis habitatoribus Comaclo*") have been granted the chance to trade with the Lombard

territory (Montanari, 1986, 462). In particular, this pact is formally directed to both the civic and the ecclesiastical authority, suggesting that Comacchio was perceived as a structured centre with political, religious and military purposes. Moreover, the use of the expression "*habitores comaclenses*" emphasise the idea that Comacchio in the early eighth century was perceived as a whole civic entity (Gelichi et al., 2012, 191).

Tenth century historian John the Deacon in his "*Istoria Veneticorum*" defines Comacchio in three different ways (Gelichi, 2007a, 83): first as *insula* (III, 44), then as *castrum* (III, 28), and finally as *villa* (III, 12). A general agreement has been recognised over an increasing of military settlements in Byzantine Italy (Brown and Christie, 1989, 381). The foundation of Comacchio can be seen as a defensive response from the Exarchate of Ravenna to the Lombard's presence in Italy in the early seventh century (Gelichi and Calaon, 2007, 390). In this perspective, the use of the word *castrum* fits into the picture. In the light of the archaeological findings, currently scholars prefer to define Comacchio as an "*emporium*" (McCormick, 2007; Gelichi et al., 2012). With these premises, both Franks and Byzantines would have certainly made an absolute priority to maintain good economic connections with the Comacchio territory.

3.2.2.2 Previous excavations

Comacchio territory became previously famous for the presence of the important emporium of *Spina* dated between the 6th and the 3rd century BC. It was not until the 1960s that the first excavation of medieval contexts in the area of Comacchio were undertaken in the area of *Motta la Girata* channel/*Valle Pega,* 4 km west to Comacchio: in this area, Nereo Alfieri's excavations put into light the remains of a Church with its Baptistery probably dated to the 5th century AD (Grandi, 2015, 234), which he identifies with the church mentioned in the *Liber Pontificalis*

(Deliyannis, 2006, 165-66). Interpretation and chronology of these structures is still controversial due to lack of proper excavation methods and records, especially concerning the first phases of construction (Grandi, 2015, 234).

A series of excavations (1990; 2003; 2008-2010) were undertaken in different phases since the beginning of the 90s (Calaon, 2007, 505) in the area of Villaggio San Francesco, north-west from the Comacchio town. In the same area, in the 1920s-30s a large number of vertical poles and wooden planks were recovered by Proni (Patitucci Uggeri, 1986, 270-1). During an emergency excavation in 1996 similar structures were recovered (wooden vertical poles), even though no stratigraphic excavations were possible due to the urgent nature of the excavation itself (Calaon 2007, 505).

Villaggio San Francesco complex is structured in two main islands emerging from the water: an artificial channel (Figure 18 Figure 19), only visible with aerial photography analysis, divide the area in two separate quarters (Calaon, 2007, 508). Calaon estimate the total surface approximately about 75000 m^2 (2007, 507). The whole area was interpreted as a pile-dwelling settlement with docks and wooden walking planks. The general agreement which emerged from the 1996 archaeological discovery is that the structure seemed to have a permanent nature, but at the same time it does not appear to have been used for residential purposes (Calaon, 2007, 505, 506-7). Overall, the site planimetry and the objects associated with the remaining wooden structures, such as wooden platform, boardwalk, warehouses, and waterfront assemblages (Figure 19), led the archaeologists to consider the possibility that this territory was not intended as a residential area, but could have instead been used for commercial purposes (Calaon, 2007, 505, 506-7).



Figure 19 – Wooden waterfront structure dated to the 8th century AD, Villaggio San Francesco structures, after Grandi, 2015, fig. 6, 242.

More recent excavations (2008-2010) works have confirmed the importance of this site: the harbour itself was in direct communication with both the Adriatic and the Mediterranean Sea routes (Gelichi et al., 2012, 186). In addition, both Ravenna and Venice are located quite close to Comacchio, and the Po River network used to connect Comacchio to both Milan and Pavia. Therefore, by being a crossroads of major commercial and political routes, Comacchio became an important link in the Northern Italian trade economy, as suggested by the Liutprand Capitulary.

3.2.2.3 Piazza XX Settembre (2006-2008)

During the first half of the last century, drainage works in the area close to the modern town of Comacchio allowed the recovery of several Etruscan cemeteries: scholars associate them with the existence of a central emporium between the 6th and 3rd century BC (Gelichi et al., 2012, 169). Several Post Roman sites were investigated during the '60s and '70s of the last century: for example, the area of *Motta della Girata* channel alongside the excavations *Santa Maria in Padovetere* church, with its burials and baptistery (Corti, 2007); Via Mazzini excavation works, where some brick tombs were discovered (Patitucci Uggeri, 1986, 1976).

In 2006, Comacchio city council planned a floor renewal of *Piazza XX Settembre,* located in Comacchio modern town centre (Figure 20 and Figure 23). In this occasion, an Italian archaeologists' team under the scientific direction of Professor Sauro Gelichi from Ca' Foscari University of Venice, and Dr. Luigi Malnati, from the "*Sopraintendenza dei Beni Culturali dell'Emilia Romagna*", led a two-years archaeological investigation of the area beside the Cathedral of San Cassiano. Preliminary excavations in Comacchio town centre have been carried out in 1975 by Patitucci Uggeri and several tombs were unearthed in *Via Mazzini,* located in Comacchio's modern urban centre: only two burials were partially published from this excavation (Patitucci Uggeri, 1983, 1976).

In 2006 excavation for the first time the area concerning both the Early Medieval bishop residency and its related workshop were scientifically investigated. A preliminary report was been published in 2008 (Grandi et al., 2008, 167-8), a monograph in 2009, and a final revision in 2012 (Gelichi et al., 2012, 177-81).

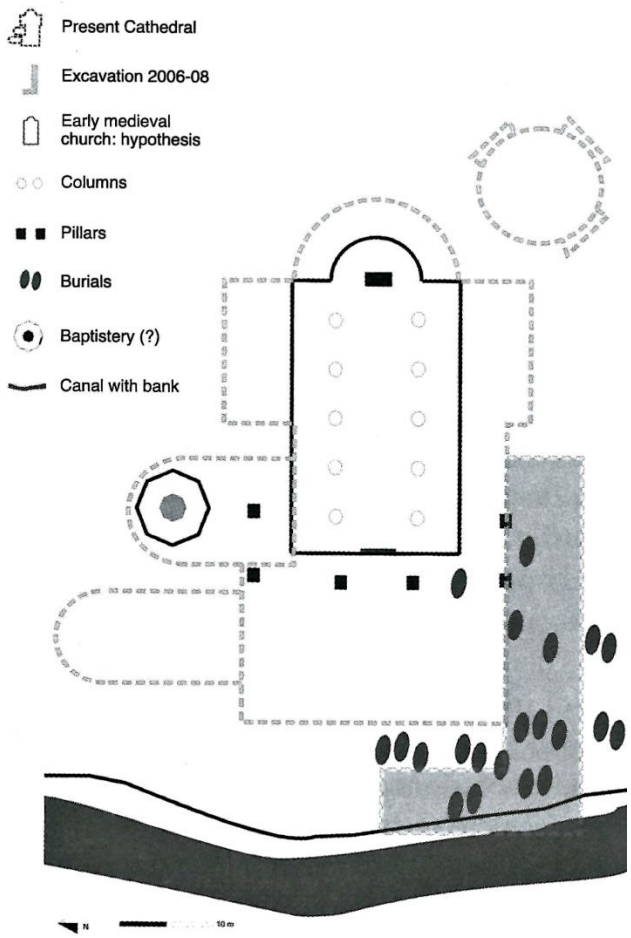


Figure 20 – Comacchio Piazza XX Settembre: 2006-2008 excavation area in medium grey, after Gelichi, 2009, 44.

The analyses reported here summarise these preliminary reports concerning the cathedral excavations.

Between 2006 and 2008 an area of 180m^2 around the perimeter of the cathedral has been investigated (Figure 20). Its relative stratigraphy covers indeed a broad time period, approximately running from to the early sixth century to the present day (Gelichi, 2009). Recent preliminary reports (Grandi et al., 2008; Gelichi, 2009; Gelichi et al., 2012) mainly focus on the early medieval phases. According to the material culture found at the site, Gelichi and co-workers date its first occupation to the end of the sixth century AD (Gelichi et al., 2012, 176).

The remains of a quadrangular wooden structure relevant to this early chronological phase (late 6th century AD, Dr. Grandi, personal communication) have been partially excavated near the southwest corner of the modern San Cassiano cathedral (Figure 20). Unfortunately, the building plan is not clearly reported due to fact that the building was erected on a fluvial outcrop island in a marshy environment: while digging, excavators encountered the water table level, making impossible to go further.

Approximately the plan must have been quadrangular, with poles sustaining the roof or possibly a wooden floor. The planking level was made with clean clays laid over a natural sand deposit, while walls are reported as been “made of planks and wattle” (Gelichi et al., 2012, 176). No other details are given about the inner space arrangement or the presence of any other peculiar architectural feature. Fortunately, more information are available about the following occupation phase, encompassing the remains of a craft quarter dated between the second half of the 7th and the beginning of the 8th centuries AD (Gelichi et al., 2012). The structure shows entirely different overall features than the building previously raised in the same area: construction methods, space articulation, and discovered materials reveal the presence of a coherent space organization and a designated function for each room. Moreover, the construction technique appears in this phase more developed and permanent, a sign that the workshop was built to endure for a longer period of time than the temporary wooden house: stone masonry elements (including foundations and an external porch) are integrated with more temporary features, like wooden planks and poles used to build the higher phase of the building. The same planimetry area suggests that different artisan activities were carried out in this building (Figure 21 and Figure 22). Nonetheless, it is indeed important to remember how the archaeological excavation involved only a part of the supposed workshop (more or less half of the supposed area concerning the working area), and therefore, reports are reflecting only partially the activities carried out

in the workshop. Overall the site was surrounded by a drainage trench, which probably collected the residual water collected from production activities.

Chronologically, the excavated area shows two periods of usage.

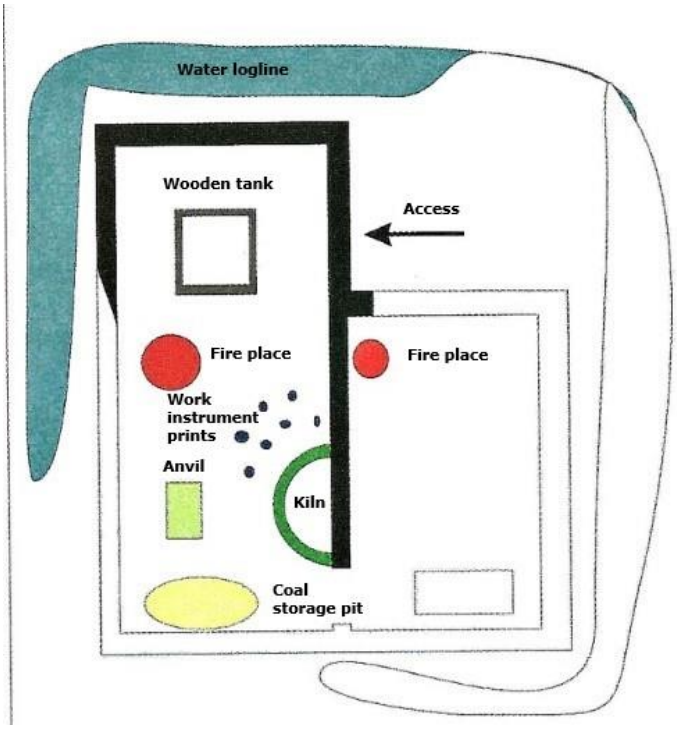


Figure 21 - Piazza XX Settembre, workshop planimetry, phase 1, after Gelichi, 2009, 312. Captions from the original illustration have been enhanced just to make them more legible. No other features have been modified in any way from the author.

In the first phase (Figure 21), the area was organized around both a furnace built along the perimeter wall, with an additional hearth placed in the middle of the room. In the area directly in front of the furnace, several circular holes probably associated with the use of pontil rods have been recorded, which also supports the presence of glass-working/blowing occurring in the workshop. A charcoal storage ditch was also found close to furnace. In association with the smaller hearth, a wooden structure (2 m x 2 m), made with wooden planks and poles still embedded into the ground, has been interpreted as a cooling tank associated to metal

working. This is only a preliminary supposition, and further work will clarify the exact function of this structure (Dr. Grandi, personal communication). It is indeed possible that metal was worked here at some point due to the considerable presence of metal-working debris (Gelichi et al., 2012, 177). This hypothesis is also supported by the presence of an anvil found alongside the furnace and the charcoal ditch.

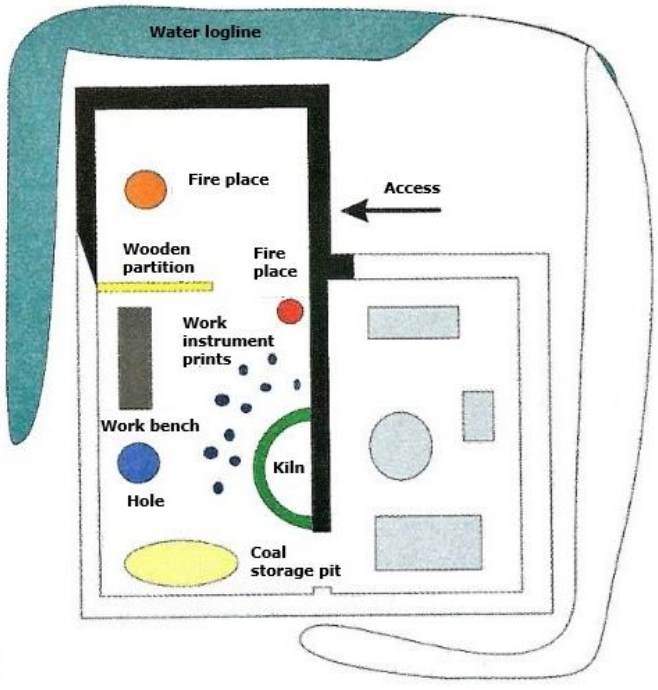


Figure 22 - Piazza XX Settembre, workshop planimetry, phase 2, after Gelichi, 2009, 312. Captions from the original illustration have been enhanced just to make them more legible. No other features have been modified in any way from the author.

In the latter period of usage (Figure 22) part of the workshop was dedicated to glass-working, as the furnace (only half preserved) attests. Many vessel fragments, glass-working debris, and glass-working crucibles with molten glass attached to their base, leaving no doubt about the use of this building. The presence of several pits of different dimensions in the area just in front of the furnace still endure, suggesting the use of working instruments, possibly a pontil for glass-blowing.

A bronze cameo depicting a young male figure with curly hair found in association with glass-working debris[63]. The same mould match closely to a type familiar in Northern Italy, and in particular with a cameo inserted within a *capsella* (reliquary) preserved in the Diocesan Museum of Cividale del Friuli. These striking typologically similarities might point out to a specialised production occurring in Comacchio and then possibly traded through Northern Italy.

According to the preliminary reports (Grandi et al., 2008, 169; Gelichi et al., 2012, 177-8), is still unclear if primary or secondary production occurred at the site. The presence of glass debris and crucibles does not imply *per se* that the production of glass from raw materials was occurring. Moreover, despite the division in two separate periods of use (Grandi et al., 2008; Gelichi et al., 2012), researchers are still debating if these two phases have to be considerate as distinct occurrences, or if glass and metal working represent a unique occupational working stage (Dr. Grandi, personal communication). Dr. Grandi suggested that the first phase of the workshop could be dated to the first half of the 7th century AD, while the later phase to the second half of the 7th – early 8th century AD (personal communication). After the second phase, the furnace is not in use anymore. Glass-working activities might have been moved elsewhere to supply the built of the new cathedral but, at the moment, is not clear where (Gelichi et al., 2012, 179).

During the 8th century a substantial reorganization of the area occurred (Figure 23). All the workshop's activities ceased, and the area was converted into a cemetery. Burials were excavated directly into the earth without any previous preparation, and no goods were found in association with the graves, in order to discuss their period and social identity (Grandi et al., 2008, 170). In the same period a church and a palace, possibly connected with the presence of a bishop, were erected

[63] The bronze cameo is associated to glass-working wasters in Us 2019, dated to the end of 7th century AD; according to the Harris matrix, this Us would represent the last load of the furnace.

alongside the cemetery. Excavations did not produce sufficient archaeological data to reconstruct a plan of both the palace and the associated Romanesque church, since they were both demolished and obliterated by the construction of the seventeen-century San Cassiano cathedral.

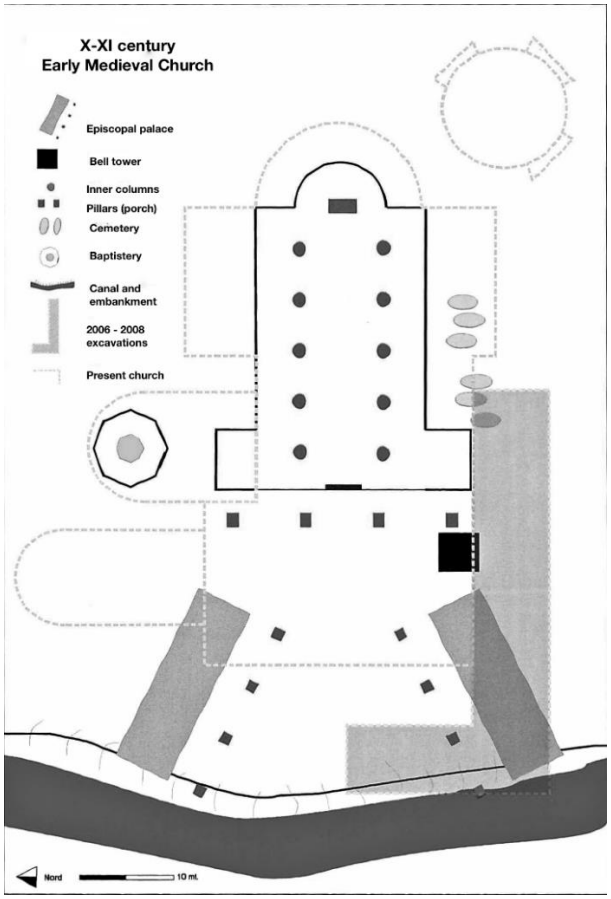


Figure 23 - Hypothetical planimetry of the 11th century Episcopal Church in Comacchio: in light grey is underlined the 2006-2008-excavation area; in medium grey the suggested planimetry of the episcopal palace, after Gelichi, 2009, 58.

Nonetheless, archaeologists have been able to infer some architectural features belonging to both buildings by examining what it is left of the planimetry and some structural remains still in place (Figure 23). The church was located to the east side of the episcopate building, oriented east to west. The very prestigious manufacture quality observed in all the decorative elements (like glass tesserae, columns, capitals, and

pedestals fragments) found in the area opposite the modern church, suit the taste of sophisticated elite, which had the power to reinvest their economic *surplus* (Grandi et al., 2008, 171). Their re-use as decorative elements attests the destruction of the previous religious building. Authors also assume the presence of a courtyard in front of the church, where they also register the presence of few privileged inhumations (Grandi et al., 2008, 171). Since no grave goods are associated to these tombs (saving from just one shell ornament in a male inhumation), I assume that the suggested privilege consists of their unique position (in front of the church).

The episcopate building shows a rectangular plan oriented (east to west, Figure 23) in agreement with the close remains of the Romanesque church and consisted of two levels: the ground floor was occupied by several storage room, while the upper level was used as a residential area.

3.2.2.4 The end of Comacchio as emporium:

Venetians seems to be the direct rival to Comacchio for the Po plain supremacy, since they were for geographically close and their commercial interests collided. At the threshold of 10th century Comacchio's fortune declined quite rapidly. Motives behind its downfall are not known, but it is indeed confirmed by both written and archaeological sources that the emporium was attacked and destroyed. Both John the Deacon (III, 44 in Gelichi, 2007b, note 55, 380), and Cessi (Cessi, 1963; Gelichi et al., 2006) mentions that the city was burned down in 932 AD by the Venetians. Before this attack, at least two other assaults were registered: John the Deacon reports a Saracen incursion in 875 AD; Byzantine attempted (but failed) to sack the city almost a century before, in 808 AD, when they were fighting against the Lombard *Regnum* (Gelichi et al., 2012, note 89, 204). During the 2008-2009 excavation campaigns

at Villaggio San Francesco some structures (bridges, banks and warehouses), showing fire and abandoning evidences, were recovered (Gelichi et al., 2012, note 89, 20).

3.2.3 Comacchio glass dataset description

Comacchio glass dataset includes 90 fragments of glass[64]. Each sample has been given a unique code based on the original excavation record provided when the author sampled the glass; each code is formed by the abbreviation “Com” (Comacchio) plus a progressive number (ex. Com01, Com02, Com03, etc...). The number assigned to each sample is totally arbitrary depending on the order it was sampled originally. In addition to this code, each sample has been associated to their excavation information, which include year of excavation (ex. COM 07), area and sector of excavation (UTS 1000/8)[65], stratigraphic unit (US or *unità stratigrafica*), plus a number arbitrarily given by the author to distinguish each sample within their stratigraphic unit.[66] Please refer to the complete list and pictures in Appendix 1 and 5.

Each sample has been given a potential chronological range based on their associated stratigraphical unit and presumed chronology. Overall, samples’ chronology range between late 6th century AD to 11th century AD (Figure 24). Given the current state of the research and the fragmentary character of Comacchio samples, at the present moment it is not possible to give a more precise or comprehensive chronology, nor it is the aim of this dissertation to do so. Roughly, we can observe that sixteen samples belongs to the phase correspondent to the supposed

[64] In this case, each object represents one unit of glass on its own; it is beyond the scope of this analysis to determine the total or minimum number of objects represented in this dataset.

[65] All glass from Comacchio dataset comes from UTS 1000/8, respectively “Piazza XX Settembre” excavation area and sector “8”, south-east corner.

[66] For example, sample COM69 will be: Com 08, UTS 1000/8, US 1842/1.

activity of the workshops (Figure 21 and Figure 22), late 7th – early 8th century AD, while eighteen belong to a range chronologically close to the supposed craft area (2nd half 7th century AD).

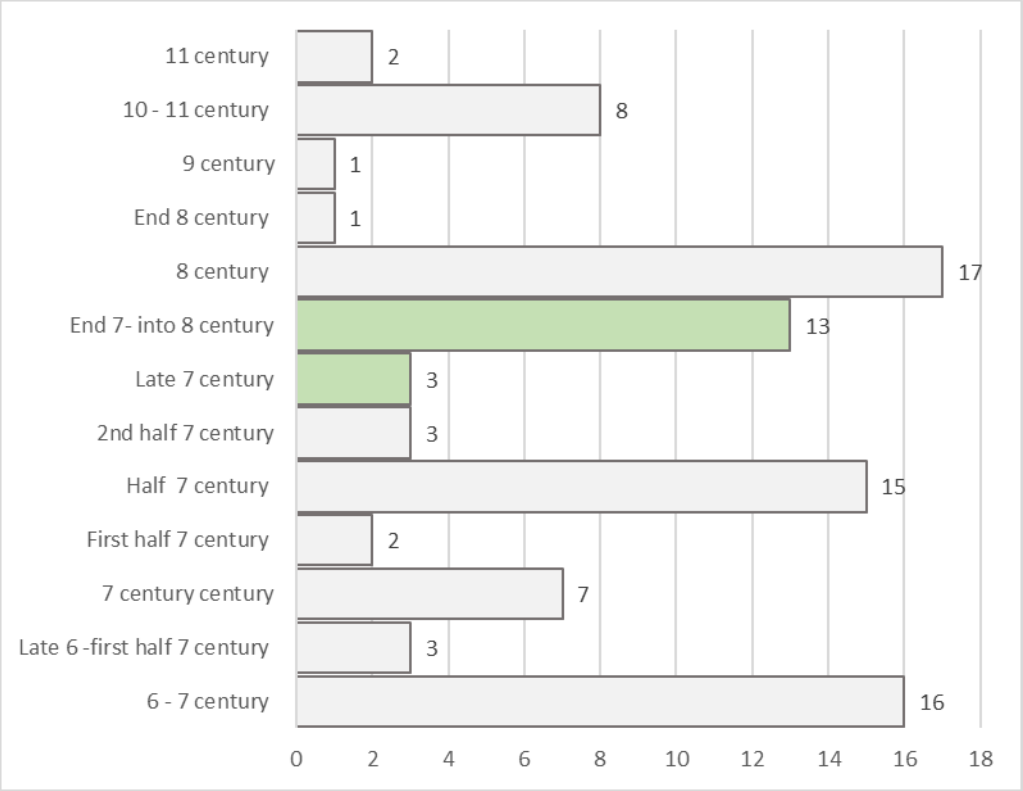


Figure 24 - Comacchio glass dataset chronology based on the chronology of their associated US. In light green is represented the percentage of samples belonging to the supposed glass workshop phase, from second half of 7th century AD to early 8th century AD (Gelichi et al., 2012).

As I remarked in the introduction, the first aim of this dissertation it is not to study these sample according to their typology. Nonetheless, a basic typological distinction has been given by the author to allow a distinguish fragments according to their supposed function. This distinction has been given after a conversation with Dr. Ferri and Dr. Grandi, who kindly sat with the author and commented on most samples hypothetical form and decoration.

Unfortunately, most of Comacchio glasses are heavily fragmented. Hence, in many cases it was not possible to assign a more precise

typological classification aside from a generic “goblet”, “cup”, or “vessel”. As showed in Figure 25, the majority of samples (thirty-one) fall into the “glass-working” category, which include glass layers from crucibles, wasters such droplets and spills, pontil marks, and chucks of glass.

Most of glass-working debris and crucibles are associated with the workshop area (chronology). A small group of three artefacts have been associated with a later chronology (10th -11th century AD), coeval with the foundation of the church phase and the cemetery area[67].

The presence of such crucibles (Figure 28 and Figure 29) together with droplets, chunks of glass associated to the furnace structure leaves no doubt that some form of glass-working activity was occurring in Comacchio.

A total number of nine crucibles are included in this dataset, all of them layered with green/light green glass: two crucibles (Figure 28 and Figure 29) are lined with translucent green glass together with small bits of opaque red glass, which could possibly suggest the use of tesserae as source of colourant.

Unfortunately, the current state of research involving Comacchio glasses does not allow at the moment to reconstruct the shape of such crucibles. Coeval crucibles have been found in Torcello (Leciejewicz et al., 1977, 92-104) and San Vincenzo al Volturno (Hodges, 1991; Schibille and Freestone, 2013, fig. 1 and 3).

[67] Without a more recent and detailed publication concerning Comacchio workshops area, it would be premature to comment further. Given though that Gelichi and colleagues suggest that the workshop area changed location when the Cathedral was built, this few pieces might be in connection with the new workshop phase not yet revealed, or they might as well be isolated residual fragments.

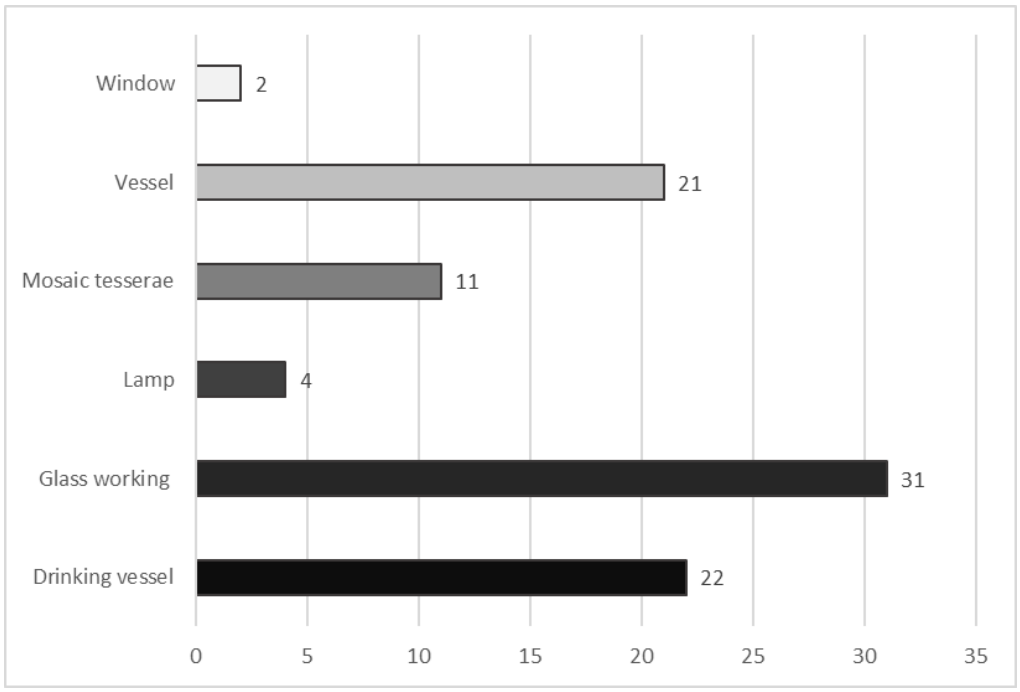


Figure 25 – Comacchio glass dataset arbitrary typology.

Mostly of Comacchio fragments are translucent of a blue-green, green, blue, colourless, yellow, and light grey. Concerning the blue-green ones, most of the time it is not possible to distinguish between blue or green colour. When possible, a further distinction has been assigned (as in light blue or light green)[68]. Only Com96 (Figure 27), a goblet fragment, is decorated with multiple (at least three) trails of white glass. Other fragments do no present any sort of decoration[69].

Another significant portion of glass falls into drinking glass typology, which includes goblets (fourteen), bottles (one), and cups (five). Lamps (four), and windows (two) are poorly represented.

[68] Please refer to Appendix 1.

[69] One fragment (Com 48-49) is characterised by the presence of 2 colours (translucent light blue with red opaque swirls) but unfortunately only the light part was analysed in this dissertation. See Appendix 1 for further description of the artefact.

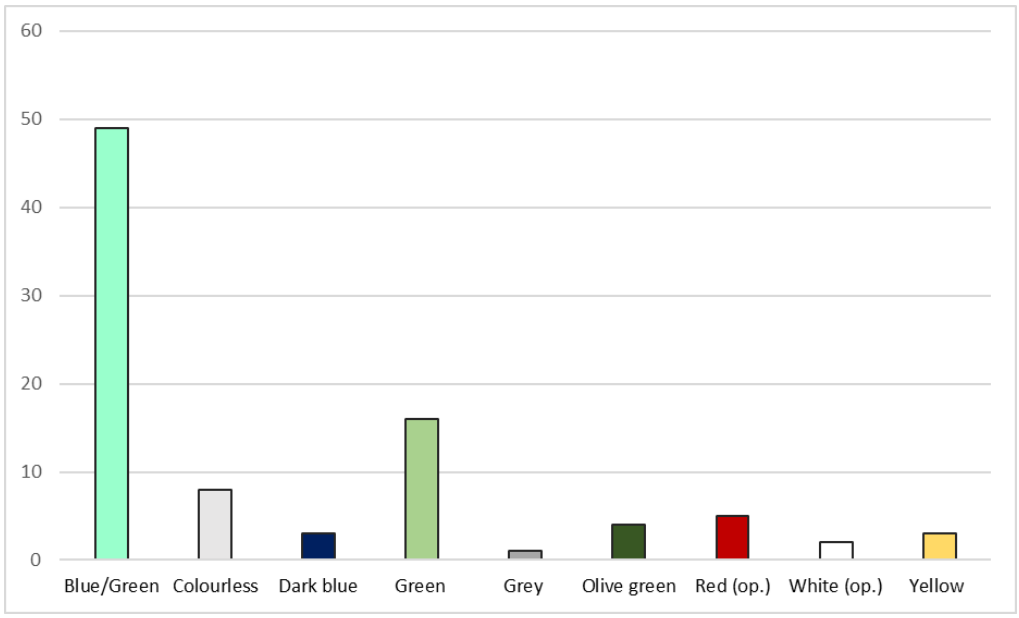


Figure 26 - Comacchio glass fragments divided by colour. “Op.” stands for opaque.

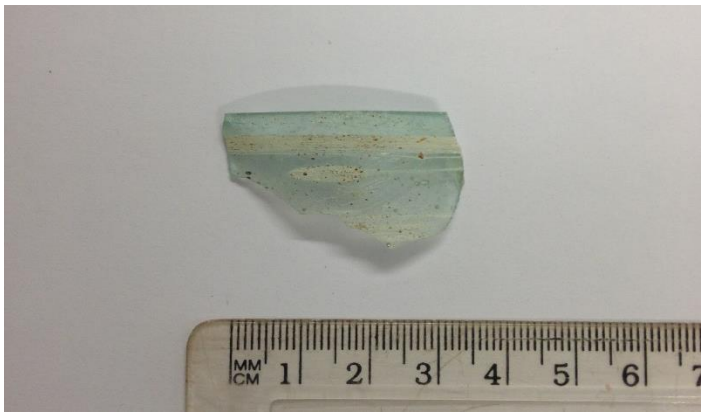


Figure 27 – Com96, a goblet fragment decorated with multiple trails of opaque glass.



Figure 28 – Crucible with layer of green translucent and red opaque glass (respectively Com 93 and 94).



Figure 29 - Crucible layered with translucent green and with red opaque glass in the left area (respectively Com 30 and 31).



Figure 30 - Com69 and 70, both mosaic tesserae from Comacchio.

Goblets are amongst the most diffused shapes in Italy between the 6th and the 7th century AD (Sternini, 1995, 261; 101-2) usually decorated along the stem or body with thin filaments with a contrasting colour usually white (Figure 27), but also red and blue, or with diagonal ribs along the body, while they start to be become rare from the 11th century onwards (Stiaffini, 1999, 106)[70].

Most of Comacchio goblets are associated with the workshop area with a supposed chronology between half 7th century to the 8th century AD. Aside Com96, all goblets are undecorated, with a blue-green or green colour: similar goblets have been found at the site of Torcello, Venice (Ferri, 2006; Gelichi et al., 2012, note 25, 178). Given their association with the workshop area, it has already been suggested that goblets were one of the products of the same workshop (Gelichi et al., 2012, 178). In addition, similar ones have been found at San Francesco harbour: Gelichi and colleagues (Gelichi et al., 2012, 178) suggest that they might have

[70] See Com96 (Figure 27),

been produced in Comacchio and then traded inland to other sites along the Po Plain network.

A small number of mosaic tesserae (eleven) is included in this dataset (Figure 30) most of them translucent blue-green, colourless, or dark blue coloured; three are opaque (red and white). Similar tesserae associated with a glass workshops in Italy have been found at 9th century AD site of San Vincenzo al Volturno (Hodges, 1991) and 7th-8th century Torcello (Leciejewicz et al., 1977, 139-40). Aside Com 6[71], they are all associated with the workshop phase, dated between the 6th and the 8th century AD: their presence at the workshop might indicate that they might have been used source of colourant or possibly to produce new glass, as witness at Nogara or Vincenzo al Volturno (Silvestri and Marcante, 2011, 2517-8; Schibille and Freestone, 2013, 9)[72].

[71] Com6 is dated to the 10th–11th century AD and it is associated with the cemetery phase, tomb n. 50.

[72] In Late Byzantine and Early Medieval times, mosaic tesserae were frequently added to fresh raw glass to "extend" the amount of available glass to be worked, such in the case for Nogara and San Vincenzo al Volturno glass.

3.3 Barking Abbey

3.3.1 Archaeological context

3.3.1.1 Historical context

The Benedictine nunnery of Barking stood upon the eastern bank of the River Roding, about a mile above its confluence with the Thames. The precise date of the Abbey's foundation is uncertain but Clapham, who was the first person to properly excavate the site in the early years of the 20th century, believed that the date reported by the Chertsey register is correct (Clapham, 1911,70). The monastery should have been found in c. 666, or at least before Erkenwald (abbot of Chertsey, Surrey) became bishop of London in 675 AD (Clapham, 1911, 71).

The Abbey was sacked and destroyed by the Vikings in c. 870 AD (Clapham, 1911,71) and then rebuilt around the 10th century AD during the Benedictine Reform (Bussell and Brown, 2012, 3-4). Originally intended as a Benedictine double house for both men and women, Barking Abbey was converted as a women's community after the Viking invasion in the 9th century AD, and it remained so until the dissolution in 1539. First attestation of the new establishment is accounted in the Ilford Hospital charters dated to c. 946-51 AD (Bussell and Brown, 2012), in addition, the event is accounted in both Æthelstand and Eadred charters (Bussell and Brown, 2012, 4-5; note 9, 5). The Abbey surrendered to the King's commissioners on the 14th of November 1539, and from there on the declined of the Abbey started: buildings were levelled to the ground, leaving no trace of the pre-existing structures.

In the Doomsday book, Barking's importance is attested by reporting that at the time it was the third richest women's religious house after Wilton and Shaftesbury Abbeys and it remained as such till the dissolution in 1539 (Bussell and Brown, 2012, note 30, 7). In addition to this, Barking's

abbesses were appointed directly from the crown until 1215 as well as its holdings. Nonetheless, the Abbesses defended their autonomy and their self-governance even in the most pressing moments: for example, they pressured King John's candidate abbess of choice Prior Sybil into retirement and substitute her with their own choice, Mabel of Boseham, who they considered more suited for the role because of her being a skilled administrator (Bussell and Brown, 2012, 10).

Several structural improvements and refurbishments by its abbesses prove that the abbey was wealthy and well established: among these were included its plumbing system and its kitchens which, according to Bussell and Brown, were not usually found in women's communities and were seen as non-necessary luxuries (2012, 9). Can the Barking furnace also be considered a luxury or an expression of wealth?

3.3.1.2 Lethieullier and Clapham excavations

After the dissolution, the Abbey upper levels were completely razed to the ground, leaving no trace of the once prosperous nunnery. The only section that remained visible part was the Southern wall of the Abbey Church. The few remains are show in some drawings dated to the early 18th century made by Lethieullier conserved at the British Museum (Clapham, 1911, 73-4).

Lethieullier, a Lithuanian immigrant who become Secretary the Society of Antiquities, was also the first to "rediscover" the Abbey and excavate the site. Two plans were made as a result of this excavation both made by Lethieullier in the early 18th century: one in particular identified the monastic site north of the present Parish church. Clapham (1911,74) describes his plans as "… *hopelessly inaccurate as to be almost valueless* …". Nonetheless, both of these plans demonstrate that at least from the 18th century AD the presence of the Abbey was acknowledged.

After Lethieullier's work, the next person who excavated in the Abbey premises was Joshua King, headmaster of Barking's National school (north - eastern end of the Abbey Church). While digging in his garden, he found a tomb which he identifies as the tomb of one Abbess who had been interred under the high altar (MacGowan 1996, 174).

As mentioned in the previous section, Clapham was the first to properly excavated the site in the early years of the 20th century, thanks to some work in connection with the building of a road in the middle of the Abbey land. He also noticed that the site was probably previously looted after the Dissolution and by Lethieullier himself during his inconclusive excavation. His main aim was to register the main precinct and extent of the monastic buildings, such as Abbey church, the cloister and other building in connection with the nunnery (Clapham, 1911,77-86). In his report, he does not mention the recovery of any glass objects (Clapham, 1911, 77-86-7).

3.3.1.3 1985-86 excavation

The first modern archaeological investigation started in the mid-80s but, unfortunately, MacGowan's work (1996) is the only published account concerning both 1985-86 and 1990 excavations. The construction of Barking retail park in the mid-1980s allowed archaeologists to uncover and map new archaeological evidence for both Medieval and Saxon occupation (MacGowan, 1996, 174). The first archaeological campaign lasted a year and a half (from April 1985 to September 1986), and was undertaken by the Archaeological Section of the Passmore Edwards Museum (now Newham Museum service) under the direction of Michael Stone and later of MacGowan himself. The excavation trench (40 m x 30 m) revealed the main drain system, the *garderobe*, and some walls belonging to the Medieval phase (Figure 31).

For the first time, evidence for the Saxon occupation was recorded at the site: a series of aligned structures were mapped beyond the medieval boundary wall. Sceatas dated between the 720-730 century AD were found in various floors (MacGowan, 1996, 174).

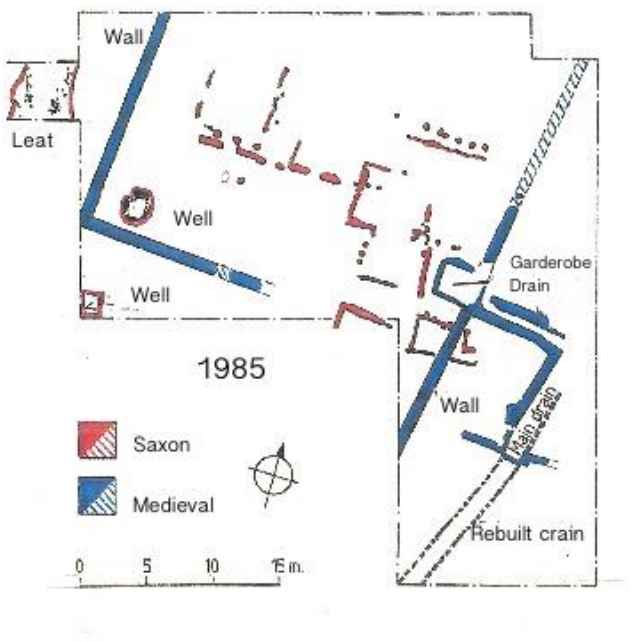


Figure 31 - Barking Abbey: 1985 planimetry excavations, after MacGowan, 1996, 172. Saxon areas are in red, medieval are in blue. Captions from the original illustration have been enhanced just to make them more legible. No other features have been modified in any way from the author.

A large number of finds belonging to the Saxon occupation indicate the presence of rooms used as workspaces: spinning and weaving are attested in form of spindle whorls made of bone, clay, and glass, loom weights, and bone rods recovered in and under the floors of these structures. Fragments of gold thread suggests that high class clothing was made on the site.

At the Western edge of the site an early mill was also found, Timbers from the leat have been dated by dendrochronology to after c. 705 AD, within 39 years from the foundation of the abbey: this evidence suggests that the mill itself might be in existence since the early construction days

(MacGowan, 1996, 175). In the south west part of the site, two wells were discovered. Each of them has evidence for two phases of use: the phases of the first well were dendrochronologically dated respectively to 730 and 835 AD. For the second well instead, it was possible to assign a chronological frame only the first phase, which was in the end dated to 800 AD (MacGowan, 1996, 175).

3.3.1.4 1990 excavation and the glass furnace

During the 1990 excavation, a Saxon glass furnace was discovered in a 50 m trench number 4, south of a previous trench excavation in 1985 (MacGowan, 1996, 178). The kiln measures 2 m in diameter and just 20 cm in height (the part that actually survived of the upper part of the kiln) and lays close to the later precinct medieval, in the middle area of the site (Figure 32). The upper layer is made by a stratum of laid broken pieces of Roman *tegulae* (Figure 33), while instead the ground floor was covered with rake-out material. Adjacent to the south-east part of the kiln, the remains of a heavily baked surface lay, which MacGowan interprets as an earlier kiln or possibly an associated surface (MacGowan, 1996, 178). Close to the furnace, some pits also dated to the Saxon phase contained coloured glass in association with broken kiln parts, such as broken Roman *tegulae*, a broken *tuyère*, glass ingots, slags, fragments of vessels, fragments of reticella, and millefiori rods.

An archaeomagnetic chronology has been produced for both the kiln and the associated baked surface, but the results have been proved problematic. The first has been dated to the 925±50 AD, the latter to 920±50 AD, suggesting a chronological range for this material is between 875 to 975 AD: the kiln therefore might have used by the Saxons before the abandonment or by the Vikings during its abandonment, or by the Saxons again during the re-foundation and subsequent refurbishments.

The chronology assumed from the archaeomagnetic analysis does not fit with typological evaluation: Barking glass finds (such as reticella rods) have been compared to Glastonbury Middle Saxon ones (Bayley, 2000, 138), and Evison has dated typologically some of the Barking material to the eighth century (Evison, 1991). Recently, Willmott and Welham (2015, 233) rejected the mid-10th century chronology given for Glastonbury furnace 1 and 3 supporting instead a date in the late 7th century AD, in light of recent ^{14}C dating. Until further investigation, a similar chronology could also be carefully considered for Barking materials.

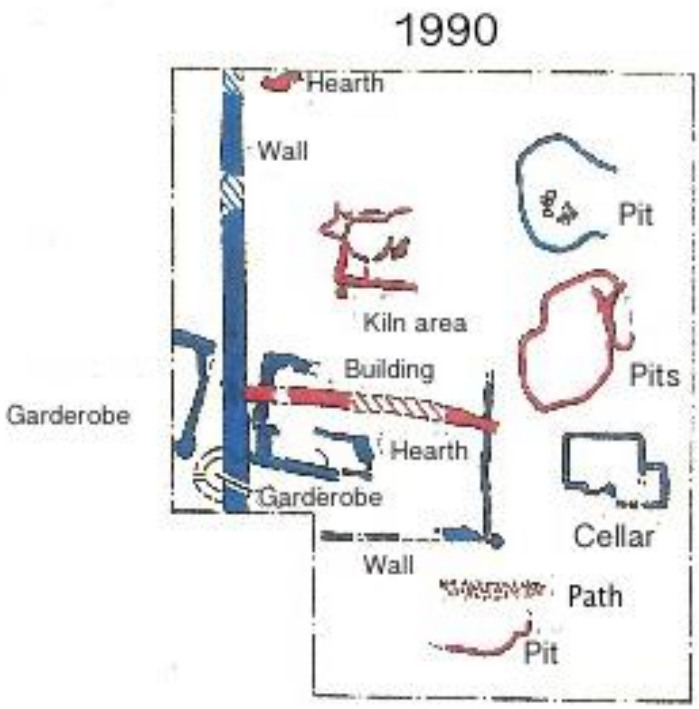


Figure 32 - Barking Abbey: 1990 planimetry excavations, after MacGowan, 1996, 172. Saxon areas are in red, medieval are in blue. Captions from the original illustration have been enhanced just to make them more legible. No other features have been modified in any way from the author.



Figure 33 - Barking Abbey, glass kiln: the base was made of re-used Roman roof tiles, after MacGowan, 1996, 177.

The presence of the furnace and the associated materials debris seems to indicate that at least glass was secondary worked here. MacGowan seems cautious in assuming with certainty that the evidence for Saxon industries discovered in both excavations are certainly connected with the ecclesiastical presence in Barking. It is definitely a possibility though, since similar evidence is found for Saxon industries at other sites (he cites in particular Hamwic, Ipswich and Londonwich), but not entirely certain at the moment.

3.3.2 Barking glass dataset

Barking glass dataset includes 78 fragments of glass. Each sample has been given a unique code based on the original excavation record provided when the author sampled the glass, where each code is formed by the abbreviation “Ba” (Barking Abbey) plus a progressive number (ex.

Ba01, Ba02, Ba03, etc...). The number assigned to each sample is totally arbitrary depending on the order it was sampled originally. In addition to this code, each sample has been associated to their excavation information provided by the label included in their bags, which includes an identification context (CON), a grid, and a small finds numbers (SF). Please refer to the complete list and pictures of artefacts in Appendix 1 and 5.

All artefacts have been recovered from the clearing of trench 4 during the 1990 campaign (BAIE-90 area), around the kiln and in the adjacent pits.

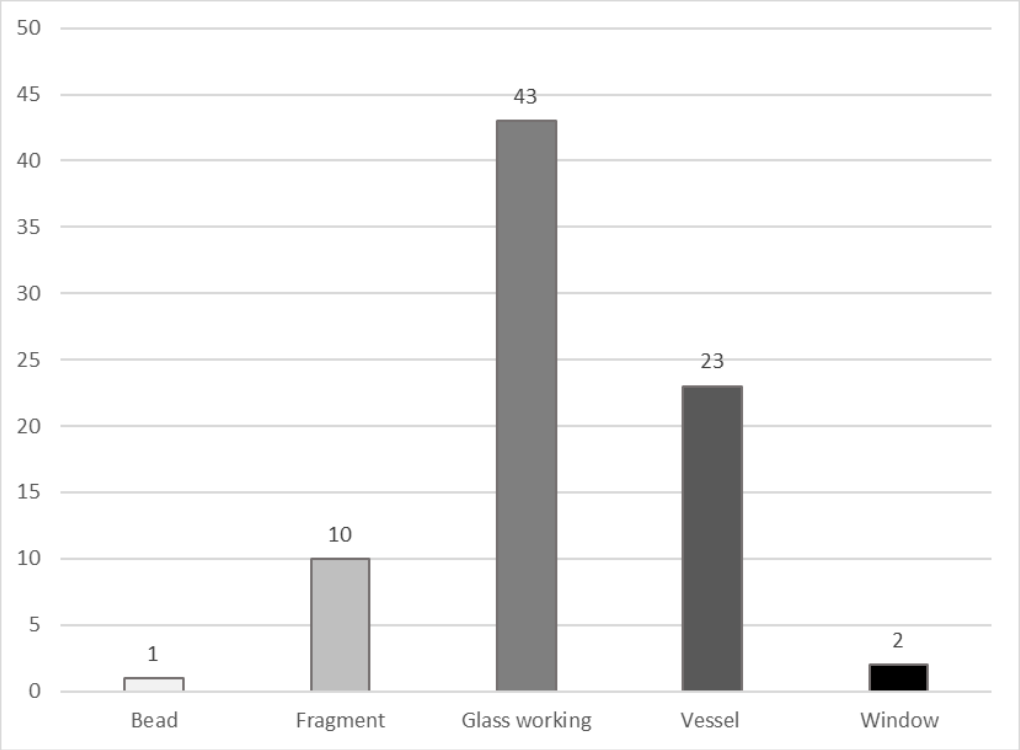


Figure 34- Barking Abbey glass dataset arbitrary typology.

To this day, Barking Abbey glass remains unpublished. Nonetheless, a basic typological distinction has been given by the author to allow a distinguish fragments according to their supposed function (Figure 34).

Unfortunately, most of Barking Abbey glasses are heavily fragmented. Hence, in many cases it was not possible to assign a more precise typological classification aside from a generic “vessel”, or “reticella rod. As showed in Figure 34, the majority of samples (forty-three) fall into the “glass-working” category, which include glass layers from crucibles, wasters such droplets and spills, pontil marks, and chucks of glass, reticella and monochrome rods, and glass-threads (Figure 35). Undetermined vessels are also represented (twenty-three), while window (two) and beads (one) are underrepresented (Figure 34).

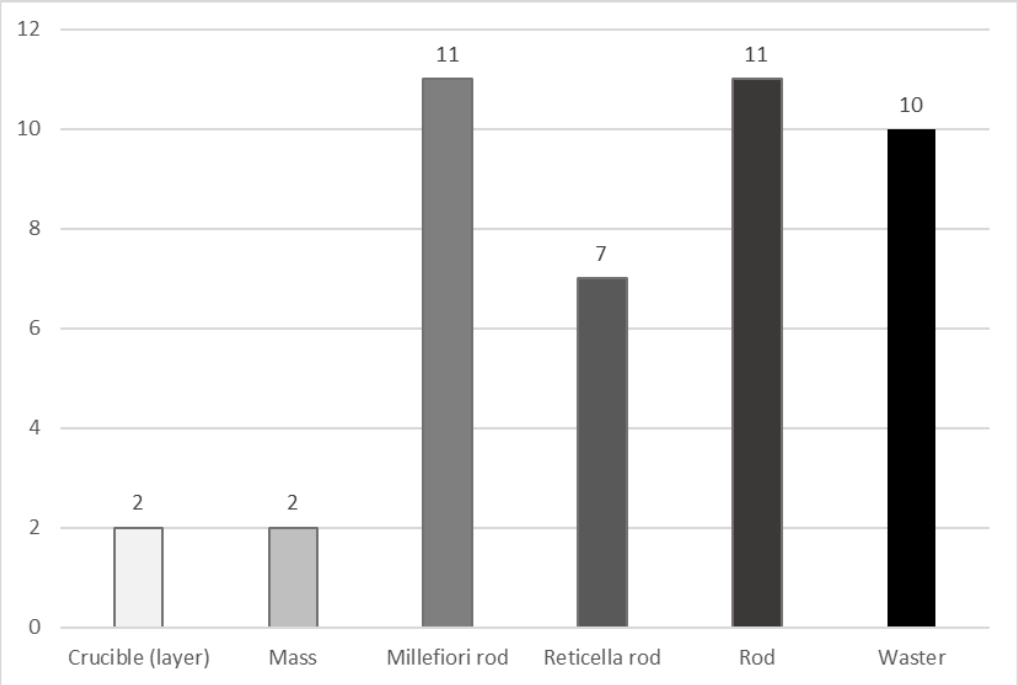


Figure 35 - Barking Abbey glass-working samples divided by category: waster and rods are the most represented objects, while very few slags of glass and crucible layer (both 2 in number) have been included in this dataset.

Most of Barking Abbey glass is translucent, with prevalence of blue-green and blue colour, but a considerable number of samples are opaque, mostly in white and blue colours (Figure 36). Few samples show signs of decoration, such as opaque glass trailed over the object. The only bead present in the dataset has a white trailed decoration which follows its profile (Ba50). Another vessel type object has a yellow opaque trailed

decoration (Ba21), while one blue-green transparent glass is decorated with a trail of yellow opaque glass (Ba20). Similar decoration patterns have been found in glass from Hamwic (Hunter and Heyworth, 1998, plate 4, 177 498, 28; plate 5, 24, 554, 29; plate 8, 15 460, 29). Finally, another undetermined olive green displays a small blob framed by white opaque glass (Ba26).

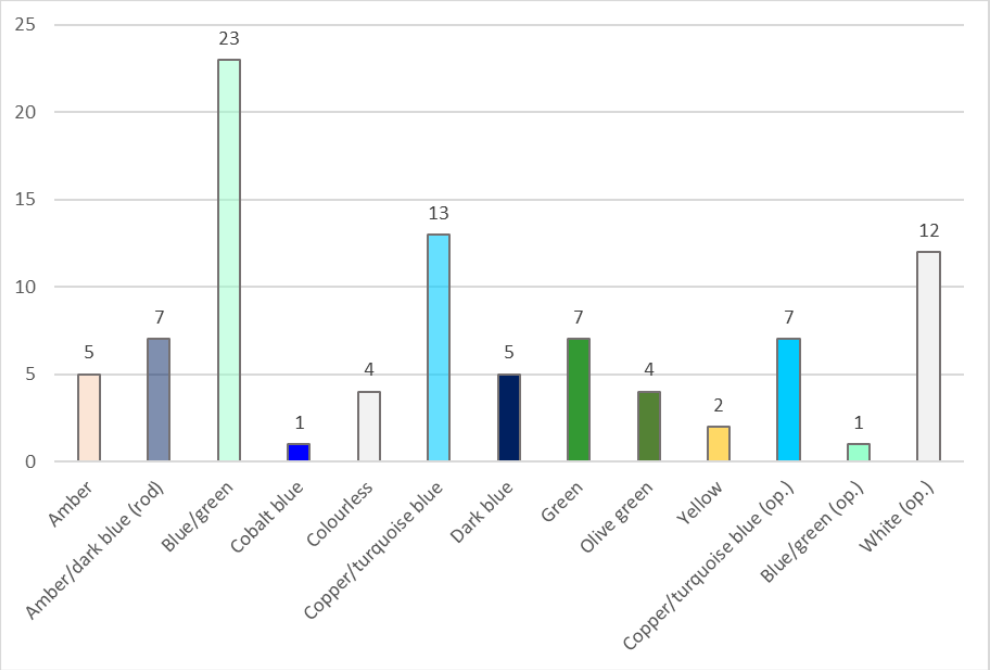


Figure 36 – Barking Abbey samples divided by colour. “Op.” stands for opaque.

Aside the presence of the furnace, droplets, and crucibles (Ba38 and Ba39), other artefact seems to be wasters from glass-working production (vessel, reticella rods and bead, Figure 41 and Figure 42). This hypothesis is supported by the presence of malformed pieces (Figure 37 and Figure 42) and waste cullet with ferrous scale from the gathering iron where the glass was wound around to make the bead (Figure 38 and Figure 39). If the presence of malformed vessels could also be interpreted as cullet (and therefore have been made somewhere else), pulled reticella rods, polychrome wasters, or bead-making wasters might be explained as wasters from local glass production, possibly beads and

reticella rods. Other pieces that would indicate the presence of local glass manufacture would be simple monochrome rods cut at the end (mostly in white and blue opaque) and glass threads, used in millefiori/mosaic rods production.



Figure 37 – Deformed waster (drinking vessel base?) possible connected with vessel glass production (Ba53). Alternatively, such malformed pieces could have been taken to the site to be used as cullet to produce new material.

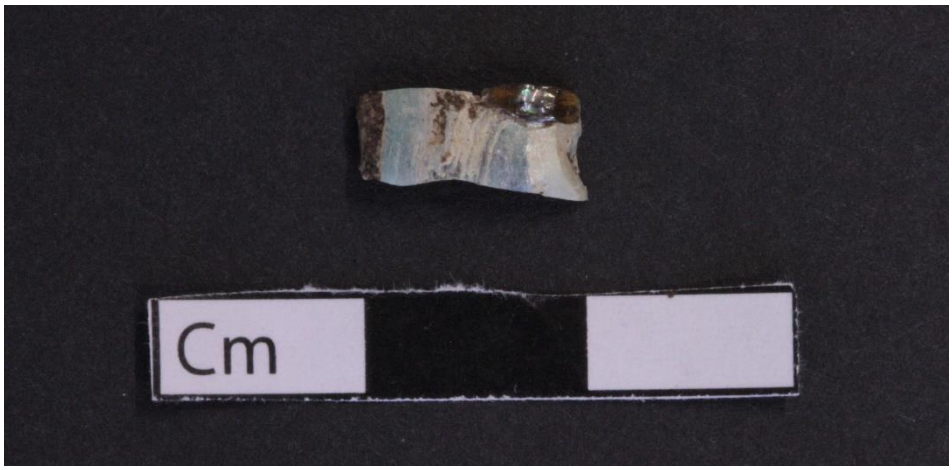


Figure 38 – Waster from millefiori rod production (Ba81); the same colour patterns are used in other millefiori rods find at Barking (such for example Ba8). The back is characterised by a residual iron layer from the gathering iron, possibly evidence for bead-making manufacture.

Five fragments of millefiori rods have been found at Barking, characterised by chequered patterns (Figure 41 and Figure 42). Millefiori rods have also been found at Jarrow and Wearmouth complexes (Cramp, 2006, 263 - 67). Millefiori rods are used to decorate beads: beads with millefiori decoration have been previously found at Ribe (Andersen and Sode, 2010, 52; plate 1, 55; plate 4, 58).

The presence of such wasters has led to the conclusions that both at Ribe and Jarrow/Wearmouth could serve as a manufacturing centre for such artefacts. In light of fact that similar objects have been recovered at Barking too, I suggest that it is entirely possible that such objects were made at Barking, while I do not know if any beads with millefiori decoration have been found at the site: it might therefore possible that such millefiori rods might have been traded to other manufacture centres to be used in bead-making, or simply that we have not yet found evidence for such industry at the site.



Figure 39 – Ba5, residual iron layer from the gathering iron; possibly evidence for bead-making manufacture.



Figure 40 – Waster from millefiori rod production (Ba10).

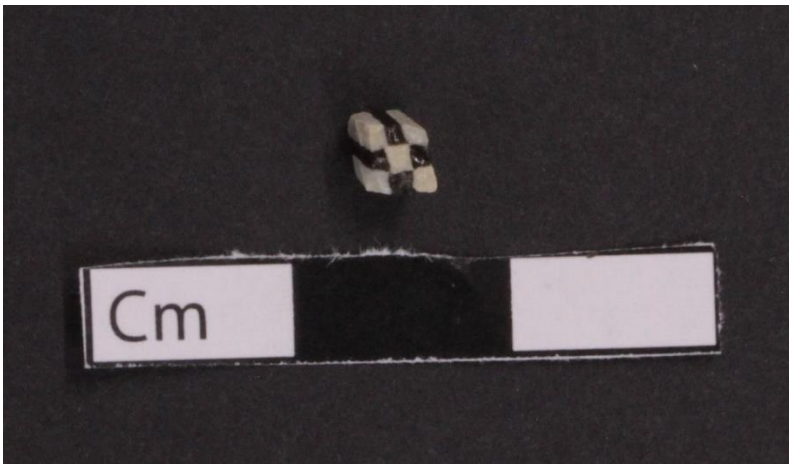


Figure 41 - Waster from millefiori rod production, chequered pattern (Ba01)

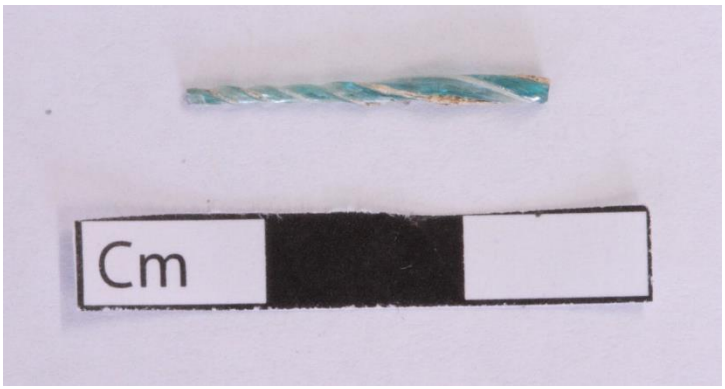


Figure 42 - This reticella rod (Ba2) is deformed at its right extremity, and therefore it is possible that it represents a waster from local glass-working manufacture.

Reticella rods in two coloured variants (blue transparent base plus white or yellow opaque trails) could also have been made at Barking (Figure 42). Evidence of pulled reticella rods (Ba2) could be the result of the manufacture itself: reticella rods are made from a rod of translucent glass (blue in this case), melted together with thinner, parallel rods of opaque yellow or white glass. The now striped rod is then held at each end with tongs, pulled out to form a thinner rod, and at the same time twisted to create the special reticella pattern (Näsman, 1986, 76).

Reticella rods with blue and white pattern have been found at Ribe (Andersen and Sode, 2010, 31-33; plate 1, 55), Whitby Abbey (Paynter and Dungworth, 2011; Paynter et al., 2014), and San Vincenzo al Volturno (Schibille and Freestone, 2013, 1A, 3). Vessels with reticella decorations have been discussed in various publications (Evison, 2000a; Näsman, 2000, 1986).

Reticella decoration was very popular on vessels in the West between 700-900 AD, (Evison, 2000, 92), while there are no example in pagan Anglo-Saxon or continental graves: such evidence, according to Evison (2000, 92), would suggest a date no earlier than 7th century for its initial distribution. In Scandinavia reticella decorated vessels are dated from the 7th century up until the 10th century AD (Näsman, 2000, 37). The place of production of glass vessels with reticella rods is still unknown, but Ireland, England, and France/Belgium have been suggested (Näsman, 2000, 1986; Feveile, 2006a).

3.4 Ribe (8th-9th century AD)

3.4.1 Archaeological context

Ribe is situated in the south-western part of Denmark, north of the present-day border with Germany and east of the Wadden Sea (Figure 43). The river Ribe, running east to west into the Wadden Sea, divides in half the modern town. The Western area of Ribe is dominated by marshlands, formed by recurring high and low tides from the Bronze Age (c. 1500 BC), until barricades were built in the early 20th century. Boggy wetlands dominate instead the eastern part. The areas north and south of the town are generally flat, sandy plains, no more than five to ten meters above sea level. The choice for location of Ribe was made definitely considering all those elements and, therefore, in a convenient point where the sandy plains from the north and south reach out towards the river to wetland.

3.4.1.1 Written sources

Ribe's foundation is registered in the written sources. In his biography of Ansgar (Archbishopric of Bremen), Rimbert mentions that in c. 870 AD that Ansgar was given by the Danish King *Haarik* a plot in his town Ribe to build his church (Bencard and Jørgensen, 1990, 576). Again in 948 AD the bishop of Ribe (*Liopdag* or *Liesdac*) is mentioned as participant in King's Otto's synod in Ingelheim (Skovgaard-Petersen, 1981, 20, 22-3). Therefore, written sources seem to indicate that Ribe must have been founded at least before c. 870 AD. About the precise location of the Old town though, written sources remain vague.

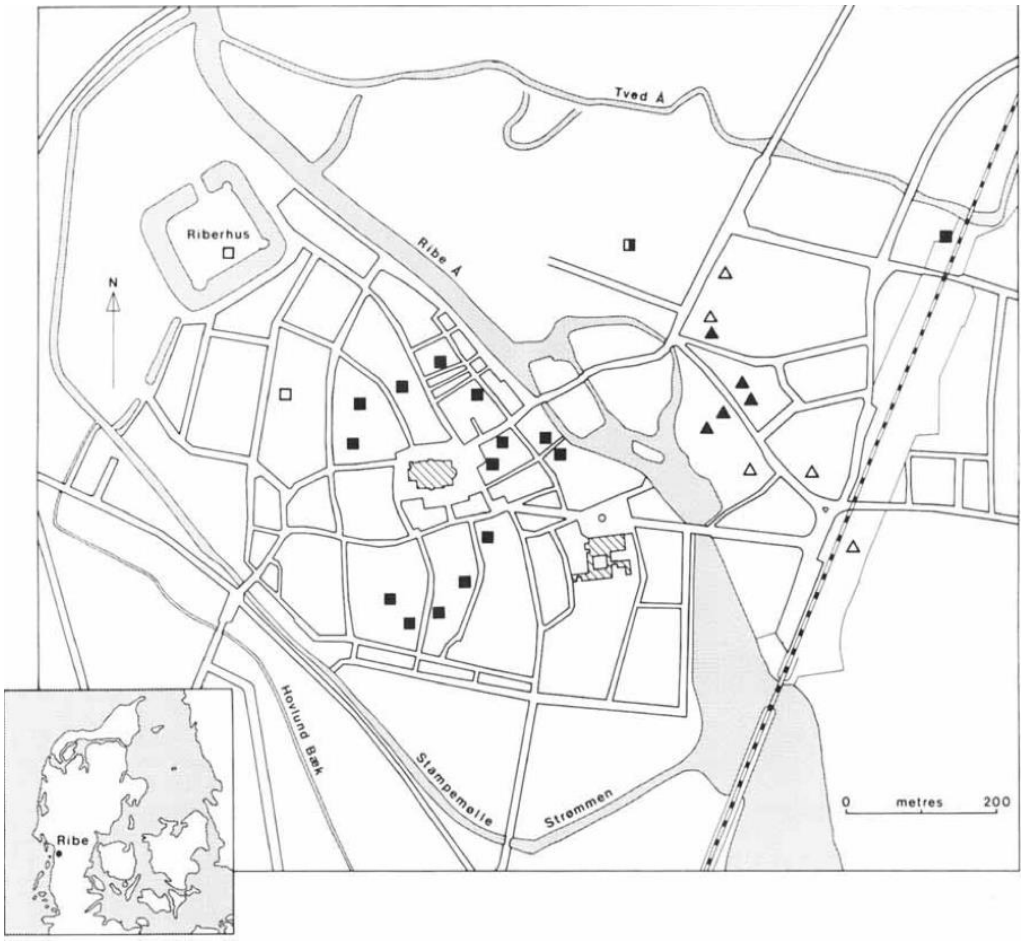


Figure 43 – Map of modern Ribe together with updated excavations and trial trenches up to 1976, after Bencard et al., 1990, fig. 2.6. Ribe Å river runs southeast-northwest and divides the modern city in two parts: north and south Ribe. Excavations where Medieval and later materials have been found (solid black squares) are concentrated all in the southern side of the river; on the other hand, sites with evidence of Viking materials are concentrated in the northern part of town (solid black triangle).

The oldest part of Ribe (Old Ribe or better "*Gamle-Ribe*") is distinguished by Terpager, in his account concerning the city itself dated 1736, from the more recent part of the town referred instead as "New Ribe" (*Nye-Ribe*). According to Terpager, the old part would have been located on the north side of the river together with St. Peders Church, which is mentioned by several authors as the oldest in (Terpager, 1736; Thorup, 1839; Kinch, 1869 in : Feveile, 2006a, 65-6). Galthen (1792 in : Feveile, 2006, 65-6) mentions that instead "New Ribe" from the beginning was located in the southern part of the city and that it would not be older that the beginning of the 9th century AD. More recent accounts express doubts

on the location of Ribe itself on the Northern side of the river. Given the contrasting evidence described in the available written sources concerning Ribe foundation and location, it is understandable how the location of the old part of the city remained uncertain before proper excavations began.

3.4.1.2 Ribe excavations and chronology

During the 1950s and 1960s the first proper excavation was focused in recovering the ancient evidences of the earlier Ansgar's Ribe (9th - 11th century AD) following the written sources indications and therefore by preferring the cathedral area south of the river and later the area outside Ribe (Feveile 2006a, 66). Unfortunately, no traces of Ansgar's Ribe (9th century settlement) were found. In the early 1970 the research for Early Ribe (8th - 9th century AD) moved in the Northern side of the Ribe by focusing in particular around the Marketplace area with three major excavations campaigns: between 1973-76 (Bencard and Madsen, 1981; Bencard, 1984; Bencard et al., 1991, 1990, 2004) and 1986 (Frandsen and Jensen, 1987, 1988) two major excavation campaigns involved 8th century AD marketplace, and in particular the areas of *Dommerhaven*, *Kunstmuseets,* and *Sct. Nicolajgade 8* (Figure 44 and Figure 45).

A third large excavation (80 m^2), between September 1990 until March 1991, revealed evidence for cultural layers in the central part of 8th - 9th century Old Ribe, at the Posthuset - Post Office (Figure 45).

Overall, Ribe residential phase in the Northern side of the river can be subdivided in to three main structural phases (Feveile, 2012, 114), which span across the 8th and 9th century AD. Written sources and archaeological evidence do not match for the following period (10th-11th century AD): in the written sources Ribe is mentioned in different contexts, while we cannot find any archaeological evidence for the corresponding later period (Feveile 2006a, 84-88). The reason has still

to be assessed, but Feveile (2006a, 87-8) suggests three possible reasons to why the evidence are scarce for this period.

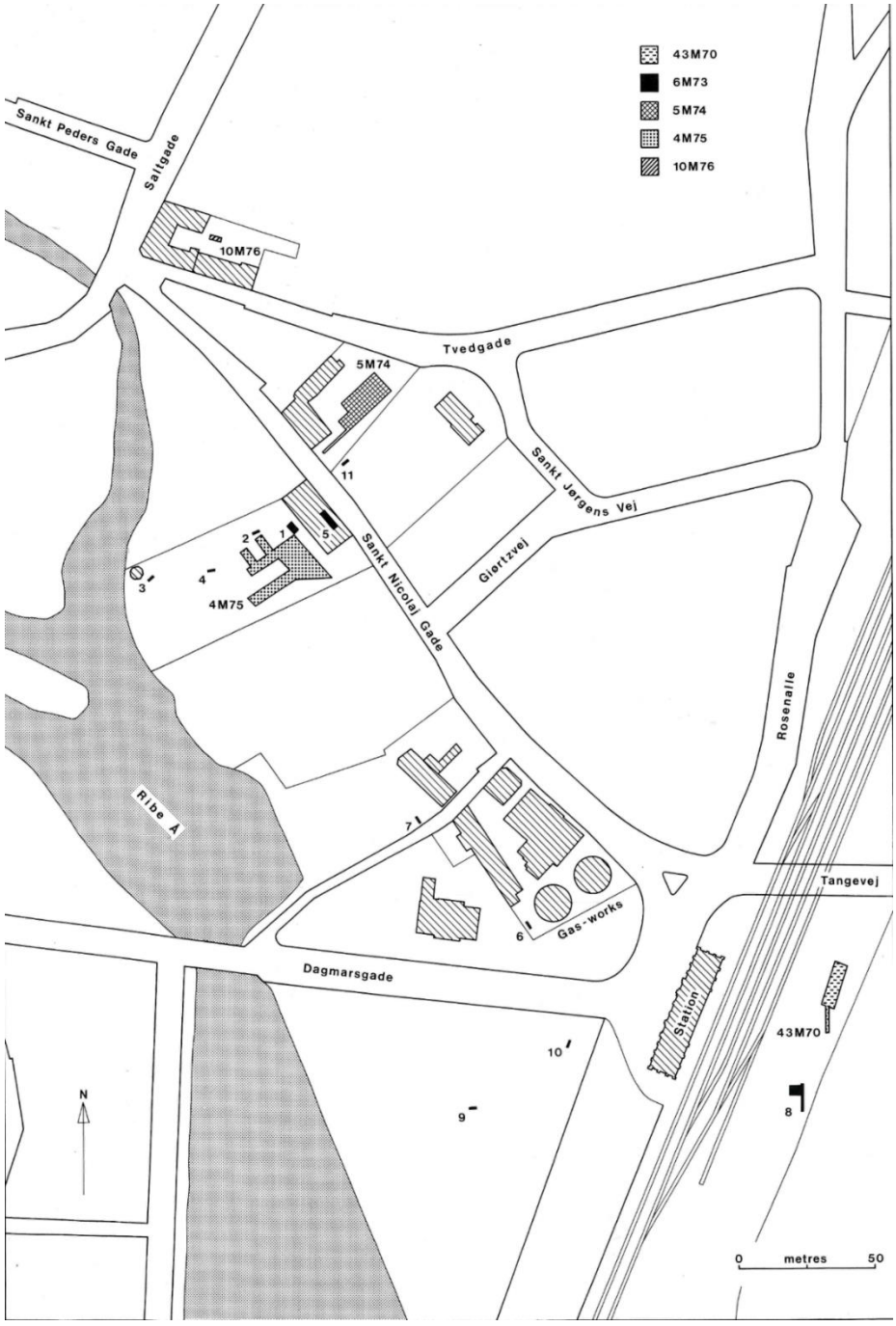


Figure 44 - Ribe, Northern side, map of 1970-76 excavations, after *Bencard et al., 1990, fig. 2.6*: 43M70 Sankt Nicolai churchyard; 5M74 Dommerhaven; 4M75 Kunstmuseets have.

The first possibility has to do with possibly unfortunate circumstances connected with the choice of place to investigate and with research methods. Secondly, Ribe could have been disappeared or moved, but there is no tangible proof that the site moved on the southern side until 1077 (Feveile, 2006a, note 3, 91), so it appears that this has to be excluded as reason for not finding evidence on the northern one in the same period. Finally, it is possible that all the major activities that were located in Ribe could have been moved away to another centre. As a result, not all chronological phases are equally documented: major excavations in 1970s, 1985-6 and 1990-91 mostly document the early 8th to the 9th century AD.

3.4.1.3 Main structural phases (8th – 9th century AD)

I will here describe the Ribe Marketplace structural sequence between the 8th and 9th century AD. The first structural phase is pertinent to the first decade of the 8th century AD and it involves a natural brown sand layer, which was originally believed to have been artificially placed there to level the area probably by some sort of authority figure, in addition to regular ditches plus cultural layers deposited in-between.

Jensen (1991, 9) suggested that Danish royal power itself could have been involved in this operation, to prepare terrain for the workshops or to drain the area or raising group. Later on, archaeological evidence proved this assumption wrong, since the market place extends also in areas where the sand layer is not recovered and that the strictly association between sand and workshop layer in some points in interrupted by a vegetation layer which has formed before the marketplace (Feveile 2006a, 71). This means that some time passed (Feveile suggests 25 years) between the sand layer deposit and the following cultural layers.

Several ditches running in curving and partly irregular stretches associated also with this phase were found at ASR 9 *Posthuset*, ASR 951

Riberhus Plejehjem, Dommerhaven, Kunstmuseets Have and *Kunstmuseets Kælder*, area 5 (Feveile, 2006a, fig. 9, 26). Feveile argues that this phase must have occurred in the first few years of the marketplace, and it should have last no more than 5 to 10 years (Feveile, 2012, 114).

Apparently, the irregularity pattern of these ditches should exclude that they were part of a system, but it cannot be excluded that they were used to divide the area in some sort of way, maybe into plots, as it will happen in the next phase of the marketplace. Sporadic evidence for cultural layers has also been associated with these ditches. For example, at the excavation of Posthuset some evidence for a bead-makers workshop was found, with the presence of two fireplaces with hundreds of glass pieces in the associated layers (Feveile, 2006a, 74).

The second phase, lasted at least for the first three quarters of the 8th century, is constituted by a regular series of plots located side to a narrow street (Figure 45), which Feveile suggest to be at least as 40 or 50 in number (Feveile, 2012, 114). This phase would correspond to the proper market-place in Ribe with extensive evidence for craft activities and imports (Bencard et al., 1990, 144), like for example bead-making, metal casting, and comb-making. These activities were considered as the temporary kind, possibly seasonal or recurring.

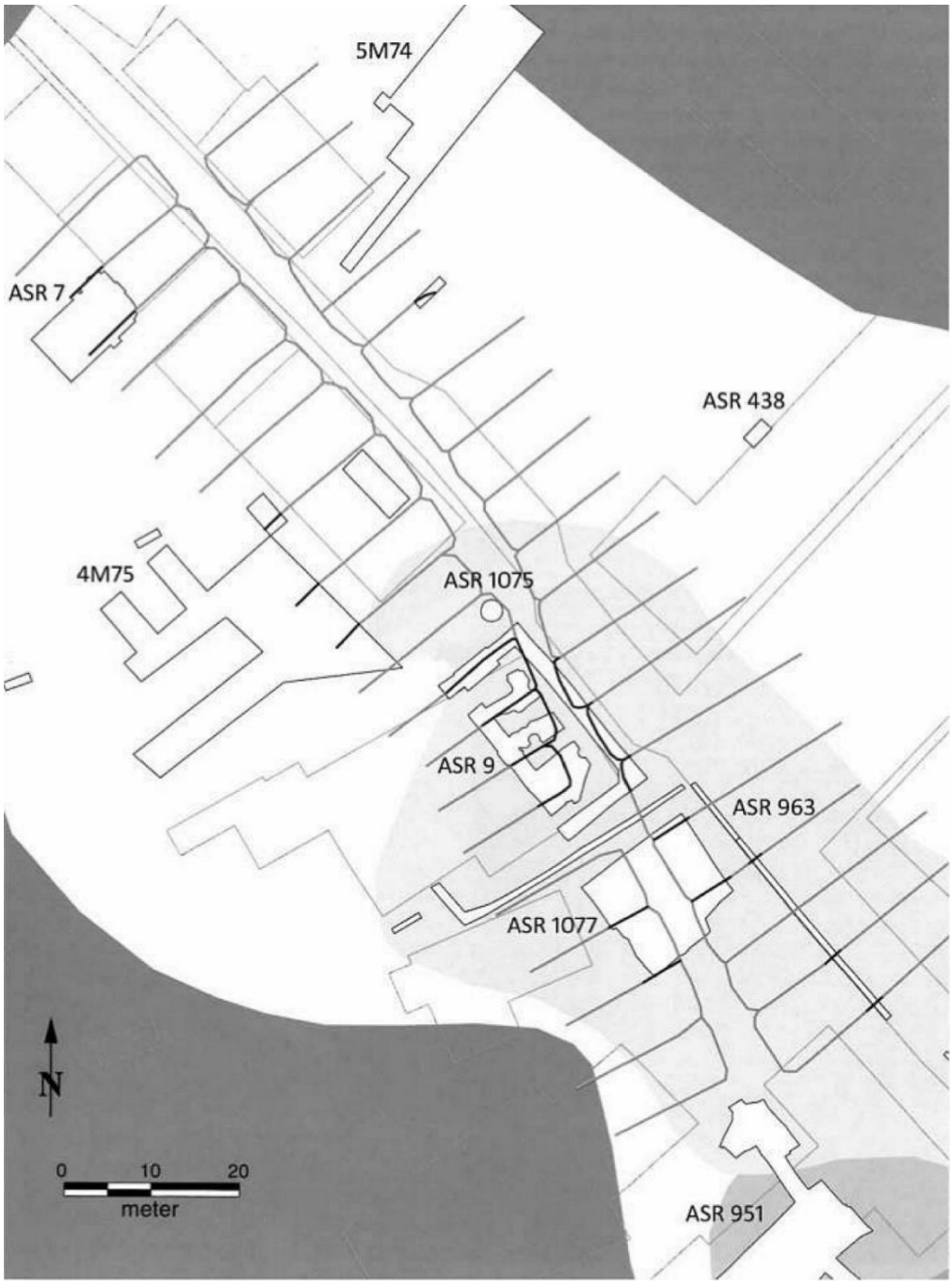


Figure 45 - Reconstruction of the layout of the 8th to early 9th century plot system at the market-place in Ribe, after *Croix, 2014,* fig. 1, 502. Excavation campaigns before 2006 are outlined (modified by Croix after Feveile 2006a, fig. 10, 29. Excavation campaigns: 5M74: Dommerhaven (1974); 4M75: Kunstmuseets Have (1975); ASR 438: Biblioteket (1984); ASR 7: Sct Nicolajgade 8 (1985-86); ASR 951: Plejehjemmet Riberhus (1990); ASR 963: Nicolajgade 14 (1990); ASR 9: Post Office (1990-1991); ASR 1075: Posthusskulptur (1993); ASR 1077: Sct Nicolajgade 14 (1993).

As Bencard and Jørgensen remark (1990, 581), the presence of a bead-maker and bronze-founder in the market-place are considered as temporary, given the nature of the stratigraphy of the site itself:

> *"… One plot was that of a bead-maker; here, four-five hearths were found almost exactly on top of each other, separated only by the levelling layers. The beads, however, are not identical, so these need not represent the same man. Another plot was that of a bronze-founder. Four successive layers contained debris of moulds of tortoise brooches… Both examples suggest that itinerant craftsmen returned to the market-place, and even to the same stall, at regular intervals. The plots that have been found have no traces of any solid constructions such as buildings, and the craftsmen must have worked under the open sky, or possibly. sheltered by a tent or a light screen. All these features indicate a periodic market… ".*

Also, we should not forget the fact that, within the excavated areas, there is no sign of what it can be interpreted as permanent buildings that could have been used all year long: crafts-men must have worked under the open sky or sheltered by some sort of temporary construction (tent or screen). As Feveile remarks though, all of these suggestions are not sufficient to rule out the possibility that a more permanent settlement was associated to the market-place (2006a, 76).

Evidence for the existence of a permanent settlement associated with the seasonal market can be adduced first by considering plough marks together with the so-called "village layer" (L phase in Bender Jørgensen and Jensen relative chronology system) at *Sankt Nicolajgade* site (Bencard et al., 1990, 144). Also evidence for textile production in form

of loom weight and the presence of high proportion of elderly sheep (kept for their wool, not for their meat) would indicate the existence of slow crafts carried out in 8th century AD Ribe (Bencard and Jørgensen, 1990, 581).

Unfortunately, evidence for the existence for a permanent settlement was never found.

With the late 8th century, the composition of plots changes: evidence for a settlement outside the market-place dated to the middle of the 8th century AD has been indeed found in different excavations (Feveile 2006a, 79-80), but the characteristics and the development that will characterise Ribe permanent settlement from now on has still to be assessed properly.

Traces for structure outside the market-place have been found in Katalog ASR 863 Seminarievej, ASR 926 Ribelund I, ASR 937 DSB Øst 2, ASR 985 Tvedgade, ASR 1000 Ribelund II, ASR 1357 Giørtzvej, and in the earlier investigations ASR 43M70 and ASR 6M73 field 8 (Bencard et al., 1991, 23 and 44). Unfortunately, given the partial nature of the recovered for each of these excavations, it is not possible to describe a broader and comprehensive picture of the perimeter and development of these buildings, given also the sparse nature of the cultural remains associated with these sites (Feveile 2006a, 80).

As I fore mentioned, at the present time it is not possible to establish with certainty that there was a permanent settlement before the middle of the 8th century. However, it is possible that the small scale of the investigation and the limited amount and nature of the materials recovered might have influenced the final outcome.

On the other hand, based on evidence a year-round settlement associated with the market-place must have existed around the middle of the 8th century (Feveile 2006a, 80).

3.4.1.4 Market-place structural phases and relative chronology

Ribe's stratigraphy is been renowned to be rich in well-preserved cultural layer (1.5 - 2 m thick) but, as Feveile specifies (2012, 113), this richness is confined to the part close to the workshop area, while the situation in other parts of Ribe is completely different: almost no cultural 8th -9th cultural layers are recovered in the other excavated areas, with the only archaeologically preserved features include potholes, wells, ditches, etc. This leads to the conclusion that matching the extremely detailed workshop area chronology (both relative and absolute) with the one extrapolated in other areas of the town is not an easy task. It has also to be taken into account that three-different relative chronological subdivisions have been used by the authors for each of all three major excavations (Figure 46), so the reconstruction of the development and chronological phases in Ribe becomes particularly challenging.

<table>
<tr><th>MB 1973-76</th><th>LBF/SJ 1985-86</th><th>CF/SJ 1990-91</th></tr>
<tr><td>4</td><td rowspan="2">G2</td><td>H/I</td></tr>
<tr><td rowspan="4">3</td><td>G</td></tr>
<tr><td rowspan="3">VH3-6 + VH2a</td><td>F</td></tr>
<tr><td>E</td></tr>
<tr><td>D</td></tr>
<tr><td>2</td><td>VH2</td><td>C</td></tr>
<tr><td rowspan="3">1a</td><td>G1 + VH1</td><td rowspan="2">B</td></tr>
<tr><td>L</td></tr>
<tr><td rowspan="2"></td><td>A</td></tr>
<tr><td>1</td><td></td><td>AA</td></tr>
</table>

Figure 46 - Comparison of the three different systems for division of the market-place layers into phases *(*Feveile*, 2006a,* fig. 1, 15*)*. MB 1973-76, after Bencard, 1981); LBF and SJ 1985-86, after Frandsen and Jensen, 1988; CF and SJ 1990-91, after Feveile and Jensen, 2000. The "thickness" of a phase must not be confused with the length of the phase.

Bencard and Jørgensen (1990) divided the marketplace layers into four phases on the basis of the excavations in Kunstmuseets Have and Dommerhaven 1973-76 .

Fradsen and Jensen (1988) divided the layers into six workshop-sequences and two ditches on the basis of the 1985-86 excavation at Sct. Nicolaigade 8. Finally, Feveile and Jensen divided the layers into nine phases, on the evidence of the 1990-91 excavation at Posthuset (Feveile and Jensen, 2000). The two earliest of those phases, AA and A, are distinctly earlier than the marketplace.

It would be definitely interesting to discuss and compare all the three different chronologies together, but this is not primary aim of this chapter. I suggest instead to read in depth the work of Feveile (2006a), that does an excellent account of Ribe structural development between the 8th and 12th century AD, together with the Bencard and Bender Jørgensen (Bencard et al., 1990) and Feveile and Jensen (2000) accounts.

3.4.1.5 Bencard and Bender's relative chronology

I use the original subdivision suggested by Bencard and co-workers (1990) as base to describe the other chronological frameworks. The majority of cultural layers from the 1973-76 excavations have been found around both *Kunstmuseets* and *Dommerhaven* sites plus a dozen of other small sites (Bencard and Jørgensen 1990b, 576). The stratigraphy is divided into 4 main phases (Bencard et al., 1990, 130-6):

Phase 1: the surface is of natural base, which includes agrarian activity with evidence of ploughing over most of the excavated area. The material associated with phase 1 is sparse (Bencard and Jørgensen 1990, 130-136).

Sub-phase 1A: A later sub-phase (1A) has been associated with features (like wells, ditches, etc.) which overlay the plough marks. It is not possible to pin point with certainty if the ditches have been assigned to a later phase 1 or to the earliest part of 1A. The finds in 1A are still sparse, but they include comb-making and smiting evidence.

Phase 2: a thin layer of undecomposed or mineralised manure, which covers the overall central area of investigation. Refuse from crafts such as comb-making, bead-making, shoe-making, metal casting, amber work, and textile production are recorded in this phase.

Phase 3: a series of alternate thin layers of sand (levelling layers) and humic layers (activity layers). The series of layers are the product of craft activities workshops. The materials founds in this phase are particularly consistent and include *sceattas* and the bi-products of the activities already cited for phase 2.

Phase 4: a series of unstructured and mineralised layers on top of the workshop layers intersected by medieval and chronologically later layers.

Bencard and co-workers (1990, 136) underline the continuity in the development of the stratigraphy through all 4 phases (1-4). Moreover, the time passed between the creation and the end of the market in phase 3 must have been not greater than 20 years.

3.4.1.6 Other subdivisions

As I mentioned, the same phases described by Bencard and Jørgensen have been given other names in other publications. Fradsen and Jensen (1988) distinguished archaeological layers in 1985-86 *Nicolaj Gade* 8 excavation with letters: the village layer (L), the workshop levels (VH1-6) and ditches (G1-2). In 1990-91 Posthuset excavations, a phase-

system divided in phases from AA to J (Feveile and Jensen, 2000, 10-12; Feveile, 2006a):

- **Phase A** is the original arable land plus traces of cultivation in the underlying alluvial sand.
- **Phase AA** consists of yellow sand deposited as drifting sand;
- **Phase B** includes workshop activity (rubbish layers, fireplaces), ditch system, and two pit-houses remains.
- **Phase C** consists in a uniform peat-like deposit, with large and varied artefact content, some of which are from different workshop activities.
- **Phase D – I** consist of workshop and activities layers occurring from the top of phase C to the final preserved deposits of the market-place. Rubbish layers are also registered, especially in phase H and I.
- **Phase J** is formed by 12th and 13th century layers dug into the Viking layers.

3.4.1.7 Relative chronology discussion

The chronologic framework of the main sites described by Bencard and Bender Jørgensen (1990) was defined by presence of few key objects, but the discussion revolves around one artefact in particular, the so-called "*sceattas*" (32 in number)) in two different types: the Wodan/monster and the Porcupine type.

Bendixen's study (1981) demonstrated that these coins were minted around c. 720-55 AD and circulating down to the year c. 800 AD. Bencard and Jørgensen (1990, 138) add to this discussion that 4 of these sceattas were sealed in one of the manure levels at Kunstmuseets kælder below

the level that was dendrochronologically dated to c. 719 AD. Before the dendrochronological data were available, these coins were of primary importance to define the cultural layers' chronology.

Feveille and Jensen report an overall number of 46 sceattas for the 1990-91 *Posthuset* excavations, 36 of which were found in phase C (phase 2 in Bencard and Bender Jørgensen chronology) and were Wodan type (2000, 14). Phase G (last period of phase 3 in Bencard and Jørgensen chronology) is the last period with evidence for sceattas at *Posthuset.*

The analysis of both iconography and epigraphy with parallels in both *Hedeby* and *Tissø* represented on a Byzantine seal dates phases H/I to 820-850 (Feveile and Jensen, 2000, 13- 4).

Another category of artefact that is discussed is the Berdal type of brooch, which was found in the upper layers of phase 3 (Bencard and Jørgensen 1990). This group of Brooches is not usually dated to the 8th century AD, but to the early Viking Age, after c.800 AD. This later chronological evaluation originates from Jensen (1986, 20) since he associated a mould for the production of these Brooches in G2 filling-ditch phase (his excavations in *Sankt Nicolaj Gade* 8) following the workshop phase with some sceattas associated. Later on, Bencard and Jørgensen reported that Jensen has reviewed the material from the same excavation and a mould fragment from the VH6 uppermost workshop level has been retrieved (1990, 139), together with three sceattas (Frandsen and Jensen, 1988). This is the first time that a mould for Berdal brooches has been found, and therefore that an evidence for its production have been recorded (Bencard, 1988, 227). 364 fragments of Berdal brooches have been recovered in the market-place layers at *Posthuset* excavations (Feveile and Jensen, 2000, 17): the majority of these occur in phase F (phase 3 in Bencard and Jørgensen chronology). Two fragments of a mould used for the production of this brooch type has been recovered from the contact layer between phase E/F. Feveile and Jensen suggest that its occurrence could belong to phase F (Feveile and Jensen, 2000, 17). Moreover, the association with Berdal type and other

jewellery types (equal armed brooches, round buckles, sword-guard-shaped brooches, and rectangular brooches) characteristic of late 8th Scandinavian chronological horizon from c. 790 AD until the middle of the 9th century AD, allow us to assign with confidence the occurrence of Berdal brooches from c.790 AD (Feveile and Jensen, 2000, 19).

3.4.1.8 Ribe's absolute chronology

The dendrochronological results do not support Bencard and Jørgensen's theory according to which the sequence from the beginning of phase 1 to the end of phase 3 would have lasted only twenty years. Wood was found in large quantity at two sites: *Kunstmuseets kælder* and *Dommerhaven*. In particular, three sectors gave access to 12 samples (Bencard and Jørgensen, 1990; Christensen, 1990): seven were from the parcelling of the area of the market-place (1A), and 5 samples from *Kunstmuseets kælder* dung layer - phase 2, which cover a period that goes between phase 1A, the transition from 1A to 2, and phase 2.

To summarise, the well of phase 1A according to Christensen was constructed between 704 and 710 AD (1990, 178). The layer of dung, that covered not only part of the parcelled-out area, but also the well, contained a piece of wood felled around c. 719 AD and buried shortly afterwards. Lastly, the samples belonging to some timber fences in Kunstmuseets kælder, felled after the 730 and 759 AD, were on top of the dung layer. In conclusion, the chronological framework between phase 1A and phase 2 should have lasted at least c. 40- 50 years (704 to 730 or 759 AD), which does not agree with Bencard and Bender Jørgensen previous observations. 58 samples were collected to be dated by dendrochronology from the Posthuset 1990-91 excavation, but only 31 gave successful results (Feveile and Jensen, 2000, 11-2). Feveile and Jensen report the results for phase B (part of phase 1A in Bencard and

Bender Jørgensen chronology) and phase C (phase 2 in Bencard and Bender Jørgensen chronology).

For phase B, only 2 samples from some vertical posts from what they call “doorstep construction” leading from the road to one of the plots have usable produced data of 721 or 722 AD. Concerning the lower half of phase C on the other hand, 23 samples were considered good to be analysed. The results showed that the start of phase C should begin around the c. 725 AD. No dates have been suggested for the late C phase.

3.4.1.9 The end of 8th-9th Ribe

While Ribe is cited in different written contexts, mostly ecclesiastical, there are no structural evidence or archaeological finds for the 9th - 10th century in Ribe or in the area around Ribe (Feveile 2006a, 87; 2012, 120), with no dendrochronological dates until the mid-11th century on the south side dendrochronologically dated to the 1077 AD (Feveile, 2012, 2006b).

Feveile (2006a, 87-8) suggests different reasons for this lack of evidence: it obviously possible that new archaeological evidence is hidden in some part of Ribe that has not yet been explored yet, or that the city has been moved for some reason, or that the activity themselves have moved. More recently, Feveile suggest that the reasons must be searched outside the emporium itself, and in particular within the troubled North European economic and historical context at the time.

In the end, even if a lot of work has been done in the past 40 years, is clear from this summary that the development of Ribe has still to be assessed properly. Much attention has been given to the well-documented 8th century market-place area, but more research is needed to better understand Ribe later phases. Moreover, even though it seems now proven that Ribe started in its early days as a seasonal market-place

and then evolved around the second half of the 8th century into a more permanent settlement, the extent and associated evidence for the latter still needs to be clarified.

3.4.2 Ribe glass dataset

Ribe glass was originally analysed for its major and minor elements in 1990 by Henderson. Some of that material has been previously discussed (Henderson, 2000), but no compositional data have yet been published. I was able to include in dissertation a small number of Ribe samples (n=20) to compare with Comacchio and Barking Abbey datasets. Each sample is identified by a unique code based on the original code given when the glass was sampled originally in 1990: each code is formed by the abbreviation “Rib” (Ribe) plus a progressive number (ex. Rib35, Ba37, etc...). The number assigned with each sample is totally arbitrary depending on the typological grouping assigned when originally sampled.

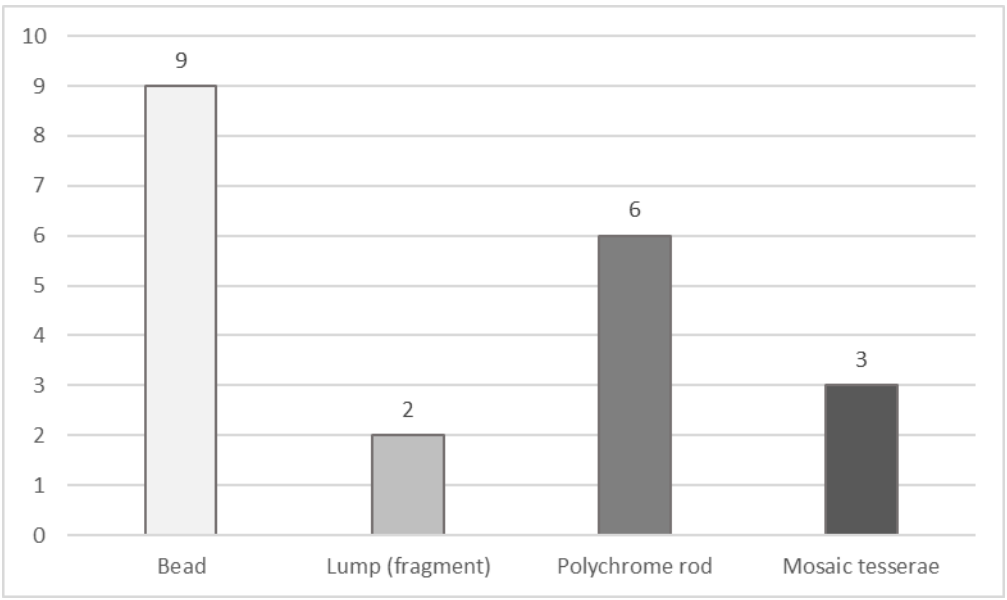


Figure 47 – Ribe glass dataset typology.

In addition to this code, each sample has been associated to their excavation information provided in Andersen and Sode's catalogue (Andersen and Sode, 2010, 60-128)[73]. Each sample is identified by its inventory number, chronological phase, and area of recovery (ex. Rib35, D6976, phase 1a, 6M73 area 5). Context information is included in Appendix 1.

A comprehensive typological classification has been given in Andersen and Sode (2010). As for Comacchio and Barking Abbey, a basic typological distinction has been given by the author to allow a distinguish fragments according to their supposed function (Figure 47). As showed in Figure 47, the majority of samples (9) fall into the "bead" category, followed by monochrome and polychrome rods (6). Mosaic tesserae are also represented (3) together with chunks of raw glass (2).

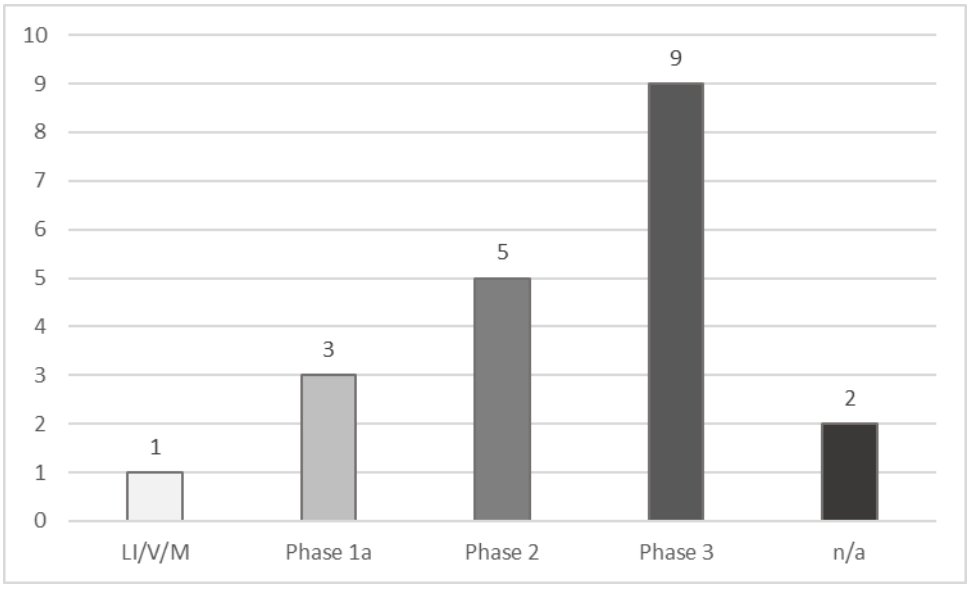


Figure 48 – Ribe glass chronology, after Andersen and Sode, 2010, 60 - 128.

[73] Two samples, Rib77 and Rib78, are not present in Andersen and Sode's catalogue of materials (2010, 60-128).

Each sample has been associated with a chronological phase of Ribe marketplace (Figure 48), phase 1, 1A, 2, and 3 (Andersen and Sode, 2010, 39). Some of Ribe assemblages consist of finds from mixed layers, which were originally labelled as Late Iron Age (Li), Viking Age (V), and Middle Ages (M). Such layers have been combined between themselves, resulting in combinations as Li/V or Li/V/M where the chronology of such samples is uncertain. Each chronological label assigned by Andersen and Sode (2010) has been as been reported in Appendix 1. To my knowledge, there are no pictures of the material from where these samples were originally sampled from.

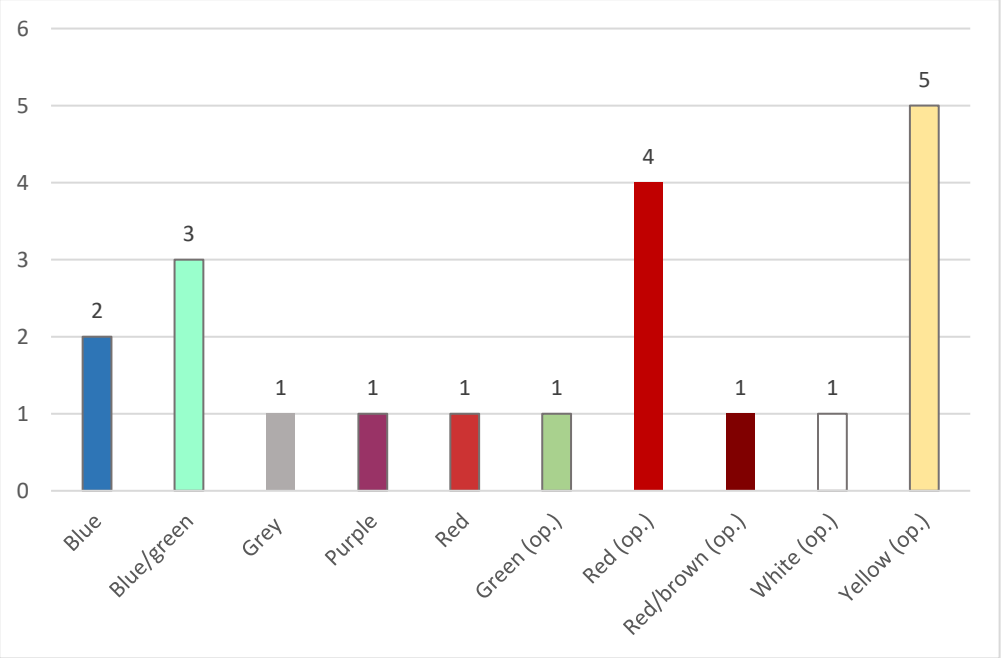


Figure 49 - Ribe glass fragments divided by colour. “Op.” stands for opaque.

Ribe samples almost divide equally between opaque (twelve) and translucent (eight), with a prevalence of yellow and red opaque overall in number (Figure 49). For a description of Ribe samples, please refer to Appendix 1.

3.5 Summary and dataset limitation

In this chapter I have describe the archaeological context behind each of the three glass datasets included in this dissertation: Comacchio (3.2), Barking Abbey (3.3), and Ribe (3.4).

Both Comacchio and Barking Abbey groups have a consistent number of samples. Comacchio has most blue-green samples, which will allow me to assess the degree of recycling that these samples have undergone throughout their technological history. Barking Abbey also has a consistent number of blue-green samples, but also displays a good degree of diversity in complex waster materials: monochrome, reticella, and millefiori rods, slags, glass threads, and crucible layer, which undoubtedly is connected to its glass-making nature.

Even if it includes only twenty samples and no pictures of the actual material, the Ribe dataset included in this dissertation is an invaluable comparison tool for both Barking and Comacchio. This limitation will not influence significantly my analysis, since the first aim of this project is to study the chemical and isotopic composition of these three datasets rather that their typology. I have already explained in chapter 2 how Southern England and Continental typology are connected between each other between the 7th and 9th – 10th century AD and how some artefacts might share a common production area. Also, it has been suggested for many years that tesserae found in Ribe have been made in Northern Italy (Feveile, 2012). The same can be said for reticella and monochrome rods which, as I remarked in section 3.3.2 of this chapter, were possibly made in England but also found in Ribe. Finding the compositional similarities on major, minor, trace and isotopic levels between these three datasets will allow us to make solid assumption on glass trade between the three production areas.

4 Methodology

4.1 Introduction

The importance of combining typological analysis and traditional archaeology with a scientific approach and analysis has already been discussed in 2. The corpus of data obtained via scientific analysis is an objective source of knowledge. Nonetheless, the final interpretation can be biased by a series of circumstances, which includes (among the many) a poor choice of samples, preconceived ideas based on pre-existing knowledge, limited and unclear research questions, bad experimental design, wrong choice of technique, inexperience and human error and, finally, the choice of data representation (bi-plots, histograms, box plots and similar).

Ideally, a series of steps needs to be followed to ensure the integrity of the final study.

Research questions should be formulated from the start, especially when multiple sites are considered in the same study. A combination of general research questions should be expressed first and afterwards a more focused one based on the specific issues associated with each site should be formulated. This process will not only allow us to consider the differences between the results for our material but also to choose the right technique to answer each of these research questions.

Secondly, we need to ensure that the samples chosen to be analysed are typologically representative (shape, colour, and time period) of those available; also, the sample weights need to be considered when dealing with isotopic analysis (this chapter, section 4.3.2). Limitations associated with each dataset should also be considered carefully. When multiple sites are involved, the limitations of each dataset should be addressed

first separately, and then compared. This step is essential not only in order to understand the restrictions that the work will face (and therefore to try to overcome such difficulties), but also to avoid future criticism.

Finally, the right techniques to address each group of research questions need to be considered carefully and so as to plan efficiently the analysis and to maximise the outcome from the glass dataset material.

A total of 188 objects have been analysed in this dissertation (Table 2). For each technique a different number of samples have been chosen according to object function, chronology, and colour.

Table 2 - Summary of objects and samples analysed in this dissertation divided by technique.

	Total analysed objects	EMPA	LA-ICP-MS	Sr	Nd
Comacchio	90	91	62	34	22
Barking Abbey	78	90	61	22	17
Ribe	20	20	18	n.a.	n.a.
Total	188	201	141	56	39

The number of objects analysed differs from the number of samples because each sample is paired to a colour and not to the specific object. The number of samples analysed by each technique is reported in Table 2.

Professor Julian Henderson liaised with Professor Sauro Gelichi, director of excavation of Piazza XX Settembre (Ca Foscari University) to obtain Comacchio glass materials, as well as with Newham Museum for Barking Abbey glass samples. Ribe materials were previously analysed by Julian Henderson himself in 1990.

Trace elements analysis was run in collaboration with Dr. Chenery at the Inorganic Geochemistry Laboratories located at the British Geological Survey, Keyworth. Dr. Chenery had previously collaborated to other projects involving trace elements application on ancient glass analysis (Henderson et al., 2016; Paynter et al., 2015).

Isotopic analysis was done in collaboration with Professor Jane Evans at the NERC Isotope Geosciences Laboratory in Keyworth. Professor Evans had already worked on a number of successful studies application of isotopes and glass provenance (Henderson et al., 2005, 2009; Meek et al., 2012).

The purpose of this chapter is to create a foundation for the analytical work presented in this dissertation. Since research questions have already been discussed in chapter 1, I will first describe the procedure for each different analytical technique (compositional analysis, section 4.2; mass spectrometry techniques, section 4.3) with a specific focus on theory, standards, sample preparation and methods; and finally I will summarise the content and discuss the potential outcome of compositional and isotopic analysis (section 0) to introduce the work discussed in chapter 5.

4.2 Compositional analysis

4.2.1 Sample preparation

Samples of <5mm were taken from the both Comacchio and Barking Abbey glass. Ribe samples have been sampled and mounted in epoxy-resin blocks originally by Julian Henderson. Weathered areas have been avoided because they would have not produced a good analytical result caused by de-alkalinisation of the surface layers, due to leaching of potassium and sodium oxides (Davison and Newton, 2006, 175); secondly, they do not represent the compositional bulk of the original glass, but instead they would be representative of the weathering stratum. Grinding and polishing stages (see below) also helped get rid of weathered areas, when present.

Samples were arranged in plastic moulds lined with a Buehler Release Agent to facilitate the release of the mould later on. After mixing two components (the resin and the hardener), the Buehler epoxy resin was poured into the moulds and then left overnight to cure. The next stage was first to expose the samples and then to create a flat surface for microprobe analysis.

A Buehler Beta Grinder-Polisher was used for both the grinding and polishing stages. For grinding, Buehler SiC (Silicon Carbide) 10" grinding paper was used under running water, with a speed set between 150 and 250 rotations per minute: three different stages corresponding to three different grits of paper (P800, P1200 and P2500) were used to expose the sample surface. Between each grinding stage the sample was cleaned with detergent and then washed to eliminate any type of residue (both from the soap and from the grinding). Samples were polished using a Buehler P10" Texmel of 6µm and 3µm grades and Microcloth of 1 µm,0.25 µm, and final polishing stage, with the addition of the relative Buehler MetaDi Supreme Polycrystalline Diamond Suspension in spray form. The sample was finished with a final polishing stage with a non-crystallising colloidal silica polishing suspension at 60 rotations per minute. After each polishing stage the sample was cleaned with detergent and sprayed with ethanol and allowed to dry. The samples were then ready to be prepared for electron microprobe analysis. The same blocks were used later for LA-ICP-MS analysis.

4.2.2 Electron microprobe (EMPA)

Nowadays, EMPA has become a routine analytical method in the study of ancient archaeological glass, primarily aimed at measuring the major and minor elements characterising the basic recipe of any specific archaeological dataset. Analytical electron microscopy combines the high image resolution of the electron microscope with analysis of the

characteristic X-rays produced when the sample is bombarded with electrons (Pollard, 2007, 109).

In a simple electron microscope (Figure 50), a primary beam of electrons is produced using a conventional electron gun, where a heated cathode, maintained at ground potential, emits electrons which are drawn out by a positive potential (typically 30kV) to form a high energy electron beam. This beam is easily electrostatically and/or magnetically focused (since electrons are charged particles) to a few microns across, and can be directed to any point on the sample by a series of magnetic lenses (Pollard, 2007, 109).

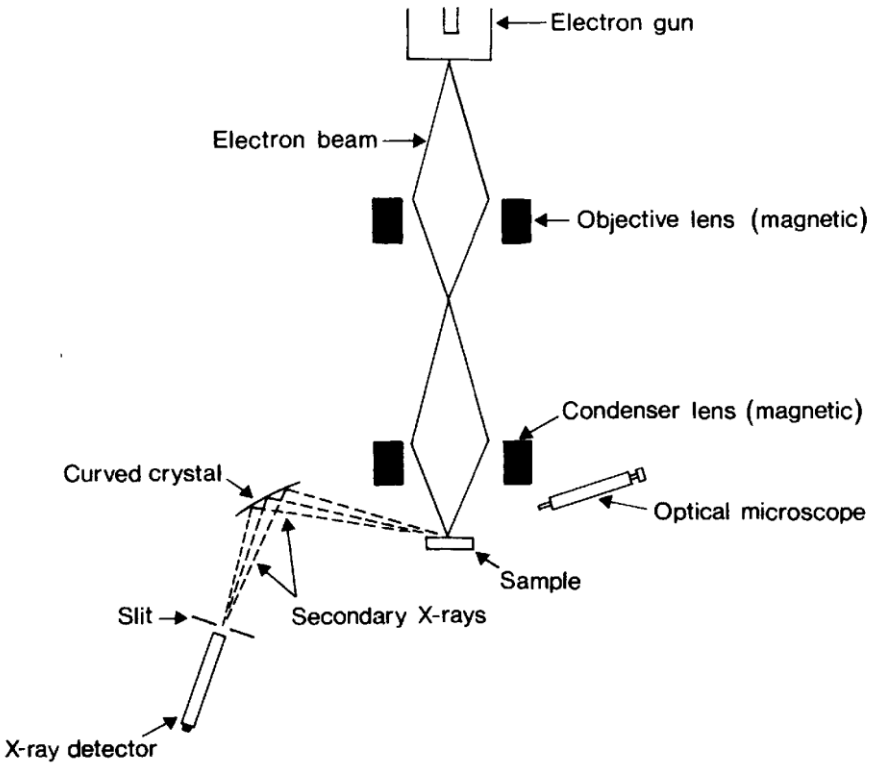


Figure 50 - Schematic diagram of an electron microscope with a WD-X-ray detector, after Pollard and Heron, 1996, 50, but originally after Willard et al., 1988.

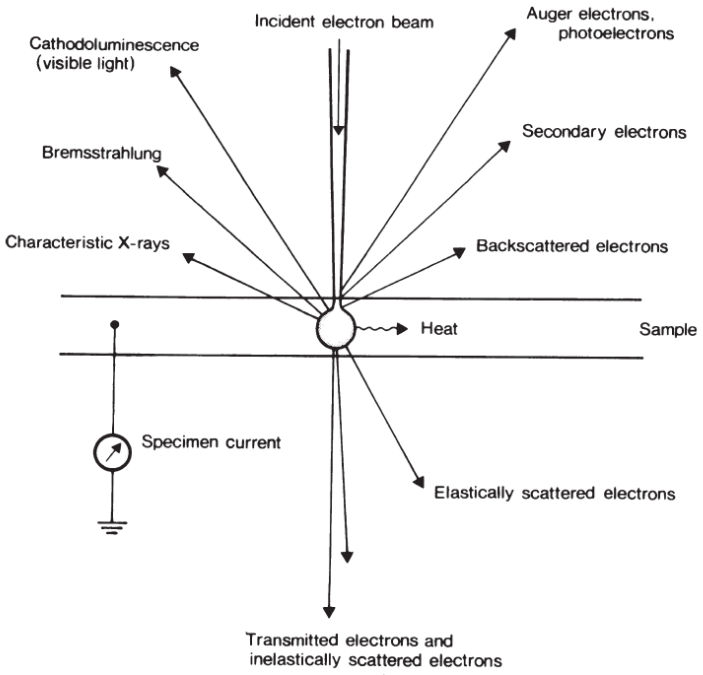


Figure 51 - Interaction of a beam of primary electrons with a thin solid sample, showing the various processes which can take place, after Pollard and Heron, 1996, 51, but originally after Woldseth, 1973.

When an electron beam strikes the sample, a number of processes take place, as illustrated in Figure 51 (Pollard, 2007, 109). Some incident electrons will create inner shell vacancies, in a manner similar to that of X-rays described above. The inner shell vacancy can de-excite via the emission of characteristic X-rays (Figure 52): the composition of the material can be determined by measuring the wavelengths (or energy) of the characteristic X-ray emitted from the atom inner shell with WDS detector.

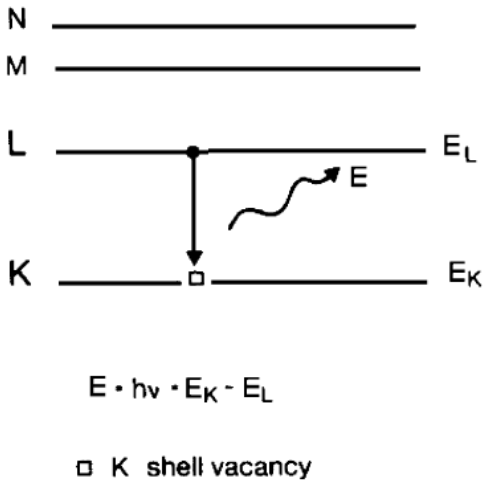


Figure 52 - An inner vacancy in the K shell de-excites via one of two competing processes, after Pollard and Heron, 2008, fig. 2.6, 34: X-ray emission, in which an L electron drops down and the excess energy is carried away by an X-ray photon.

Secondary electrons (Figure 51) are very low energy electrons (less than 50 eV) knocked out of the loosely bound outer electronic orbitals of surface atoms. Because of their low energy, they can only escape from atoms in the top few atomic layers; therefore, they reflect the topography of the sample and they form the basis of the image formation process in electron microscopy.

Finally, backscattered electrons are the result of the interactions between the incident beam and the nucleus of the atoms. Unlike secondary electrons, they do not reflect the surface topography because they escape from deeper within the sample because of their higher energy. Their intensity is proportional to the atomic weight and atomic number of the interacting nucleus, and the intensity variation across a surface is therefore proportional to the average atomic number of the surface. A backscattered electron (BSE) image can be made, allowing one to observe contrasts from the background composition across the flat surface of the sample, such as inclusions in the matrix or weathering for example.

The secondary X-rays from the sample are regarded as being electromagnetic waves, whose wavelength is characteristic of the atom

from whence they came (Pollard and Heron, 2008, 43): a dispersion device is used to separate the radiation into its component wavelengths, and a separate detection system records the intensity of the radiation as a function of wavelength.

As an analytical tool, the electron microscope can be operated with either a wavelength-dispersive X-ray detector or WDS (in which case it is often called an electron microprobe), or an energy dispersive detector, or EDS. Verità and colleagues (Verità et al., 1994) discussed and compared the quantitative results for both techniques and they conclude that both techniques yield acceptable results for both precision and accuracy. WDS technique was used for this project and has lower levels of detection for some elements than a SEM.

4.2.2.1 Analysis and standard

A total of 201 samples were chosen for electron microprobe analysis[74]

The standard protocol for EMPA analysis has been described in detail by Henderson (1988, 78-79). The same protocol has been followed for this project. Analysis of a selection of Comacchio samples of 1-2 mm was performed using a JEOL JXA-8200 electron microprobe in the Microanalysis Research Facility in the Archaeology department of Nottingham University. The system is equipped with four wavelength-dispersive X-ray spectrometers with LIF, TAP, PETJ and LIFH crystals, a single energy-dispersive X-ray spectrometer and both secondary- and backscattered detectors.

[74] In this case, each sample matched one colour. For example, Ba01 sample is made out of two colours (and therefore two measurements), Ba01a and Ba01b, respectively opaque white and opaque dark blue.

The remaining samples from Comacchio and the whole dataset from Barking Abbey were analysed with Cameca SX100 microprobe located at the Open University.

A carbon coating was applied to the polished surface to prevent localised charging and any resulting distortion and deflection of the electron beam, as suggested by Henderson (1988, 78).

Each sample was analysed at least three times at 20 kV accelerating voltage and 50 nA incident beam current with a 50μm defocused electron beam. A defused beam is used to reduce the effect of the migration of alkalis and other volatile elements within the samples (Henderson, 1988; Henderson et al., 2016). The counting time was 30 seconds on the peak (20s for sodium) and 20 seconds on the background (10s for sodium).

Similar beam parameters have been used for Ribe samples analysis: each sample was analysed at least three times at 20 kV accelerating voltage and 40 nA incident beam current with an 80μm defocused electron beam. Further details are described in Henderson, 1988.

The EPMA-WDS was calibrated against a series of certified mineral, pure metal and synthetic standards. Analytical results were corrected using a commercial ZAF program as the matrix corrections. Results are reported in Appendix 2. In total, 26 elements have been detected: sodium, copper, titanium, zinc, aluminium, iron, calcium, tin, arsenic, manganese, antimony, nickel, magnesium, chlorine, potassium, cobalt, barium, lead, sulphur, chromium, vanadium, silicon, zirconium, phosphorus and strontium.

Accuracy and precision of both first and second analytical runs have been checked by comparing both sets of results with Corning B standard, which has been analysed at the start and at the end of each analytical session, for a total of ten for the first run, and twenty-two for the second run. Averaged values for Corning B and our measured values are reported in Table 3Table 4 for both runs, together with the standard deviation for each element, relative standard deviation value, and error

value. The precisions of SiO_2, Al_2O_3, Na_2O, K_2O, CaO, MgO, FeO, MnO and CuO are ideal (RSD<5%). For minor elements, the RSD of them are above 5% but below 20% aside V_2O_5 Cr_2O_3, and ZrO_2 in the first run.

Table 3 - Known and measured values for Corning B (wt.%) for the first round of analysis (Microanalysis Research Facility, Archaeology department- University of Nottingham), standard deviation of measured values and percentage error between known and measured values. Nd: not detected; nr: not reported (Brill, 1999b); na: not applicable.

Sample: Corning B **Number of analysis: 10** **Number of analytical sessions: 5**					
Corning B	**Measured**	**Quoted**	**Stdev**	**Rsd (%)**	**Error (%)**
Na_2O	17.33	17.00	0.76	4.37	1.96
K_2O	1.03	1.00	0.03	2.57	2.68
ZnO	0.21	0.19	0.01	5.33	9.42
SiO_2	60.30	61.55	1.41	2.35	-2.02
Cl	0.16	0.20	0.01	5.06	-17.90
CaO	8.60	8.56	0.11	1.24	0.48
CuO	2.74	2.66	0.05	1.72	3.12
Al_2O_3	4.52	4.36	0.08	1.67	3.65
PbO	0.41	0.61	0.02	5.40	-32.72
TiO_2	0.09	0.09	0.02	19.73	-3.78
SnO_2	nd	0.04	na	na	na
As_2O_5	nd	nr	na	na	na
P_2O_5	0.92	0.82	0.05	4.93	12.66
BaO	0.05	0.12	na	na	-60.83
NiO	0.10	0.10	0.01	5.27	-2.73
MgO	1.16	1.03	0.03	2.18	12.81
Sb_2O_5	0.39	0.46	0.03	6.96	-15.02
CoO	0.04	0.05	0.01	17.22	-9.35
V_2O_5	0.03	0.04	0.02	58.40	-21.76
SO_3	0.50	0.54	0.03	5.74	-8.07
FeO	0.30	0.34	0.01	3.61	-11.21
MnO	0.25	0.25	0.00	1.49	-1.84
Cr_2O_3	0.01	0.01	0.01	38.32	192.00
ZrO_2	0.03	0.00	0.01	35.40	1010.00

Table 4 - Known and measured values for Corning B (wt.%) for the second round of analysis, standard deviation of measured values and percentage error between known and measured values. Results are compared to the quoted composition of the Corning B standard (Brill, 1999b). Nd: not detected; nr: not reported; na: not applicable.

Sample: Corning B **Number of analysis: 22** **Number of analytical sessions: 6**					
Corning B	**Measured**	**Quoted**	**Stdev**	**Rsd (%)**	**Error (%)**
Na_2O	17.27	17.00	0.20	1.15	1.60
K_2O	1.03	1.00	0.02	1.76	3.19
ZnO	0.20	0.19	0.03	15.61	5.93
SiO_2	60.68	61.55	0.93	1.52	-1.41
Cl	0.18	0.20	0.02	9.38	-11.43
CaO	8.71	8.56	0.08	0.95	1.70
CuO	2.89	2.66	0.07	2.37	8.69
Al_2O_3	4.13	4.36	0.04	0.95	-5.34
PbO	0.52	0.61	0.06	12.22	-15.40
TiO_2	0.11	0.09	0.02	23.21	18.74
SnO_2	0.03	0.04	0.04	135.59	-21.02
As_2O_5	0.10	nr	0.15	147.87	na
P_2O_5	0.85	0.82	0.13	14.79	4.13
BaO	0.09	0.12	0.05	50.97	-26.14
NiO	0.10	0.10	0.02	20.70	6.01
MgO	0.99	1.03	0.04	4.12	-3.57
Sb_2O_5	0.48	0.46	0.08	16.37	4.56
CoO	0.04	0.05	0.02	39.41	-11.26
V_2O_5	0.04	0.04	0.03	61.39	18.31
SO_3	0.49	0.54	0.04	8.97	-9.35
FeO	0.34	0.34	0.02	6.15	-0.12
MnO	0.23	0.25	0.03	11.61	-6.58
Cr_2O_3	0.02	0.01	0.01	88.51	236.36

In the second run, the precision of all fore-mentioned major oxides is ideal (RSD<5%), minus TiO_2 (23.23%). For minor elements, the RSD of them

are above 5% but below 20%, aside Sn_2O_5, As_2O_5, BaO, CoO, V_2O_5, and Cr_2O_3.

Accuracy needs to be discussed further. The percentage error of 20% is seen as a critical value to check whether an analytical data is acceptable as a quantitative result. For the majority of oxides, the measured value was within 20% in the first and second run, and most are much lower, and therefore the values can be considered acceptable.

For five oxides the error is in excess of this level and this must be considered when discussing the results. In the first run, the percentage error of element PbO, BaO, V_2O_5 is below -20%; on the other hand, Cr_2O_3 and ZrO_2 is above 20%. In the second run, the percentage error of element Cr_2O_3 is above 20%, while BaO and Sn_2O_5 is below -20%. All these results have to be considered as a semi- quantitative. Moreover, in the first run both Sb_2O_5 and As_2O_5 have not been detected when Corning B was measured.

Analysis of glass samples from Ribe was performed with Cambridge Microscan 9 electron microprobe in 1990 by Julian Henderson.

In order to discuss further the analytical results' accuracy, EMPA and LA-ICP-MS results are compared by plotting them one against each other[75]. I will now describe three different potential scenarios.

In the first, Al_2O_3 results are compared. A 1:1 line is added to the plot to visualise the ideal scenario between EMPA and LA-ICP-MS. If results are comparable, the points should fall on this line. Samples falling above or below the 1:1 line most likely are due to analysis of inhomogeneous portion of glass, or different sampling volumes[76].

[75] Before plotting, LA-ICP-MS results have been converted from part per million to oxides (elements by weight) by using a conversion factor (Geol.umd.edu., 2018).

[76] LA-ICP-MS analyse 16 times the volume of sample compared to EMPA (Chenery, personal communication).

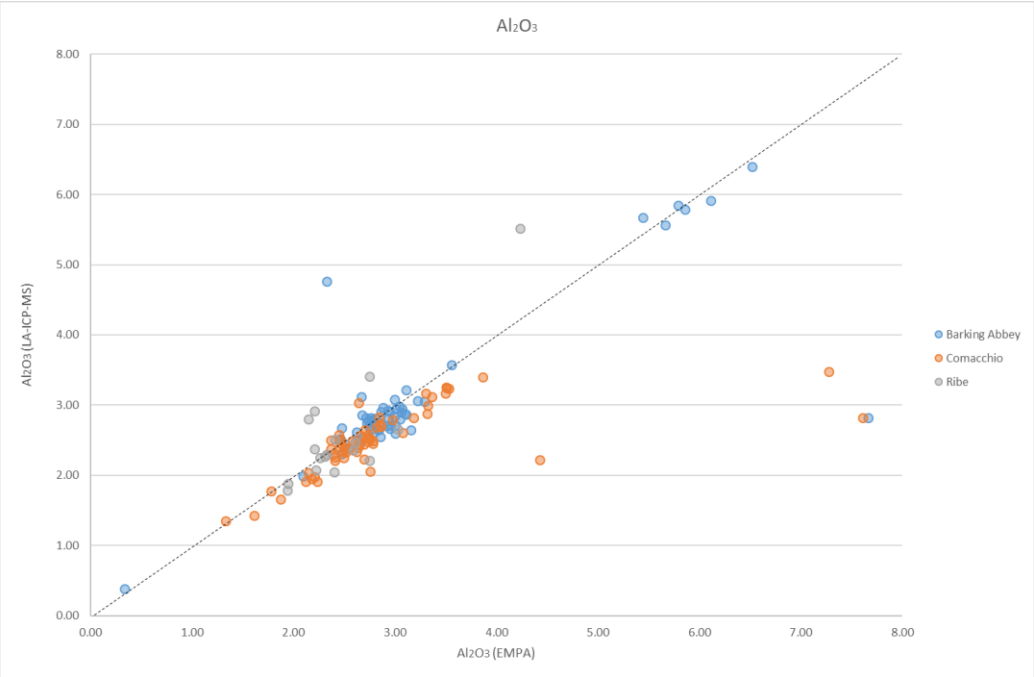


Figure 53 – Al_2O_3 contents by EMPA and LA-ICP-MS results in glass from Barking Abbey, Comacchio, ad Ribe.

In Figure 53, LA-ICP-MS and EMPA results do agree well in all three sites. Three samples from Comacchio, a couple from Barking Abbey, and one from Ribe scatter far from the 1:1 line, but the majority of the samples from the three sites falls on the same array, which indicates that results between the two techniques and different analytical sessions are comparable.

In Figure 54, MgO results are compared. In this case also most of the samples falls close to the 1:1 array, but the three sites array pull towards higher MgO values in EMPA results, indicating a minor discrepancy between the two techniques.

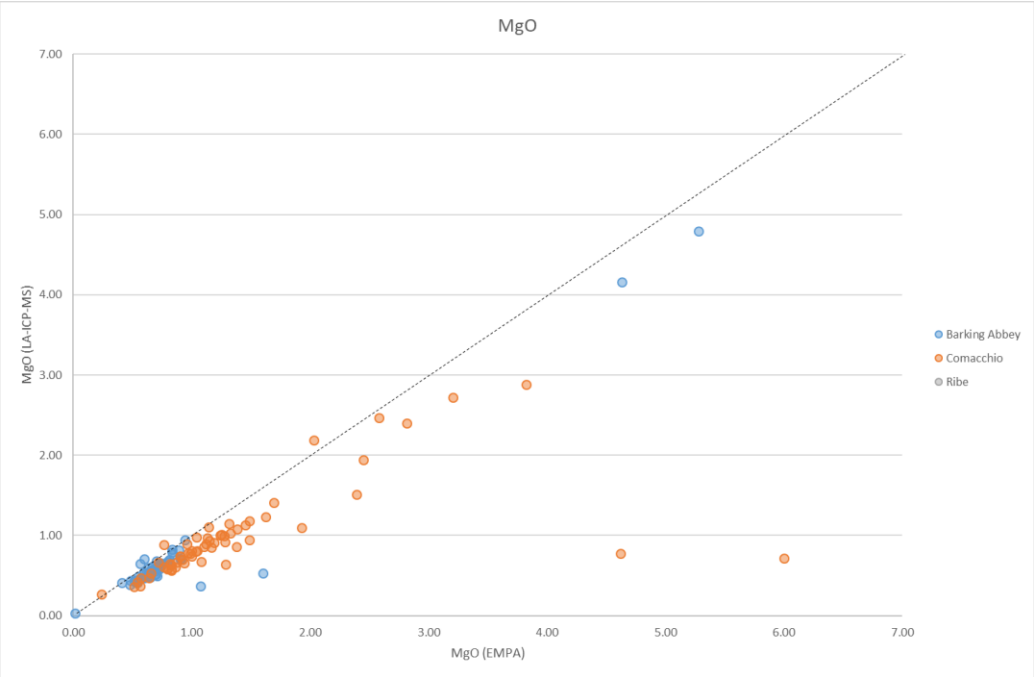


Figure 54 – MgO contents by EMPA and LA-ICP-MS results in glass from Barking Abbey, Comacchio, and Ribe.

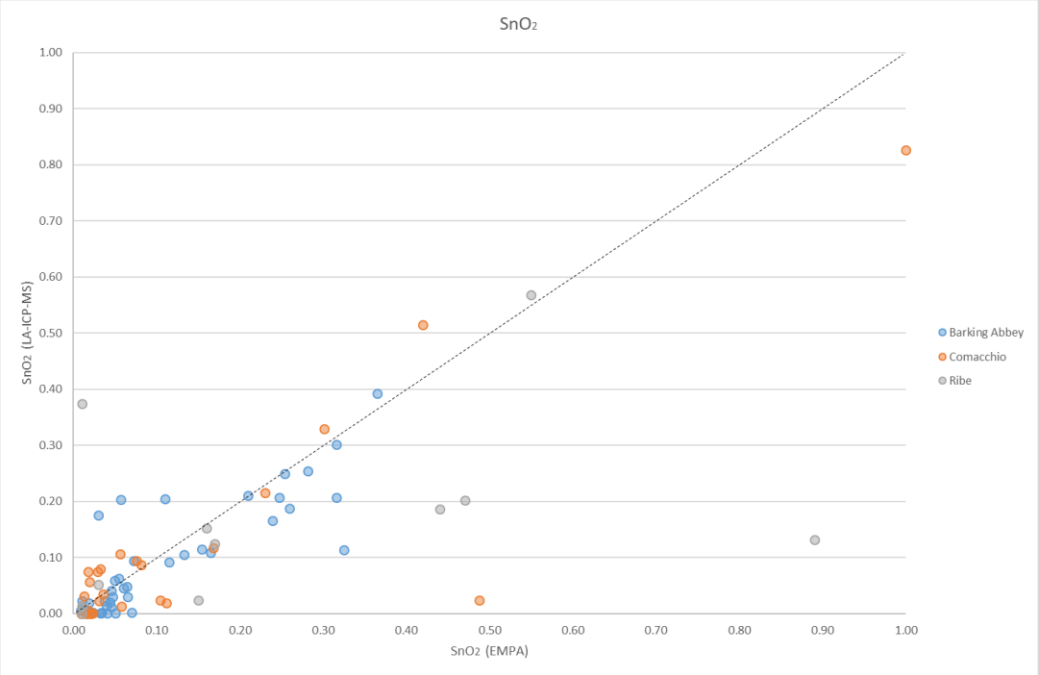


Figure 55 - SnO_2 contents by EMPA and LA-ICP-MS results in glass from Barking Abbey, Comacchio, and Ribe below 1%wt.

Finally, if SnO_2 is considered (Figure 55), results from the three sites are scattered above and below the 1:1 array, which indicates some compatibility issues between the two techniques and this specific element.

These comparative biases between EMPA and LA-ICP-MS are mostly due to the nature of the techniques themselves. First, LA-ICP-MS do not allow to evaluate with precision the area where the laser is pointed, while in EMPA the microscope attached to the probe allows to avoid non-homogeneous areas (such as crystallites), and therefore to analyse just the "base glass".

Secondly, the two techniques operate at different depth (5μ in EMPA against 40μ in LA-ICP-MS), which might cause the laser to hit underlying crystals or non-homogeneous areas of the glass not visible on the surface. This latter might be the reason behind the higher SnO_2 values in LA-ICP-MS (Figure 55). Finally, both techniques rely on averaged results from three points taken per each sample, which might lead inevitably to biases.

These issues are currently under investigation[77]

4.3 Mass spectrometry

Mass spectrometry is based on the principle that the trajectory of electrically charged ions or molecules moving through an externally imposed electrical and/or magnetic field is controlled by their atomic masses (strictly, mass to charge ratio, m/z), and this can be used to separate charged particles of different masses (Pollard, 2007, 160). The

[77] Dr. Chenery, personal comment.

basic components of mass spectrometers can be summarised as (Faure, et al., 2009, 64; Figure 56):

- A source of monoenergetic beams of ions;
- A magnetic analyser for the separation of these particles;
- An ion collector to measure the current flowing in the selected beam;

Since we are analysing heavy isotopes such as strontium and neodymium, all the samples were presented in dissolved form or on a wire rather than in a gaseous form. The sample will be sputtered by a beam of heavy ions, thus that ions are physically knocked off the surface (Pollard, 2007, 161). For LA-ICP-MS analysis (section 4.3.1) we used the same epoxy-resin blocks prepared for the Electron microprobe.

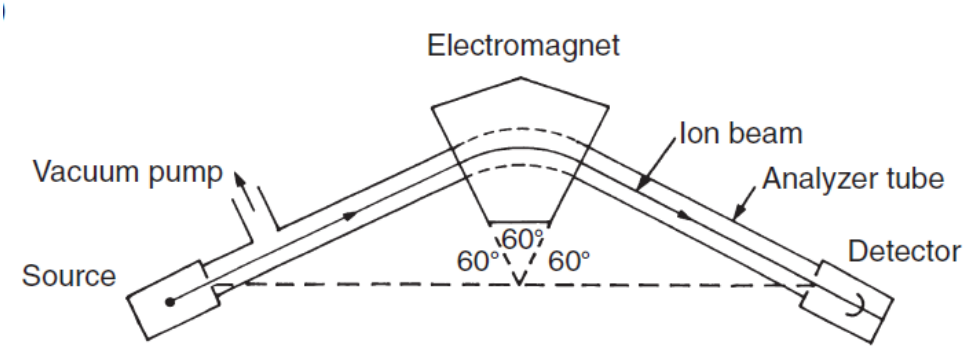


Figure 56 - Schematic diagram of a 60°-sector mass spectrometer showing arrangement of ion source electromagnet, and collector, after (Faure et al. 2009, fig. 4.4, 65).

The principles behind most mass spectrometers can be described as follows (Faure, et al., 2009, 64). A salt of the element is deposit on a filament that is then mounted on the source. The filament (composed of Ta, Re, or W) is heated electrically to a temperature sufficient to volatilise the element to be analysed: the high temperature of the evaporating filament (single) or of an adjacent incandescent filament (double) causes ionisation of the atoms in the vapor. The resulting ions are then

accelerated and collimated into a beam. The beam then enters a magnetic field generated by an electromagnet in a way that the magnetic field lines are perpendicular to the direction of travel of the ions.

The magnetic field deflects the ions into circular paths whose radii are proportional to the masses of the isotopes: the heavier ions, which are deflected less than the light ones, will be later collected through the analyser tube and the detector (or collector). By varying the magnetic field or by increasing the voltage, the ion beam of that particular element will be focused into the collector in succession, in order to obtain the mass analysis of that specific element (and relative isotopes). The resulting signal consists of a series of peaks and valleys which form the mass spectrum of that element: the height of these peaks is proportional of the relative abundance of the isotopes (Faure, et al., 2009, 65).

In many cases, mass spectrometers are coupled with another device to improve the detection sensitivity, such as ICP-MS machines. I will describe below the different machines that have been used in this dissertation, together with the protocol followed for each different analytical run.

4.3.1 Laser ablation Inductively Coupled Plasma Mass Spectrometry (LA-ICP-MS)

Laser ablation paired to ICP-MS techniques started to be applied to archaeological samples in the last twenty years. Despite the undoubted potential that this technique has showed throughout the years, not many articles have been published used this specific technique.

Gratuze and Blet-Lemarquand described the basic of techniques applied to glass material for the first time in 2001 (Gratuze et al., 2001). The potential of laser ablation in discriminating between compositional groups (at trace elements level) has been demonstrated by Shortland and

colleagues (Shortland et al., 2007): the difference in concentration between Zr, Ti, La, and Cr reflected the use of different sand sources and therefore the identification of at least two potential areas of production in Late Bronze Age: Egypt and Mesopotamia. More recently Henderson and colleagues used laser ablation to investigate Early Medieval plant ash glass from the Middle East (Henderson et al., 2016). In this case also trace elements were able to point out evidence for regional production in three different areas such as the Levant, northern Syria and in Iraq/Iran. More interestingly, they also provided evidence for movement of glass between the same regions and their major commercial hubs, together with evidence for technological specialisation, such as colourless cut glass made in Nishapur and wheel-cut glass made in Ctesiphon instead (Henderson et al., 2016, 141-42).

There are numerous advantages in using laser ablation over other mass spectrometry techniques. First, most elements can be analysed, except some of the light elements (H, He, C, N, O, F, Ne, Cl, Ar), and some actinides (Pollard, 2007, 195). Second, the area initially ablated with the laser is equivalent to a few tens of nanometre, so the technique could be considered minimally destructive. Also, the same epoxy-resin blocks prepared in EMPA analysis can be used, so it will save time in sample preparation. This means also that very small samples can be analysed, which is appropriate when dealing with archaeological materials.

LA-ICP-MS has much lower detection limits when compared with EMPA (Speakman and Neff, 2005, 4): it can determine elements present in the low-parts per million (ppm) to parts-per-trillion (ppt). Finally, it is possible to target specific components in heterogeneous materials (Speakman and Neff, 2005, 4), such as targeting specific crystals in the glass matrix to investigate their nature or to avoid weathered areas on the glass surface to get a more accurate composition of the basic glass recipe of that specific sample.

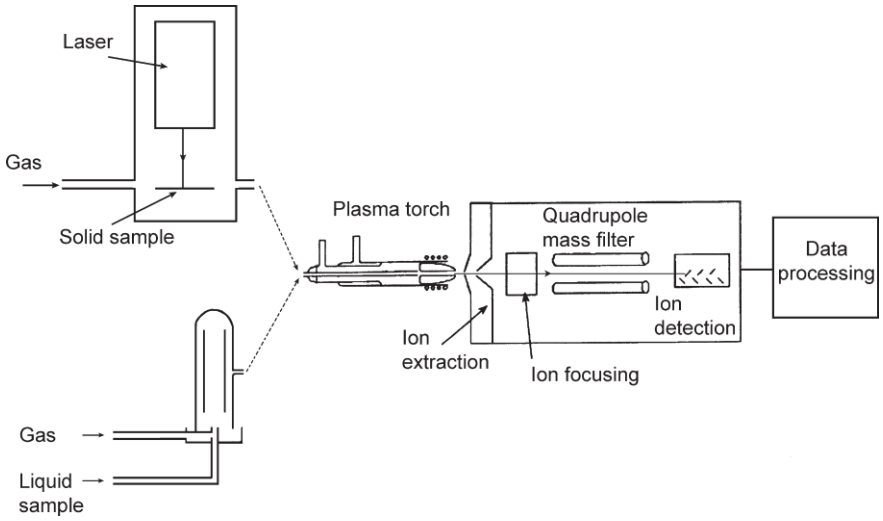


Figure 57 - Schematic diagram of a quadrupole ICP–MS capable of working in laser ablation mode, after Pollard et al. 2007, fig. 9.2., 197. In the solid mode, a vertical laser ablates material from the sample which is mounted on a moveable horizontal stage. A stream of argon gas carries the sample into the plasma torch, where it is ionized at high temperature and injected into the quadrupole mass selector.

In the case of LA-ICP-MS (Figure 57), the sample is introduced into the plasma by laser ablation of a solid sample with minimal preparation (provided that the area picked for analysis is flat, so the laser can maintain its focus during the ablation). For this purpose, the same resin blocks prepared for EMPA analysis have been used. A movable stage and integral optical microscope allow the user to visualize and select the area to analyse. A series of ceramic apertures and optical lenses will allow the user to adjust the laser beam and focus it onto the sample surface; the crater pits produced by the laser can vary between 80-100 µn (Gratuze et al., 2001, 645).

The laser beam evaporates a discrete area of the sample, which is carried in a stream of argon directly into the plasma torch (Pollard, 2007, 198), where the matter is dissociated, atomised, and ionised (Gratuze and Blet-Lemarquand, 2001, 645). The produced stream of ions is then focused through a so-called two aperture system (sampling and skimmer cone) which enables the ions to transition from atmospheric pressure to the vacuum chamber of the quadrupole system. The ion beam produced is then extracted and focused by a series of cylindrical electrodes

(quadrupole mass filter), where the ions are selected according to their mass-to-charge ratio (m/z). Finally, the ions are collected by charge sensitive detector.

4.3.1.1 Analysis and standards

A total of 141 samples were chosen for trace elements analysis[78].

Trace element determinations were carried out using by laser ablation-inductively coupled plasma mass spectrometry (LA-ICP-MS). Prior to analysis the epoxy-resin blocks were cleaned by rubbing a tissue soaked in dilute acid over the surface for a few seconds. The laser ablation unit used was a NewWave (Electro Scientific Industries, Inc.) UP193FX excimer (193nm) laser system. The sample was placed in a simple single volume ablation cell flushed by a stream of helium carrier gas (0.80 L x min^{-1}), mixed with an argon carrier gas (0.85 L x min^{-1}), to the Agilent 7500 series ICP-MS, set for 100 sweeps of the 47 isotopes of interest per integration.

The laser was normally fired at 10Hz with a typical fluence of 2.8 Jcm^{-2} and with irradiance of 0.85 GW/cm^2 for 45s using a beam diameter of 75μm which is approximately 30μm deep. The dwell time for each isotope was 1ms giving an integration time of 5s. Data were collected in a continuous time resolved analysis (TRA) fashion.

In addition to the sample block, NIST glass standards SRM610 and 612 were placed in the chamber: the SRM612 was used to calibrate the system whilst the SRM610 was used as a quality control (QC) material.

Prior to the laser firing a period of at least 120s of gas blank was collected, then 3 ablations were made on the SRM610, 3 ablations on the SRM612, 3 ablations on up to 8-10 samples, and finally 3 ablations on

[78] Please refer to Table 2.

the SRM610. Aggregated results for each element-isotope concentration are given in Appendix 4. All calculations and data reduction were performed manually in Excel spreadsheets and statistical analysis using MiniTab v18.

The accepted practice is to normalise results to an internal standard element, given the variability in ablation volume and transport efficiency with different materials (matrix effects). Si was chosen for this purpose with its concentration being known in the NIST glasses and provided by the EPMA data for the study glasses. Both the average analytical results and the quoted values of NIST SRM610 are presented in Table 5 and Table 6 (two analytical sessions). The calculated standard deviations and relative standard deviation (RSD%) of the measurements are also shown in Table 5 and Table 6 to check the precision and accuracy of the measurements.

Average analytical results, quoted values, calculated standard deviation, relative standard deviation, and accuracy are presented in Table 5 and Table 6. Calculated and relative standard deviation are presented to check the precision and accuracy of the measurements, which appears to be sound. The precision of most elements is good for both sessions (<5 RDS%). In addition, the accuracies for all the elements ranged between -2 and +1%, which are considered within the range of quantitative results.

Table 5 – Measured and expected values (mg/kg), calculated St.Dev values, RSD and Bias values (%) of trace elements for standard reference glass NIST610 (session 1, n= 76) by LA-ICP-MS (The expected values for SRM610 were published by GeoRem (Jochum et al., 2011).

	Expected	Average	S.d.	Rsd %	Error %
Li	468	467.42	5.74	1.23	-0.12
B	350	349.70	5.12	1.46	-0.09
Na	99407	99368.16	690.62	0.70	-0.04
Mg	432	431.68	4.14	0.96	-0.07
Al	10320	10313.55	57.57	0.56	-0.06
P	413	412.20	7.87	1.91	-0.19
K	464	464.14	4.93	1.06	0.03
Ca	81475	81588.16	1032.08	1.26	0.14
Ti	452	452.25	7.29	1.61	0.06
V	450	451.31	5.28	1.17	0.29
Cr	408	408.05	3.95	0.97	0.01
Mn	444	444.49	3.94	0.89	0.11
Fe	458	458.01	4.72	1.03	0.00
Co	410	411.13	5.60	1.36	0.28
Ni	459	458.78	4.00	0.87	-0.05
Cu	441	441.81	5.19	1.17	0.18
Zn	460	460.65	6.81	1.48	0.14
As	325	325.30	3.81	1.17	0.09
Rb	425	426.51	6.38	1.50	0.35
Sr	516	515.63	6.33	1.23	-0.07
Y	462	465.25	12.38	2.66	0.70
Zr	448	448.50	7.43	1.66	0.11
Nb	465	467.59	9.65	2.06	0.56
Mo	417	416.86	4.27	1.02	-0.03
Sn	430	429.78	5.21	1.21	-0.05
Sb	396	396.39	5.12	1.29	0.10
Cs	366	366.61	4.64	1.27	0.17
Ba	452	452.01	6.45	1.43	0.00
La	440	443.05	13.11	2.96	0.69
Ce	463	454.99	8.40	1.85	-1.73
Pr	448	451.36	14.05	3.11	0.75
Nd	430	431.90	8.91	2.06	0.44
Sm	463	455.60	11.24	2.47	-1.60
Eu	447	449.38	12.31	2.74	0.53
Gd	449	450.90	11.19	2.48	0.42
Tb	437	441.62	16.26	3.68	1.06
Dy	437	438.43	9.66	2.20	0.33
Ho	449	452.68	16.15	3.57	0.82
Er	455	456.73	9.74	2.13	0.38
Tm	435	436.05	8.70	2.00	0.24

Yb	450	450.58	8.22	1.83	0.13
Lu	439	439.37	7.32	1.67	0.08
Hf	435	435.69	7.18	1.65	0.16
Pb	426	426.25	7.25	1.70	0.06
Th	457	457.19	7.72	1.69	0.04
U	462	461.33	6.96	1.51	-0.15

Table 6 - Measured and expected values (mg/kg), calculated St.Dev values, RSD and Bias values (%) of trace elements for standard reference glass NIST610 (session 2, n=57) by LA-ICP-MS (The expected values for SRM610 were published by GeoRem *(*Jochum et al., 2011*)*.

	Expected	**Average**	**S.d.**	**Rsd %**	**Error %**
Li	468.00	468.35	6.82	1.46	0.07
B	350.00	350.34	5.62	1.60	0.10
Na	99407.00	99440.70	961.39	0.97	0.03
Mg	432.00	431.57	2.64	0.61	-0.10
Al	10320.00	10303.40	107.46	1.04	-0.16
P	413.00	413.47	8.51	2.06	0.11
K	464.00	464.28	4.86	1.05	0.06
Ca	81475.00	81450.00	877.33	1.08	-0.03
Ti	452.00	451.95	5.87	1.30	-0.01
V	450.00	449.54	3.82	0.85	-0.10
Cr	408.00	408.11	4.02	0.98	0.03
Mn	444.00	443.95	5.00	1.13	-0.01
Fe	458.00	458.84	6.65	1.45	0.18
Co	410.00	410.06	4.05	0.99	0.02
Ni	459.00	459.21	6.00	1.31	0.05
Cu	441.00	441.11	5.54	1.26	0.02
Zn	460.00	460.04	7.43	1.62	0.01
As	325.00	325.16	4.66	1.43	0.05
Rb	425.00	425.61	4.53	1.06	0.14
Sr	516.00	515.69	6.24	1.21	-0.06
Y	462.00	461.05	9.47	2.05	-0.20
Zr	448.00	447.16	8.42	1.88	-0.19
Nb	465.00	464.09	6.12	1.32	-0.20
Mo	417.00	418.06	5.28	1.26	0.25
Sn	430.00	431.03	4.95	1.15	0.24
Sb	396.00	397.20	5.18	1.30	0.30
Cs	366.00	365.68	4.75	1.30	-0.09
Ba	452.00	452.33	5.85	1.29	0.07
La	440.00	440.21	7.52	1.71	0.05

Ce	463.00	453.13	6.65	1.47	-2.13
Pr	448.00	447.33	6.23	1.39	-0.15
Nd	430.00	429.75	6.49	1.51	-0.06
Sm	463.00	452.66	6.24	1.38	-2.23
Eu	447.00	446.69	5.93	1.33	-0.07
Gd	449.00	448.17	6.92	1.54	-0.19
Tb	437.00	436.99	7.87	1.80	0.00
Dy	437.00	435.85	8.20	1.88	-0.26
Ho	449.00	448.20	9.46	2.11	-0.18
Er	455.00	453.00	8.12	1.79	-0.44
Tm	435.00	433.67	7.81	1.80	-0.31
Yb	450.00	449.08	6.93	1.54	-0.20
Lu	439.00	437.76	8.46	1.93	-0.28
Hf	435.00	433.13	8.18	1.89	-0.43
Pb	426.00	426.69	6.55	1.54	0.16
Th	457.00	456.62	7.26	1.59	-0.08
U	462.00	461.37	5.51	1.19	-0.14

4.3.2 Isotopic analysis

Radioactive decay is the spontaneous disintegration of an unstable radioactive parent isotope to a radiogenic daughter and a nuclear particle (Degryse et al. 2009a, 16). Radioactivity in elements with large atomic masses can be measured and used to date the time of formation of minerals or rocks, together with tracing the sources of detrital matter in sedimentary and biogeochemical cycles (Banner, 2004). In addition, the variations of many stable isotope ratios reflect different geological origins, due to different formation processes, the original composition of the mineral and the diagenetic or metamorphic processes the rock has been subjected to. Therefore, the geological age and origin of the material play a pivotal role in the determining the final isotopic composition of the raw material. Moreover, unlike compositional analysis, isotopic ratios are not influenced by technical processes because the isotopic fractionation of the different isotopes due to the ionization process that occurs during

analysis in a mass spectrometer is negligible (Banner, 2004, 148)[79].As a consequence, the isotopic composition of the artefact will be identical, (within analytical errors) to the raw material from which it was derived, while the signatures of different raw materials used (and therefore the resulting artefacts) may differ (Brill and Wampler, 1965, 73).

Traditionally, isotopic studies have not been easily accessible to archaeological scientists, since these techniques are time-consuming, expensive (especially when considering that most of the time two or more isotopes are paired), and a large portion of each sample portion is needed (Leslie et al., 2006, 254). When applied though, such ratios (in most studies Sr and Nd paired together) proved to be effective in assessing provenance in glass samples.

We need to remember that isotopic ratios provide a fingerprint which is typical not of the primary workshop, but of the raw materials used to produce that artefact. Every suggestion regarding the provenance of such an artefact needs to take this into account: theoretically that one workshop might have used more than one raw material (and therefore it does not have a distinctive one *per se*), as long as such a raw material was sourced conveniently close to workshop and it was available in suitable quantities. Secondly, to successfully assess provenance, raw materials must have been sourced from sufficiently contrasting geological areas in order to get distinctive isotopic ratios, otherwise there might been overlapping values and therefore it will not be possible to make any certain assumption of provenance.

[79] Fractionation (change in isotope ratio) in a stable or radiogenic isotope ratio of a given element may occur as a result of the ionization process that occurs during analysis in a mass spectrometer. Radiogenic systems, which involve relatively heavy isotopes, usually exhibit smaller extents of fractionation than light stable isotope systems because their relative mass differences are small (Banner, 2004, 148).

4.3.2.1 Sample preparation

Glass samples were crushed to gravel sized components with and agate mortar, then cleaned by placing in 2.5 molar HCl in an ultrasonic bath for 5 minutes and rinsed three times in deionised water for the same length of time and then placed into pre-cleaned Teflon beakers. The fragments, once dry, were milled to a fine powder in an agate micro ball mill. The resulting sample was transferred to a clean (class 100, laminar flow) working area for further preparation.

Standard silicate dissolution was then undertaken. Glass samples were dissolved first in 8M HNO_3 (1ml), and secondly 2-4mls of 29HF were added to the samples. After, samples were then rinsed with H_2O and left sitting overnight on a hot plate (105 C°) to dry up completely. The next day the samples were converted to Bromide form by adding 0.5M HBr. When needed, the samples were centrifuged to remove the precipitate fluorides.

4.3.2.2 Sr isotopes

4.3.2.2.1 Rb-Sr system

Rubidium (Rb) is an alkali metal belonging to group IA that has two naturally occurring isotopes (Faure et al., 2009, 75): ^{85}Rb and ^{87}Rb, whose abundances are respectively 72.1654 and 27.8346 percent. To allow for it to substitute for K^+ in all K-bearing materials [because the ionic radius of Rubidium (Rb^+) is similar to the one of potassium (K^+)] it occurs in easily detectable amounts in common K-bearing minerals such as micas, k-feldspars, certain clay minerals, and evaporite minerals (Faure, et at., 2009, 75). Rubidium-87 is radioactive and decays to stable ^{87}Sr by

emission of a negative β-particle and anti-neutrino, which share the decay energy (Q) as kinetic energy (Faure et al., 2009, 75).

Strontium is a member of the alkaline earth of group IIA, and it occurs in Ca-bearing minerals such as plagioclase, apatite, and calcium carbonate. Strontium has four naturally occurring stable isotopes (Faure et al., 2009, 76): ^{88}Sr, ^{87}Sr, ^{86}Sr, and ^{84}Sr. The abundance of each isotope is variable because they are dependent on the formation of radiogenic ^{87}Sr by the decay of naturally occurring ^{87}Rb. Therefore, the isotopic composition of Sr in a Rb-containing rock or mineral depends on the age of Rb/Sr ratio of that same rock or mineral (Faure et al., 2009, 76), because the remaining Sr isotopes do not decay.

The bulk of the strontium in many glasses is incorporated with the lime-bearing constituents in the glass, usually with the alkali source (Wedepohl and Baumann, 2000, 130). Therefore, in natron glasses with the shell (including a mineral polymorph of calcium carbonate, like aragonite) or limestone component, while in plant ash glasses with the plant component itself (Freestone, et al., 2003, 21).

If beach shells have been used in natron glass as source of lime, the $^{87}Sr/^{8}Sr$ ratio will be close to modern seawater (0.7092) while, if limestone was used, $^{87}Sr/^{86}Sr$ ratio will reflect the seawater signature at the time the limestone was deposited, together with any alteration due to diagenetic processes that occurred in the limestone over time (Freestone et al., 2003, 21). In plant ash glasses, the $^{87}Sr/^{86}Sr$ ratio reflects the age of the Rb content of the bedrock geology in which the plant grew (Freestone et al., 2003, 21). Therefore, the success of $^{87}Sr/^{86}Sr$ ratio as lime-bearing discriminant indicator depends on whether is a sufficient geological contrast in the calcium-sources (Henderson, 2013, 328).

According to Freestone and colleagues (2003, 27), the sand fraction of the batch contributed to the Sr contents and $^{87}Sr/^{86}Sr$ ratio considerably. The influence of natron on both the Sr contents and $^{87}Sr/^{88}Sr$ ratio is instead negligible (Freestone et al. 2003, 27).

4.3.2.2.2 Sr analysis (TIMS)

Sr isotope analysis of the samples was conducted using a Thermo Scientific Triton multi-collector mass spectrometer at the NERC Isotope Geosciences Laboratory, Keyworth. The TIMS procedure has been previously described by Meek in his dissertation (2011, 119). TIMS works by subjecting the sample to high temperatures, resulting in its ionisation. The filament is inserted into the vacuum system and a current is passed through it. Raising this current induces resistive heating, eventually resulting in a temperature at which simultaneous volatilisation and ionisation of the sample occurs. The ions are accelerated through a high potential before passing through a uniform magnetic field. This field defects the ions by different angles depending on their mass. The ions are thus separated by this field and are measured by ion detectors.

Excess bromine was removed by adding 2mls of 16M HNO_3 (TD) to each sample. Once the HNO_3 has dried up, 2mls of 2.5M HCl were added to the samples and then were left overnight dissolve. When needed, the samples were centrifuged to remove solid matter that could block the columns. Strontium was collected using Dowex AG50 resin columns. After the columns were preconditioned with 15mls of 2.5M HCl, the samples were loaded, then washed with 2.5M HCl, then with 46 mls of 2.5M HCl, and finally 12mls of 2.5M HCl were collected together: this fraction contains the Sr. Samples were left evaporated down on the hot plate at (100-110°C). The fraction containing REE was therefore collected by adding 20mls of 6M HC and let dry down on the hot plate at the same temperature.

Strontium was loaded onto a single Re Filament following the method of Birck (1986): 1µl of sample (mixed with 2-3ml of MQ H_2O) was loaded on a single Ta filament (previously prepared with 1 µl 1M H_3PO_4), and then heated up until it glows, and the phosphoric fumes are liberated.

The isotope composition was determined by Thermal Ionisation Mass spectroscopy (TIMS) using a Thermo Triton multi-collector mass spectrometer. For strontium, the International SRM 987 Sr standard gave 0.710273 +/- 0.000016 (2SD, n=21) while running in static mode. Data are corrected to the accepted value for this standard of 0 .710250. Results are presented in Appendix 4.

4.3.2.3 Nd isotopes

4.3.2.3.1 Sm – Nd system

Samarium (Sm) and Neodymium (Nd) are both light rare-earth elements (REEs) that occur in many rock-forming silicate, phosphate, and carbonate minerals (Faure, Mensing and Faure, 2009, 194). REEs occur as trace elements in common rock-forming minerals in which they replace major ions. Samarium has three naturally occurring isotopes, and ^{147}Sm decays by α-emission to a stable isotope of neodymium (^{143}Nd). Rock and minerals have been dated using ^{147}Sm decay in the same fashion as Rb-Sr method: $^{143}Nd/^{144}Nd$ ratio of a rock (such as a quartz) is dependent on its formation age and the concentration of the parent element (Sm) in it (Henderson, 2013, 330).

Nd isotopes have been used as an indicator of the provenance of detrital sediments in a range of sedimentary basin types (Banner, 2004). In ancient glasses, neodymium is likely to have originated from the heavy mineral content of the silica raw material (Degryse and Schneider, 1995, 2008), while natron appears to not influence the Nd budget and Nd signature of the glass, since it contains in the order of 20–40 ppb (Wedepohl et al., 2011). Neodymium ratios and concentrations therefore offer a way of distinguishing sand sources potentially used as raw materials: $^{143}Nd/^{144}Nd$ isotope ratios will reflect the average composition of the silicate source used to produce the glass, and the concentrations

are likely instead to mirror the characteristics of the silica source, as pure quartz contains no neodymium. According to Barkoudah and Henderson (2006, table 2, 309) insignificant amounts of neodymium are taken into halophytic plants from the Middle East. Therefore, the contribution to the overall Nd budget in plant ash from the alkali components has to be considered negligible.

If sand deposits used to make different glasses are sufficiently geologically contrasting, it is possible to distinguish isotopically between different sand sources. Recently, data from Degryse and Schneider (2008) show that Nd isotopic data from different sites located along both the Eastern and Western Mediterranean areas, display a wide range in isotopic composition, with a range of $^{143}Nd/^{144}Nd$ = 0.512083 - 0.512511 (εNd -10.8 and -2.5)[80]. Moreover, it was possible to distinguish between an Eastern and a Western sand source (Degryse and Schneider, 2008, 1998; fig. 2, 1998): Eastern Mediterranean primary glass has a Nile-dominated Mediterranean Nd isotopic composition (εNd higher than -6.0), while glass with a primary production location in the western Mediterranean or north-western Europe should have a different Nd isotope signature (εNd lower -7.0).

Recently, Brems and colleagues (Brems et al., 2013b) could not explain the apparent overlap of some of their εNd results in Western signatures with some previously identified as εNd Eastern signatures; they imply that such results might indicate that Nd isotopic signatures could not be considered as straightforward a provenance indicator for Roman glass as previously thought. The map that plotted the results of Western Mediterranean εNd of the beach sands analysed in the same work (Brems et al. 2013, fig. 1, 453) will nonetheless prove extremely useful

[80] $^{143}Nd/^{144}Nd$ isotope ratio can also represented in parts per 10^4 deviation from the present-day value of a model evolution of Nd isotopes in a chondritic Earth (Chondritic Uniform Reservoir, CHUR) according to DePaolo and Wasserburg (1976).

as a εNd reference values, if the previous suggestion is taken into account.

4.3.2.3.2 Nd analysis (high resolution-ICP-MS)

The neodymium isotope compositions of 41 samples were determined by a Thermo-Electron Neptune mass spectrometer (high resolution MC-ICP-MS) at the NERC Isotope Geosciences Laboratory. With a multi-collector detection system attached to ICP-MS (section 4.3) it is possible to monitor ions from the plasma simultaneously through several collectors, generally Faraday cups. The presence of more than one detector simultaneously allows to measure different masses with greater precision and accuracy in the determination of isotopic ratios by removing problems of instability in the plasma ion source (Pollard, 2007, 199). -The original project included the analysis of 67 samples for Nd isotope, but it was not possible to include the remaining 26 results in this dissertation because they could not be completed in time before the deadline.

First columns were washed twice with 1CV of 6M HCl and then later they were conditioned with 1CV 0.2M HCl. Meanwhile, 100μn 0.2M HCL into each REE beaker to dissolve the sample before chemistry. After introducing the sample into each column, Nd was separated from the REE fraction by discarding first 4mls of 0.2M HCl, then 1CV (10mls) of 0.2M HCl; Nd fraction was collected in clean beakers by collecting 3mls of 0.3 M HCl. Samples were left evaporated down on the hot plate at (100-110°C).

Samples was loaded onto a double Re Filament following the method of Birck (1986): 1μl of sample (mixed with 2-3ml of MQ H_2O) was loaded on a single Ta filament (previously prepared with 1μl 1M H_3PO_4), and then heated up until it glows, and the phosphoric fumes are liberated.

For Nd analysis, fractions were dissolved in 1ml of 2% HNO_3 prior to analysis on a Thermo-Electron Neptune mass spectrometer, using a Cetac Aridus II desolvating nebuliser. 0.010 l/min of nitrogen were introduced via the nebulizer in addition to argon in order to minimise oxide formation. The instrument was operated in static multi-collection mode, with cups set to monitor ^{142}Ce, ^{143}Nd, ^{144}Nd, ^{145}Nd, ^{146}Nd, ^{147}Sm, ^{149}Sm, and ^{150}Nd. 1% dilutions of each sample were tested prior to analysis, and samples diluted to c. 20ppb. Jet sample cones and X-skimmer cones were used, giving a typical signal of c. 800-1000 V/ppm Nd. Correction for ^{144}Sm on the ^{144}Nd peak was made a ratio for $^{147}Sm/^{144}Nd$ derived from multiple standard analyses. This correction was insignificant due to the efficiency of the column separation. Data are reported relative to $^{146}Nd/^{144}Nd = 0.7219$.

The Nd standard solution JND-i was analysed during each analytical session and sample $^{143}Nd/^{144}Nd$ ratios are reported relative to a value of 0.282115 for this standard.

4.4 Summary

In this chapter I have described the analytical methods that are at the core of this research. Even though electron microprobe analysis is nowadays routine procedure in glass research, it still constitutes the basis of any silicate research, and I am confident that the number of samples provided here will make a solid foundation for my project, especially concerning the identification of raw materials and of contamination, recycling, and mixing practices.

Laser ablation ICP-MS analysis is still in its infancy where glass studies are concerned. My hope is that this new database will provide interesting results concerning not only recycling markers (such as Cu, Co, Sb, Sn), but that it will help to discern between raw materials, sand sources in

particular: the recent article such the one published by Henderson and co-workers (2016) and their use of trace elements to define specialised production and movement of glass represents an excellent framework on which I plan develop my own discussion.

No isotopic studies have been tried before concerning Early Medieval material from Northern Italy and Southern England: therefore, this database is the first of its kind for Early Medieval Western glass. The debate concerning Eastern and Mediterranean glass-making production still continues, and this new data will definitely improve the discussion. Moreover, the origin of both Northern Italian and Southern English glass has only been partially discussed, and without the help of objective data.

Strontium and Neodymium isotope analysis in previous studies (chapter 2 and this chapter, sections 4.3.2.24.3.2.3) proves that they are partially diagnostic in determining raw material provenance, and so I hope they will be for Comacchio and Barking Abbey too: the first aim will be to connect both sites to primary workshops materials in order to finally give a solid evidence for exchange of glass between the Levant and Northern Italy or Southern England; In second place, I want this dataset to represent the first of its kind and I hope it will be used as future reference to possible many studies to come.

5 Results and discussion

5.1 Compositional analysis

Samples from Comacchio and Barking Abbey were analysed for 25 major and minor elements, for a total of 90 samples and 91 sample respectively. Samples from Ribe were analysed for 24 major and minor elements[81] instead, for a total of 20 samples.

In this chapter, the results of these analyses will be discussed and described by themed sections. First, I have divided compositional (major, minor, and trace elements) from isotopic analysis. The latter section will be used to focus on understanding the provenance for Comacchio and Barking Abbey samples. The former instead, will be dedicated to recipes and raw material identification, with a thematic digression focused on colour, production, recycling, and contamination.

For the first part of this chapter, I have described each site results on their own (Comacchio in section 5.1.1, Barking Abbey in section 5.1.2, and Ribe in section 5.1.3). In 5.1.4, a summary of compositional analysis will be presented together with further questions to be answered with the isotopic analysis.

Multivariate statistical analysis performed in Minitab (Version 18) was used to interrogate of the data. The compositional groups were identified using hierarchical cluster analysis (HCA) using Ward's method (Euclidian distance), and data was input as standardised variables. Determining oxides representative of sand and its impurities, flux, feldspars and lime components (SiO_2, TiO_2, Fe_2O_3, NaO_2, Al_2O_3 and CaO) in glass-making have been used as variable in Cluster analysis and PCA. I used the same criteria for all three sites.

[81] Please refer to Appendix 3 and 4 for a list of analysed major, minor, and trace elements.

The scores of principal components 1 and 2 with eigenvalues of >1 were plotted alongside the eight variables represented by vectors (Figure 60, Figure 87, and Figure 112). I assigned to each macro-cluster an arbitrary groups number (group 1, group 2, etc.…) based on the succession reported in the cluster analysis diagram; outliers have been identified with their own group, but then they were later excluded from the bi-plots and tables to get a better image of the plotted data.

Secondly, samples divided by PCA have been plotted together to describe the nature of the silica source (SIO_2) and associated heavy minerals (Fe_2O_3, TiO_2) alkali source (K_2O and MgO), flux (Na_2O), feldspar (Al_2O_3), and lime content (CaO). A selection of samples has been analysed for 26 major and minor elements (Appendix 2). A series of plots has been created with the aim of exploring further the nature of the raw materials connected to each group highlighted by PCA and of assess the degree of recycling.

A total of 141 samples have been analysed for 47 trace elements by LA-ICP-MS. The recent article by Ceglia et al. (2017) was used for comparison for two main reasons. First, they offer trace element comparisons for both HIMT (both for weak and strong recipe) and the Levantine I recipe. Secondly, they also distinguish non-recycled material from the supposedly recycled fraction of the dataset, which can further help in distinguishing the main non-recycled groups in my dataset. Finally, they offer an excellent framework for distinguishing both Levantine and HIMT in both of its major variant by their Zr/SiO_2 vs. Ce/La and Zr/SiO_2 vs. Sr/CaO ratios.

Plots of Zr/SiO_2 vs. Ce/La and Zr/SiO_2 vs. Sr/CaO used in Ceglia et al. 2017 will be used also for Comacchio, Barking Abbey, and Ribe, hoping to help discriminate between types further.

In order to neutralise the strong coloured and opaque nature of some of Barking Abbey and Ribe material and therefore to obtain a clearer differentiation between groups., SiO_2 percentage has been normalised in

Zr/SiO_2 vs. Ce/La and Zr/SiO_2 vs. Sr/CaO plots to avoid the influence of additives in samples. Comacchio SiO_2 has been normalised in trace element plots as well in order to compare it with the other two sites.

Recycling practices have also been discussed for both Comacchio and Barking Abbey assemblages. I decided to exclude Ribe from the discussion because most of its materials is made from strongly opacified glass: the high levels of both colourants and additives derived from the strong opacification of such samples would not allow one to detect recycling with the necessary confidence.

Comacchio does not present the same problem, since only a few of its samples are opaque (white and red), and the remaining ones varies from colourless to blue/green to green and yellow glasses.

The presence of translucent coloured samples in the Barking Abbey assemblage definitely impacts my discussion concerning recycling practices, given the colourant additives that they include in their composition. Nonetheless, I decided to include strongly coloured glass in my plot to assess recycling practices anyway and use faintly translucent glass included in the same dataset as a benchmark to describe the relationship between such glass and strongly coloured glass. The content of colourant markers will be addressed plot by plot. If such limitations are considered, some considerations can indeed be made about the recycling practices at both sites.

Firstly, I will discuss the level of decolourants, antimony and manganese oxide, in colourless, blue/green, and coloured samples: this bi-plot will allow one to distinguish the amount and the technological significance of both decolourants in each compositional types and colouration.

Secondly, I will assess the content of colourant markers (such as Co, Cu, Sn, and Pb) by plotting a selected group of Comacchio and Barking Abbey samples analysed by LA-ICP-MS with the primary aim to quantify the concentration of such markers in translucent glass in relation to their colour and to describe their technological significance in order to assess

the degree of recycling. Comacchio glass will be considered also in relation to contamination from fuel ashes and crucibles.

5.1.1 Comacchio

Based on cluster analysis (Figure 58), Comacchio glass samples fall in four main branches, which further divides in 6 groups, plus two outliers (Com 32 and 33, respectively group 5 and 6). The same groups can be plotted by PCA. Based on Figure 60, principal component 1 in Comacchio glass shows positive coefficients for Al_2O_3, Fe_2O_3, and Na_2O. On the other hand, Principal component 2 is positively correlated with SiO_2 and to a lesser extent to Na_2O.

Group 1 forms a major cluster (Figure 59), albeit group 2 seems to be more influenced by the first component, with similar contents of Na_2O, but group 1 has potentially more SiO_2. Group 3 seems to separate well from group 1 and 2, with a potential increase in both SiO_2 and CaO contents.

A sub-group of 2 samples (Com20 and Com44) on one side fall within the influence of group 1, and another sub-group of 2 samples (Com15 and Com76) falls within group 4. Finally, group 7 and 8 divide distinctively from the major cluster (group 1, 2, and 3) under the influence of the first component, with a potential increase in alumina, iron, and titanium oxide.

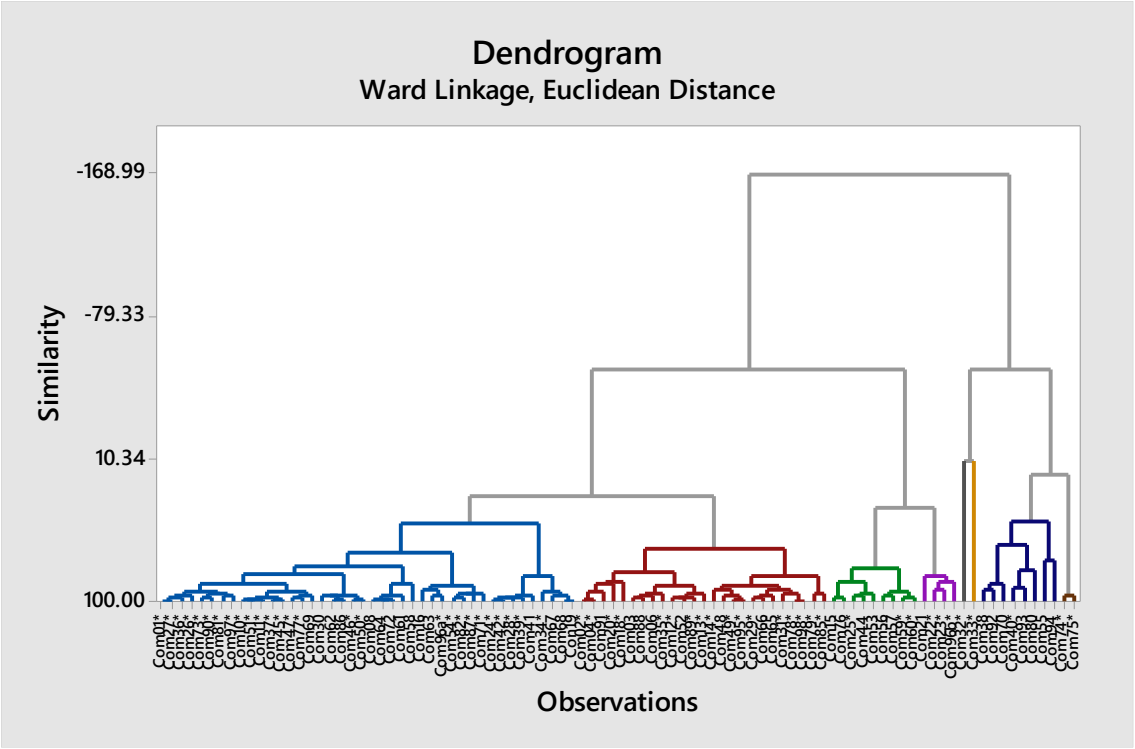


Figure 58 - Cluster analysis (Ward's method, Euclidean distance) distinguishes 6 principal groupings of samples. Determining oxides: SiO_2, TiO_2, Al_2O_3, Fe_2O_3, CaO, and NaO_2. (N= 92; Com 32 and 33 are removed from now on because outliers).

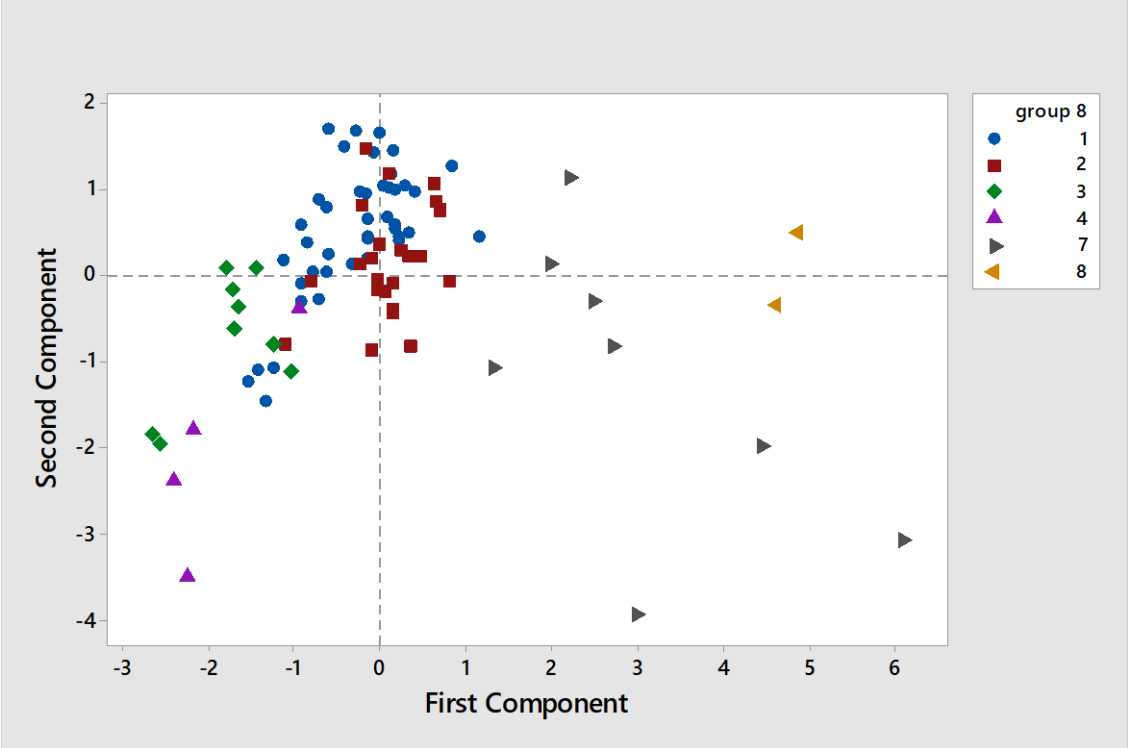


Figure 59 – PCA bi-plot of Pca 1 and Pca 2 of Comacchio glass dataset. Determining oxides: SiO_2, TiO_2, Al_2O_3, Fe_2O_3, CaO, and NaO_2. Group labels are based on cluster analysis (see this section, Figure 58).

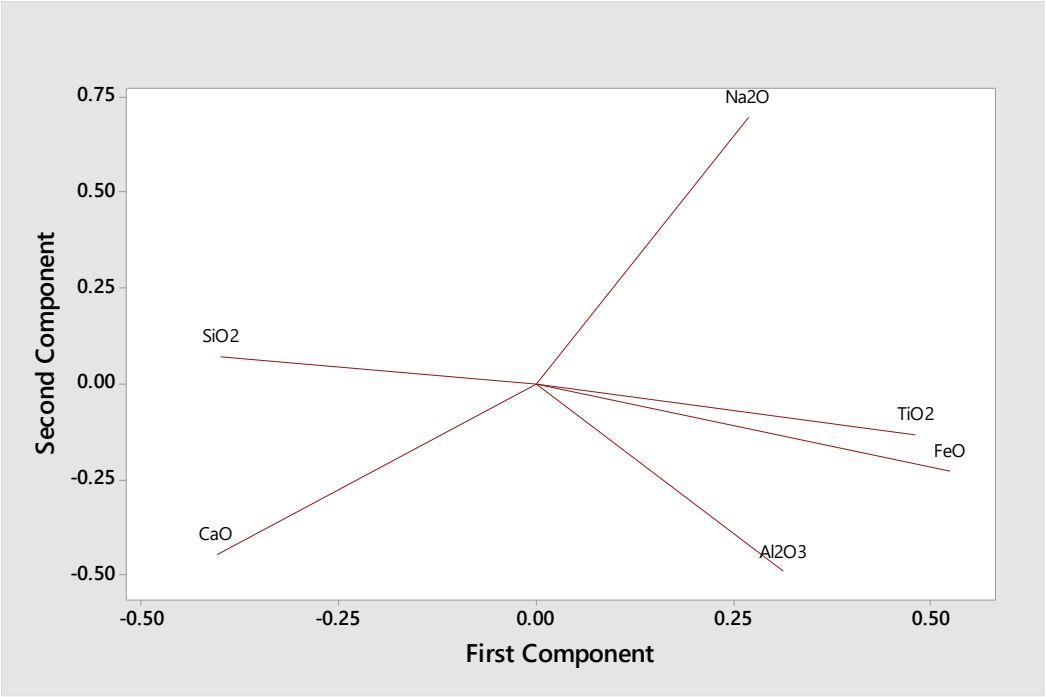


Figure 60 - The length and direction of the vectors show the contribution of each variable to the principal components 1 and 2. Principal component 1 has positive coefficients for Al_2O_3, Fe_2O_3, and Na_2O. Principal component 2 is positively correlated with SiO_2 and to a lesser extent to Na_2O.

5.1.1.1 EMPA

The aim of this section is to describe the composition of each group highlighted from cluster analysis and its raw materials. It needs to be stressed that such groups are arbitrarily created, and therefore they might miss features that instead could be vital in the course of our analysis. For this reason, each of the groups produced by cluster analysis will be reassessed for each site at the end of each major section.

Potassium and Magnesium oxides have been plotted to identify the alkali source for each of the Comacchio groups (Figure 61). The majority of Comacchio glass falls within the natron glass limits, with both K_2O and MgO lower than 1.5wt% (Lilyquist and Brill, 1993). A small subgroup of samples (Com21, 22, 23) falls within the plant ash K_2O and MgO limits (>2.0wt%). Com14 and Com80 fall close to this group, and they are positively correlated with Com 22 and 23.

Four samples (Com36, 53, 26, and 40) show an increase in potassium oxide. Another group of samples increase of MgO (>2.0wt%). Interestingly enough, most of samples from group 7 (red in Figure 61) show relatively higher levels of MgO on the other (> 2.0wt%). Other samples from group 1 (Com81 and 47) and 2 (Com98, 31, 66, 78, 79 and 91) show the same increase in MgO.

On the other hand, group 3 has instead the lowest content of both K_2O and MgO. Group 4 shows some of the highest levels of both potassium and magnesium oxides (respectively >2.0wt% and >2.5wt%), except for Com96b, which falls within the range of natron glass as group 1 and 2.

In Figure 62, SiO_2 and Na_2O are plotted to observe the variation in both silica sources and flux used. All groups separate in two distinct macro-clusters: group 1, 2, 7, 8 on one hand show relatively high values in Na_2O (14.88 wt% - 19.71 wt%) but separates according SiO_2 contents; group 2 on the other hand has relatively higher SiO_2 (> 64wt%) when compared to group 1, 7, and 8.

Group 3 and 4 instead show both relatively lower Na_2O contents when compared to the other groups (respectively <13wt% and >13<15wt%) but with different SiO_2 contents. In addition, group 4 shows similar SIO_2 contents has group 1, 2, 7 and 8, group 3 show relative higher values (>68.17wt%). One sample from group 2 (Com79) and one from group 7 (Com80) fall within the plotting area of group 3 and 4.

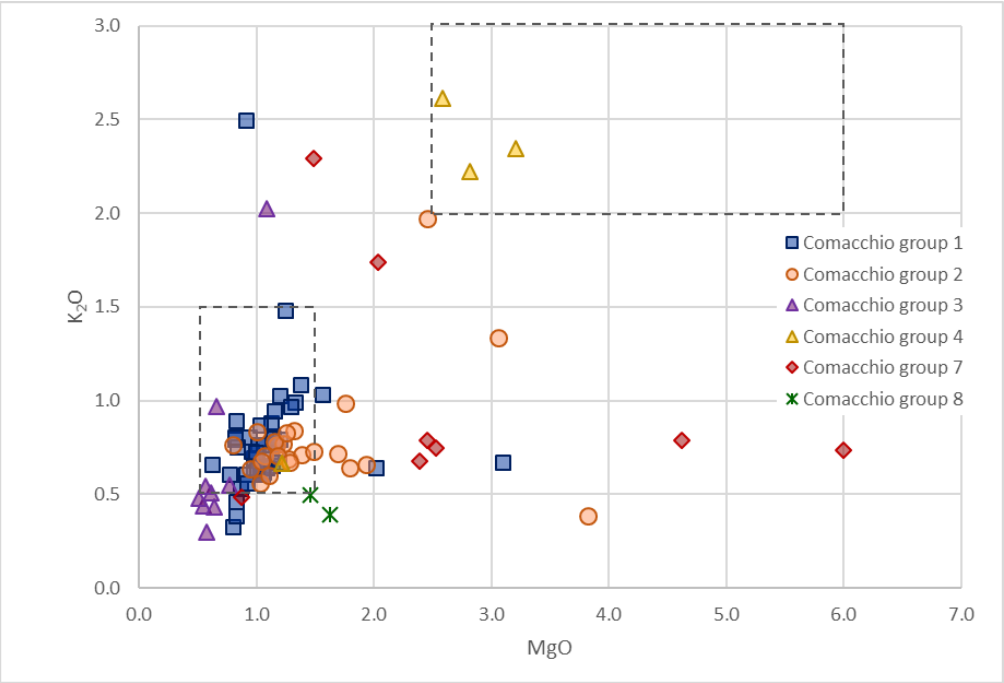


Figure 61 - MgO versus K_2O contents for glass from Comacchio divided by groups based on cluster analysis. Natron (bottom) and plant ash (top) glass potassium and magnesium oxide contents, after Lilyquist and Brill, 1993.

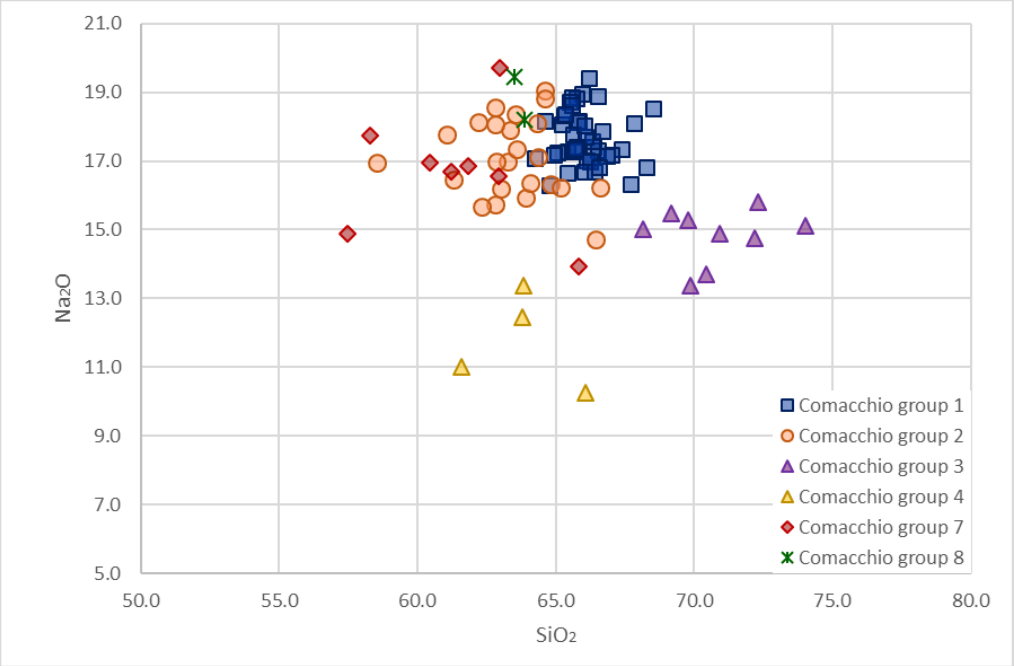


Figure 62 - SiO_2 versus Na_2O contents for glass from Comacchio divided by groups based on cluster analysis.

Al_2O_3 versus Fe_2O_3 (Figure 63) have been plotted to reflect variation in both feldspar content and impurities associated with the sand source.

Group 3 has the lowest levels of iron oxides amongst the whole dataset (<0.50wt%)[82], while Group 1 and 2 instead show increasing levels of Fe_2O_3, with group 2 relatively higher levels of Fe_2O_3 when compared to group 1. A small sub-group of five samples from of group 1 (Com16, 34, 67, 68, 19) shows similar levels of both Al_2O_3 and Fe_2O_3 as group 3. Group 8 is compact with higher levels of both iron and alumina (respectively c. 2.0wt% and c.3.5wt%).

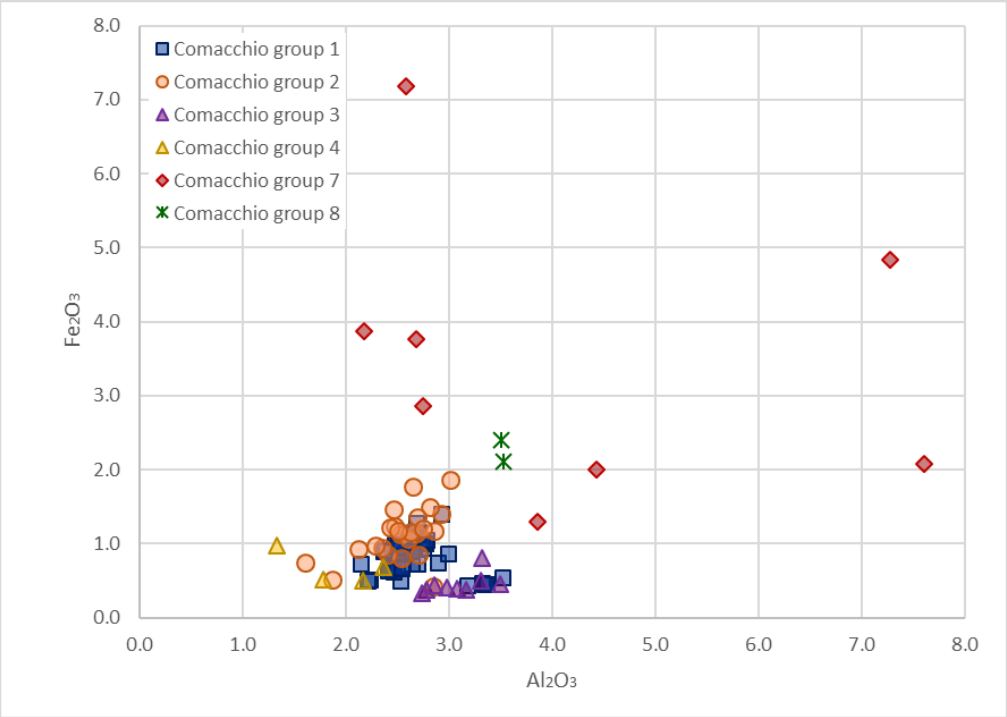


Figure 63 - Al_2O_3 versus Fe_2O_3 contents for glass from Comacchio divided by groups based on cluster analysis.

Group 7 splits into two sub-groups, showing respectively relatively higher levels of Al_2O_3 (<3.86wt%>7.61wt%) or Fe2O3 (<2.75wt%>7.19wt%). A small sub-group of four samples from group 1 (Com16, Com 68, Com19, and Com34) and one sample from group 2 (Com20) plots within group 3 alumina and iron oxide contents.

[82] Only one sample from group 3 (Com53) shows higher levels of Fe_2O_3 (0.80wt%).

Therefore, we can revaluate both group 1 and 2 according to their alumina and iron oxide contents. The small group 1A, with higher alumina and iron oxide contents (respectively around c. 3wt% and <0.50wt%) is similar to group 3, while one sample from group 2, Com20, has similar values, and from now on it will referred as group 2A. The rest of group 1 and 2, which from now on will be referred respectively as group 1B and 2B, have instead higher Fe_2O_3 content (c. 1 and 2 wt%) and lower alumina (2wt% < Al_2O3 < 3wt%).

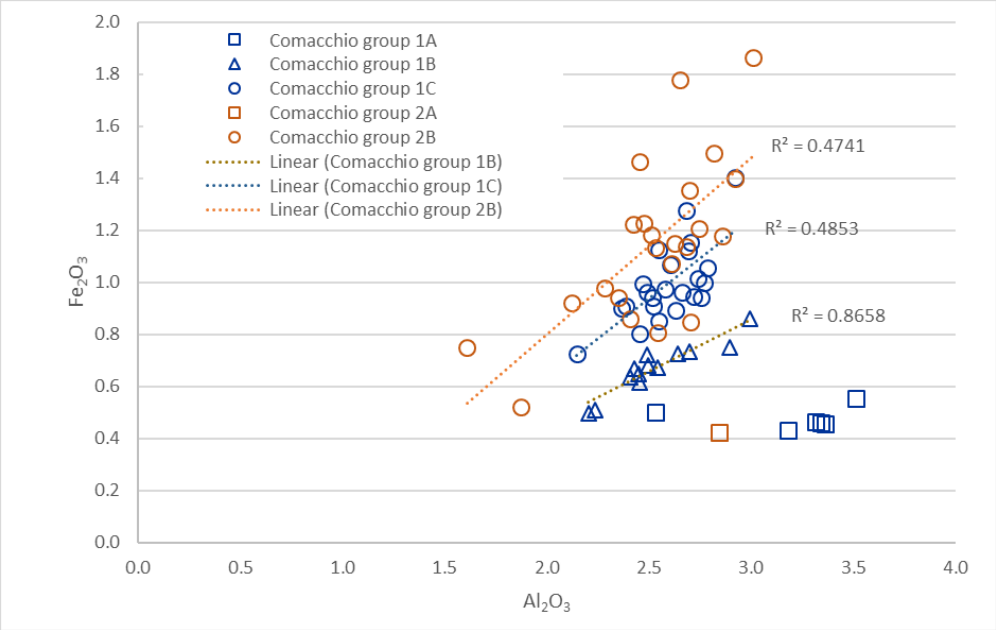


Figure 64 - Al_2O_3 versus Fe_2O_3 contents in group 1 and 2: iron oxide content and its correlation with alumina clearly define a new group sub-division for group 1B.

If only group 1 and 2 are considered (Figure 64), group 1B shows further subdivision in two sub-groups (from now referenced as 1B and 1C) according to its iron oxide content. Both groups show a positive correlation between Fe_2O_3 and Al_2O_3, but with different R^2 values (1B "R^2 = 0.8658"; 1C "R^2 = 0.4853"; 2B "R^2 = 0.4741"): the difference in iron oxides values and correlation suggests that they have been made with different sands sources. Group 1C shows an equivalent iron content (>

0.8wt%) and similar R^2 correlation value ($R^2 = 0.4853$) when compared to group 2 ($R^2 = 0.4741$).

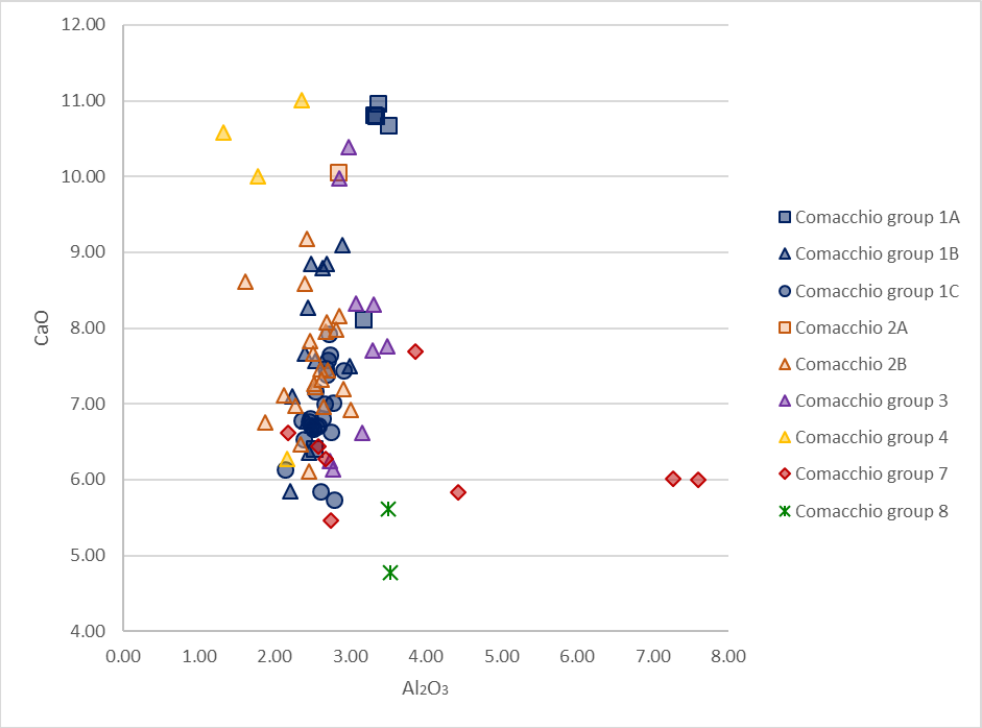


Figure 65 - Al_2O_3 versus CaO for glass from Comacchio divided by groups based on cluster analysis.

Finally, Al_2O_3 vs. CaO bi-plot (Figure 65) reflects the feldspar versus the lime contents. Amongst the plots, this is possibly the least discriminant of the four. Group 4 has the relatively highest CaO values (c. >10.0wt%) together with a relatively low Al_2O_3 content (1.33wt%, 1.78wt%, and 2.37wt%). Com96b is the only exception, plotting together with group 1 and 2, which suggests that it is base glass is closer in composition to natron rather than plant ash. The two samples from group 8 plot separately, with among the lowest CaO values of the whole dataset (c. 60wt%) together with some of the highest Al_2O_3 (3.51wt% and 3.53wt%).

The rest of the groups do not discriminate as well as the other ones. Group 1B and 1C and 2B plots show very comparable values for both oxides, and therefore they might have been made with the same

combination of sand with variable lime contents, but do not separate as instead showed by the Al_2O_3 and Fe_2O_3 plot.

Group 3 does not cluster but divides roughly in three sub-groups because of its variable CaO, which indicates a difference in lime content but stable alumina around c. 3wt%, and therefore could have been made with the same type of sand but in different batches.

Group 1A and 1B plot within the levels of group 3, but do not separate as seen in other plots. Interestingly enough group 1A split in the same manner according to CaO, so the same consideration made for group 3 is valid for this group. Two small sub-groups of samples from group 1C (Com24, 28, 39, 42,) and 2B (Com 06, 14, and 88) plot closer to group 4 and 3, with relatively high levels of CaO (>9.5wt%).

Group 7 clearly shows two major trends: the first sub-group (Com38, 70, 92, and 94; all red opaque samples) plots together with group 1 and 2, so their base glass could be the same as group 1B, 1C, or 2B. The other sub-group (Com 40, 93, 55, and 80; all crucibles), shows higher Al_2O_3 values (2.75wt% - 7.61wt%): for samples with values over 4.0wt%, contamination from the crucible should be considered.

Colours

Most translucent Comacchio samples are blue-green coloured. Their tinge varies from light blue or light green to a more intense blue-green colours. Colour distinction has been done by naked eye, hence the difficulty in differentiating between hues and hence the decision to group all the light-coloured blue-green glasses together. When the distinction was sufficiently clear, samples have been put into the dark blue or green/olive green category.

Blue green glasses have the characteristic “natural” glass colour, which is the result of the interaction between iron contained naturally in the sand

as impurities and the reducing atmosphere that the melt is exposed to in the furnace (Brill, 1988). The interaction between iron and sulphur oxide with the atmosphere of the furnace (shifting from reducing to oxidising) will change glass colour respectively from blue to a more green-green/yellow tinge. In Comacchio blue-green glasses the range of Fe_2O_3 varies between 0.38wt% and 4.84wt%, while SO_3 from 0.08wt% to 0.35wt%, which accounts for a whole range of different nuance of blue-green glasses.

Copper oxide is most likely responsible for the olive-green colour in a small group of Comacchio glasses (0.55wt% to 2.00wt%). Other less common colours include faint yellow and dark blue. Yellow most likely derived from a combination of a reducing atmosphere and combination of iron (1.18wt%-1.78wt%) and sulphur (0.27wt% - 0.32wt%), while a dark blue colour results from the addition of cobalt oxide as a colourant (0.04wt% and 0.11wt%).

A few samples look colourless or nearly colourless, with high levels of MnO (0.79wt% to 3.20wt%), which therefore has been used as a decolouriser in these glasses.

Only two varieties of opaque glasses occur: white and red. Given the levels of Sb_2O_5 (5.71wt%), crystals of calcium antimonate has been used as an opacifying agent in Com91 (Henderson, 2000, 35). The other opaque white sample (Com96b) does not show any trace of Sb_2O_5; therefore, it is probably opacified by the addition of some tin compounds (such as cassiterite), given its high levels of SnO_2 (3.61wt%).

Three red samples (Com31, 38, and 94), all sampled from crucible layers containing red veins of glass, have relatively low levels of Fe_2O_3 (1.46wt% - 7.19wt%) and PbO (2.05wt% - 3.30wt%) and levels of CuO between 0.56wt% and 0.96wt%: their values look close to the so-called “dullish red” colour described in the literature (Freestone, 1987; Henderson, 1991) , even though in this case copper oxide it is lower than

values found in literature[83]. Only two tesserae do not adhere to this pattern (Com70 and Com92) because of their low PbO contents (0.22wt% and 0.36wt%). Similar values on the other hand have been reported recently by Boschetti et al in a paper concerning Roman mosaic tesserae in Italy (Boschetti et al., 2016, table 2, 306).

5.1.1.2 Further considerations and comparison with published materials.

I now will discuss Comacchio Empa results and suggest compositional types for each of them.

Group 3 is a low alkali-based glass with low impurity connected to the sand source, such as iron oxide (0.45wt%), and titania (0.08wt%), but relatively high in alumina (3.08wt%) and SiO_2 (70.76wt%), which would suggest the use of a mature high silica sand with significant feldspar content, such as the so-called Levantine composition (Freestone et al., 2000). Also, in group 3 CaO contents vary considerably between samples (Figure 65), which might suggest the existence of multiple batches of the same recipe with variable lime contents.

Based on major elements, Group 1 and 2 are both natron-based glasses, which seem to cluster together in most bi-plots. If iron and alumina contents are examined, group 1 divides further in three sub-groups, while group 2 in two: group 1A and 2A show characteristics levels of alumina, calcium and iron oxides similar to group 3 and typical of Levantine I glass, even though they have higher sodium compared to average Levantine (c. 17 -19wt%). The remaining samples from group 1 have higher overall levels of iron (1B 0.49wt%– 0.86wt%; 1C 0.72wt% – 1.28wt%) and lower alumina (2wt% < Al_2O_3 < 3wt%) paired with higher Na_2O (c. 17wt%) when

[83] For example, in Henderson' paper (Henderson, 1991a, tab 3, 72), CuO values for duller red glass are around 1.80wt% and 1.20wt%.

compared to group 3 – Levantine I. Group 2 has the same compositional characteristic, but its values of Fe_2O_3 are tighter (>0.80wt%) and overall has less SiO_2 content (<65wt%).

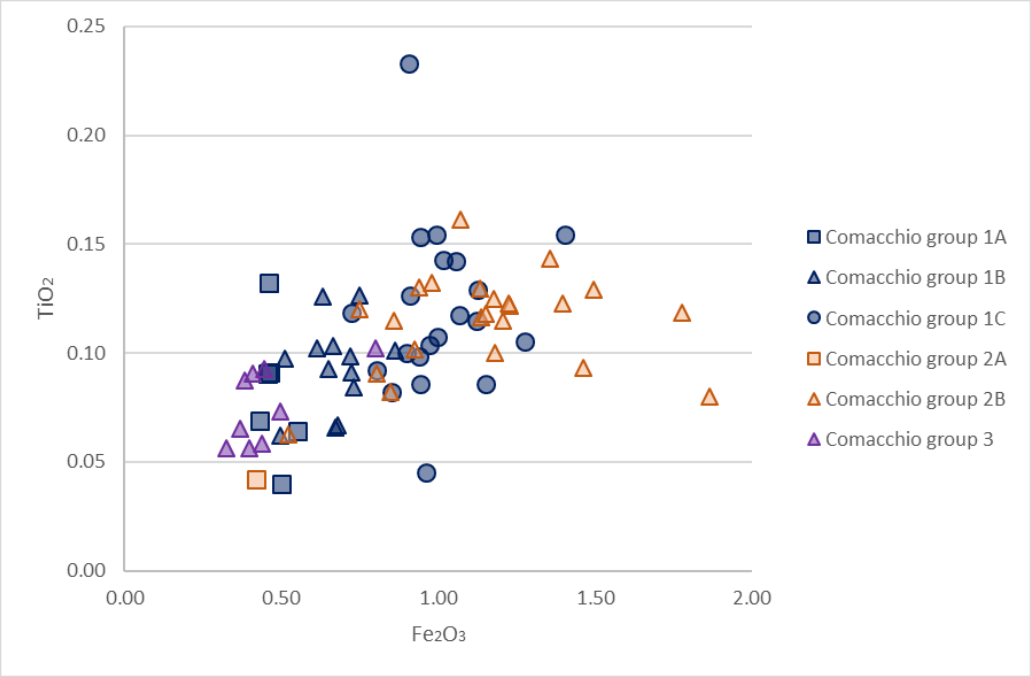


Figure 66 - Fe_2O_3 versus TiO_2 contents for glass from Comacchio in group 1A, 1B, 1C, 2A, 2B, and group 3.

In Figure 66, the relationship between iron and titanium oxide is considered. Group 1B, 1C, and 2B all plot within the same TiO_2 range of values (0.07wt% - 0.16wt%) while iron oxide content varies considerably, which suggests that the discriminant in these glasses is based on the impurity content: such impurities might derive from the use of a different sand source or through recycling[84]. Group 8 (Com74 and 75) can be considered in my opinion another variant of HIMT, given the fact that presents the same characteristics of group 1 and 2 but have overall higher Fe_2O_3 (2.25wt%), TiO_2 (0.56wt%), Al_2O_3 (3.52wt%) and Na_2O

[84] Titanium oxide results from the second run of analysis as to be consider as a semi-quantitative result, as seen in section 4.2.2.1

(18.84wt%) paired with low CaO (5.19wt%). I cannot describe with confidence their correlation as positive in Figure 66, since it includes only two samples, but it is indisputable the fact that their composition is radically different from the other samples in Comacchio dataset.

Given the high content of both potassium and magnesium oxides in Com 21, 22, and 23 (2.58wt% - 3.20wt% MgO and 2.22wt% -2.61wt%), combined with low feldspar (Al_2O_3 1.33wt% – 2.37wt%) typical of a relatively pure silica source, I suggest that type 4 could be interpreted as plant ash[85]. I would not consider Com96b (a white opaque filament decoration) as plant ash, since it does not show adequate MgO and K_2O values as a plant ash, even though it is comparable for alumina, silica, and soda content.

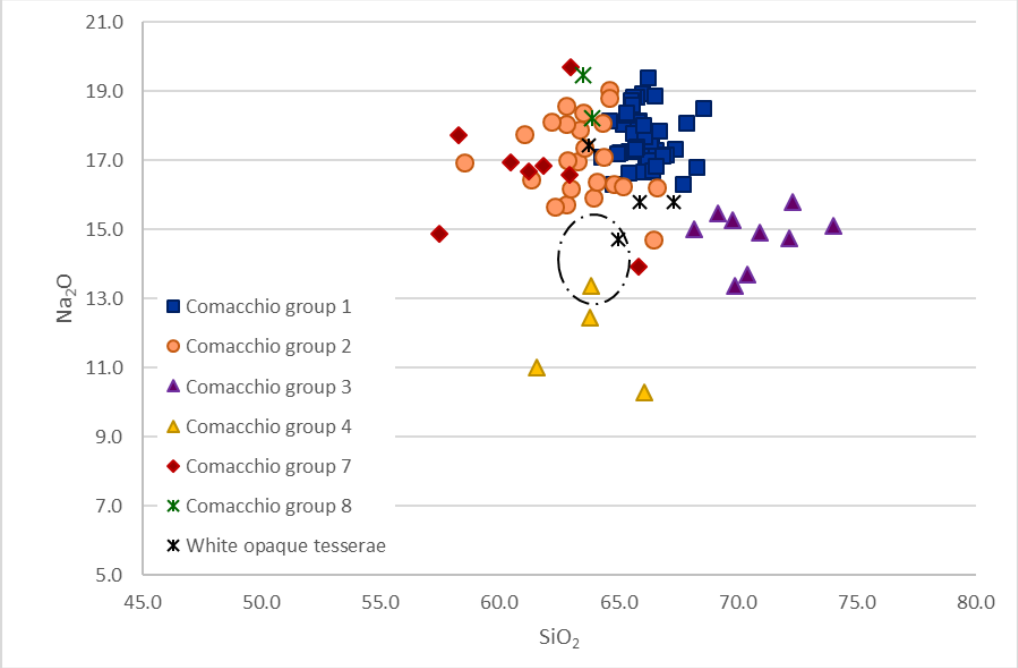


Figure 67 - SiO_2 versus Na_2O for glass from Comacchio divided by groups based on cluster analysis. Com96b (yellow triangle) and TSU 1 (black asterisk) are underlined with a black interrupted-line. White tesserae plotted samples are taken after Boschetti et al., 2016, table 2, 306.

[85] Com21 has the highest Al_2O_3 levels among the whole groups, hence such impurities might derive by a different sand richer in impurities or from contamination during glass-working.

As showed in Figure 67, Com96b has comparable silica and soda values to one Roman tesserae (TSU 1) dated to the 1st century AD from Pompei (Boschetti et al., 2016, table 2, 306); the same can be said for both alumina and calcium oxide. This suggests that it is possible that Com96b was originally one (or more) Roman mosaic tessera melted and then applied on Com96a (goblet) as decoration.

Finally, I would not consider group 7 as a properly separated group. Overall, it includes samples with blue-green crucibles layers, wasters, and red opaque tesserae as well as crucible layers with increasing quantities of MgO, Fe_2O_3, TiO_2, and Al_2O_3. If on the one hand the increase of iron oxide (c. 3.0wt%) can be justified in the red opaque samples (and therefore connected to the technology used to colour these samples), the increase in other values in blue/green wasters and crucible layers could be linked to fuel and crucible contamination.

It has been already been discussed in Chapter 2 how Palestine was the centre of primary production for the so-called Levantine recipe in the Early Medieval period, and therefore, I will now compare Comacchio results with known reference materials from potential primary and secondary workshops. As a HIMT reference, I chose Foy I and Foy 2 from Foy and colleagues work (Foy et al., 2003), while for Levantine I compared my material with the recent work of Phelps and colleagues on Late Byzantine – Early Medieval glass from Palestinian region (Phelps et al., 2016). Glass analysed by Foy and colleagues (Foy et al., 2003) has been used in countless articles as benchmark for HIMT glass (both in its so-called weak and strong variations). Even though both databases do not include material from primary production sites, at the current state of the research they represent a solid criterion for comparison for my datasets from both the chronological and compositional point of view.

In this first plot (Figure 68), I decided to plot together CaO/Al_2O_3 and Na_2O/SiO_2 ratios, which have been applied with success by Phelps and colleagues in describing variation of soda, silica source, lime and feldspar content in Levantine glass from Palestine (Phelps et al., 2016). Group 3

falls within Apollonia-type Levantine, with lower Na_2O/SiO_2 (c. 0.20 – 0.22). In the same range but with much higher and broader CaO/Al_2O_3 ratios (4.65 – 8.01), Group 4 fall within plant ash area save Com96b, which instead falls within Levantine I glass.

Group 1 and 2 splits in two major arrays. Neither group 1A or 2A plots within the Levantine I limit, as instead was expected given their CaO, Al_2O_3, and Fe_2O_3 content, but instead falls within the Foy 2 composition, with the majority of them plotting within the lower Na/Si ratio range (c.3.0wt% - 3.5wt%) and only one samples with higher Na_2O/SiO_2 ratio (Com16). The same can be said for 2A group (Com20). Group AQ2a (3rd – 6th century AD) from Aquileia which has been classified by Gallo and colleagues as comparable with Levantine I (Gallo et al., 2014, tab. 2, 14), is close to our 1A and 2A groups, even though Gallo and colleagues do not mention the higher content in soda compared to known Levantine I composition. I will therefore still consider both group 1A and 2A close to Levantine I, together with group 3.

Group 2B spreads within the Foy 2 range for both ratios together with the remaining samples from 1B and 1C, with the exception Com79 (which plots within the Levantine I area) and Com14 (which falls close to plant ash group 4). I have no reason to classify these groups under Levantine recipe given their higher content of impurities and lower feldspars (Figure 64) and therefore I would suggest that they are close to HIMT composition, potentially made with different sands given their spread range of Na_2O/SiO_2 ratios (0.24 -0.29).

Group 8 clusters within Foy 1 area (strong HIMT) with similar Na_2O/SiO_2 values to group 1 and 2 but lower CaO/Al_2O_3 ratios (1.35 – 1.60) compared to the other groups, which suggest a different source of lime. Finally, group 7 shows a broader range of CaO/Al_2O_3 ratios, which does not allow us to compare them with a specific published composition, even though they concentrate in the HIMT area of the plot with higher Na_2O/SiO_2 values compared to Levantine I type.

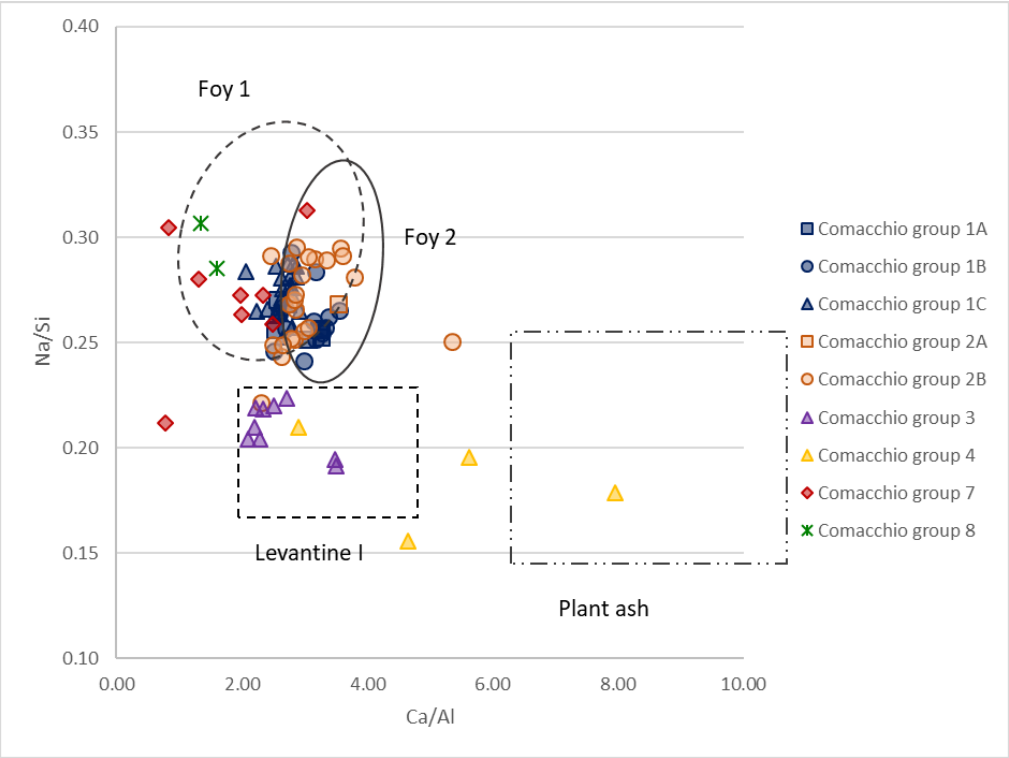


Figure 68 - CaO/Al_2O3 vs. Na_2O/SiO_2 ratios in Comacchio glass dataset, compared with known published composition; Foy 1 and Foy 2 data after Foy et al., 2003, Levantine I - Apollonia type glass after Phelps et al., 2016, and plant ash glass from Raqqa – type 1 after Henderson et al., 2004.

5.1.1.3 Recycling

In Figure 69, a bi-plot of MnO vs. Sb_2O_5 for Comacchio translucent and red opaque glass divided by compositional types is shown. MnO or Sb_2O_5 oxides have been used in colourless glass as decolourisers, and their presence in blue-green glass has been argued as a recycling indicator in faintly coloured glass, mostly blue-green (Jackson, 2005; Silvestri et al., 2008). I eliminated from both MnO vs. Sb_2O_5 bi-plots three samples with antimony oxides over 1wt%, which includes two mosaic tesserae, one white (Com91) and the other translucent dark blue (Com69), and a white opaque decorative filament (Com96b): antimony oxide in this case has been used as opacifier or is associated to the cobalt used to colour the tesserae with a dark blue tinge (Henderson, 2000, 30).

A small sub-group of samples from group 3 and group 1A and 2A have a limited quantity of both decolourisers (<0.1wt%), which indicates that this sub-group has not been recycled at all or has undergone limited recycling cycles. The remaining samples from group 1B, 1C and 2B divides in 2 sub-groups. In the first, the amount of antimony oxide is still negligible (< 0.04wt%), but they present relatively higher MnO contents (0.13wt% - 0,97wt%). In such a sub-group the main de-colouriser is manganese oxide; it has been argued elsewhere that MnO has been added to the batch if present over the amount of 0.2wt% (Sayre, 1963; Jackson, 2005, 771), but the level above which the addition of MnO is considered deliberate varies and it seems to be discrete to each dataset. Considering the gap between no MnO and low MnO samples (Figure 69), 0.2wt% seems a reasonable threshold.

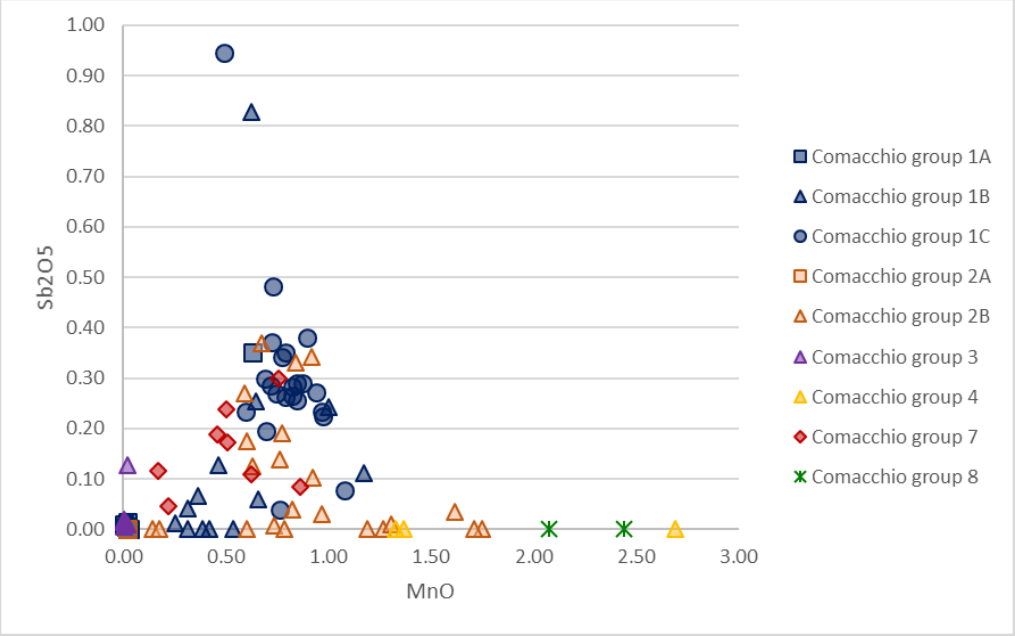


Figure 69 - MnO vs. Sb_2O_5 contents for Comacchio translucent glass divided by types suggested by cluster analysis.

In group 1B, some samples show low values of MnO (<0.50wt%) and some others the co-presence of MnO and Sb_2O_5 would suggests different phases of re-use for at least the latter sub group. The same can be said

for group 2B, which is the only one, together with group 4 and 8, to show elevated MnO levels (>1.0wt%) in some of the samples (Com06, 18, 29, 35, 85, and 88). Group 1C instead has considerable levels of both decolourisers, which indicates that they have most likely undergone repetitive cycles of re-melting. Com71 and Com82, a light blue droplet and a light green crucible layer, both contain high Sb_2O_5 amount (respectively 0.95wt% and 0.83wt%). The antimony in Com71 has been most likely associated with the cobalt used to colour the same sample, while in Com82 it might be connected to recycling (in combination with MnO).

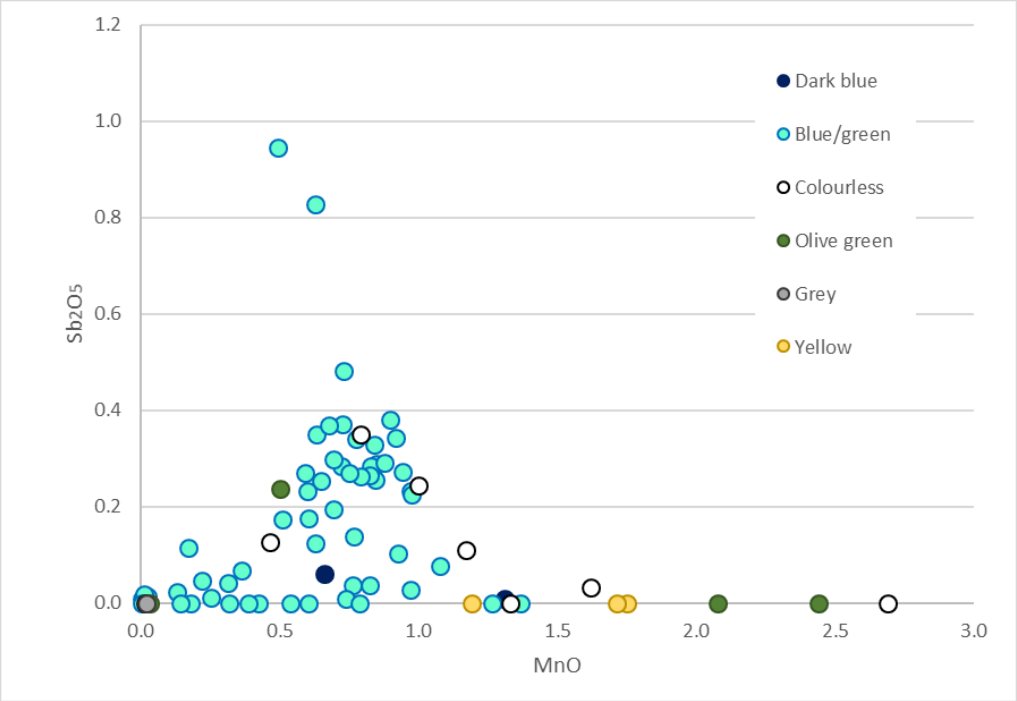


Figure 70 - MnO vs. Sb_2O_5 contents for Comacchio translucent glass divided by colour.

Group 8 – HIMT and group 4 – plant ash have higher MnO values (c. >1.0wt%), has been observed in strong HIMT and plant ash compositional groups from the literature (Mirti et al., 2000, 2001; Freestone et al., 2002; Henderson et al., 2004; Foster and Jackson, 2009; Rosenow and Rehren, 2014; Ceglia et al., 2015).

Most blue/green samples are included in the group with low MnO and in the Sb + Mn group (Figure 70). The concurrent presence of both decolourisers has no technological significance and indicates that such glasses have undergone repetitive cycles of indiscriminate mixing (and therefore recycling) of glass with different Sb_2O_5 and MnO quantities. The high MnO group includes three colourless, three yellow glasses, one dark blue coloured glass, and two olive green coloured samples (group 8, HIMT strong).

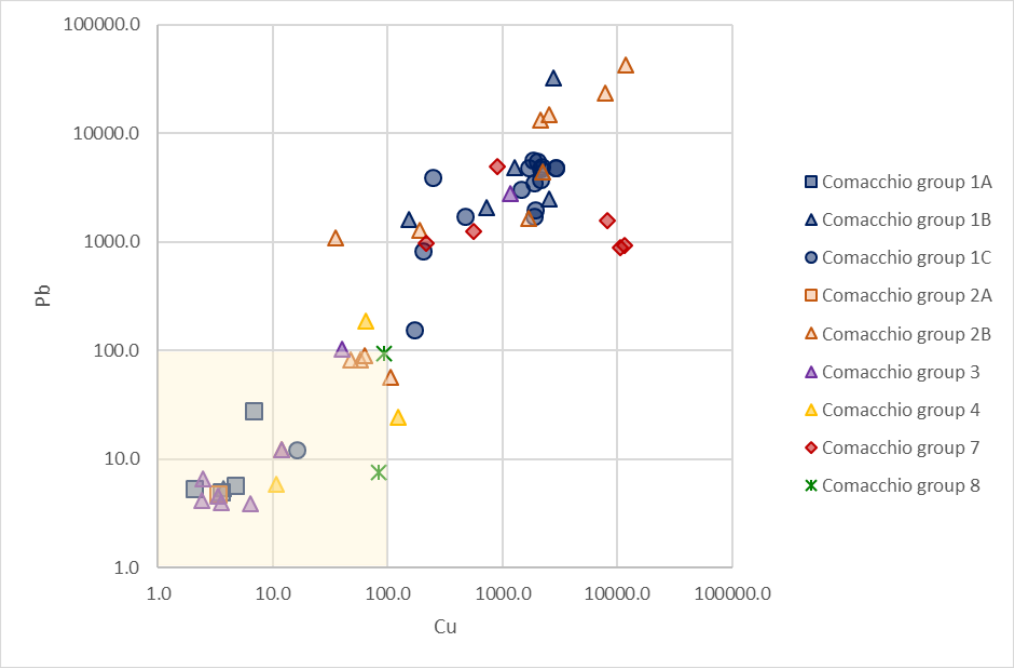


Figure 71 - Cu vs. Pb in a selected group of samples from Comacchio glass dataset, divided by group. The scale on both axes is logarithmic. The area coloured in faint yellow suggests glass with low values of colourants, which may indicate no or very limited recycling practices.

If trace elements are considered, the content of Cu, Co, and Pb can also be plotted in order to assess recycling[86]. The presence of enhanced colourant elements (such as Cu, Pb and Sb) in weakly-coloured transparent glass is now accepted as evidence of glass recycling (Mirti

[86] Trace elements have been performed on a limited number of samples, please refer to section 5.1.1.45.1.1.4.

et al., 2000, 2001; Freestone et al., 2002; Jackson, 2005; Schibille and Freestone, 2013), and in particular evidence of the addition of coloured glass rich in such markers (most likely with strongly coloured mosaic tesserae) to “fresh” glass or cullet. Such practices has been documented in many other coeval sites, like San Vincenzo al Volturno (Schibille and Freestone, 2013), and has been associated with the production of window glass by Theophilus in his *Rerum Artibus* dated to the 12th century AD: blue tesserae were mixed with colourless glass to make new translucent blue sheets to produce window glass.

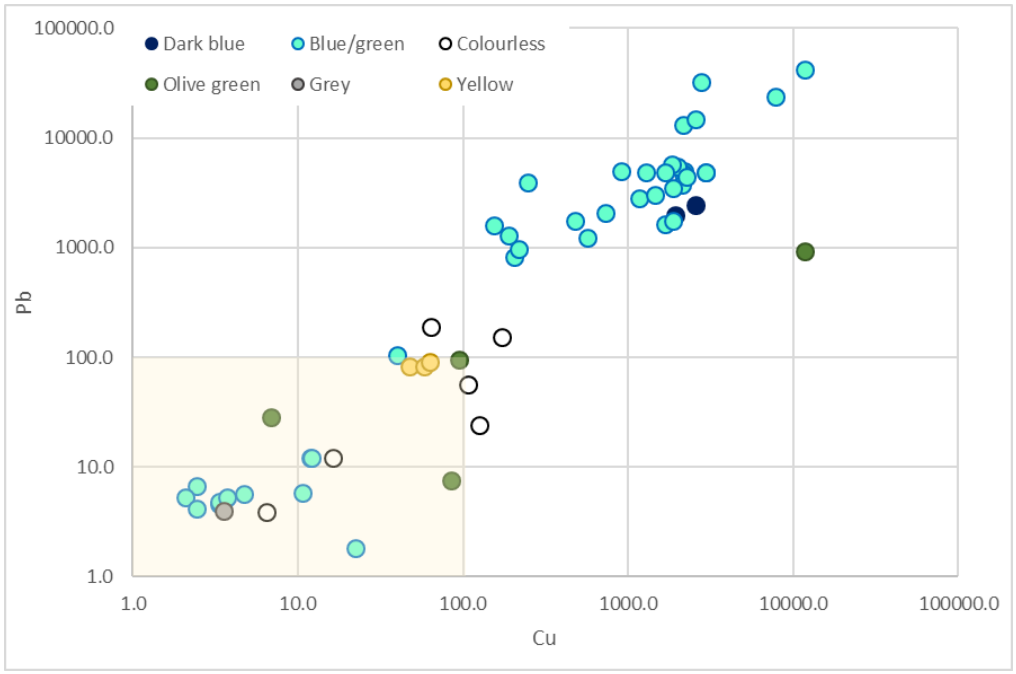


Figure 72 -Cu vs. Pb concentrations in a selected group of samples from Comacchio glass dataset, divided by colour. The scale on both axes is logarithmic. The area coloured in faint yellow suggests glass with low values of colourants, which may indicate no or very limited recycling practices.

The area coloured in faint yellow in the plots (Figure 71,Figure 72, and Figure 73) highlights glass with low values of colourants, which may indicate no or very limited recycling practices. Such values (within 100ppm of both trace elements) are conventionally agreed (Foster and Jackson, 2009, 196). Nonetheless, in all graphs it seems apparent how the material splits clearly in two groups: one within the 100ppm limits, and

the other with values way over (c. 1000 – 10000ppm). The same pattern occurs with other colourant markers (Sb and Sn).

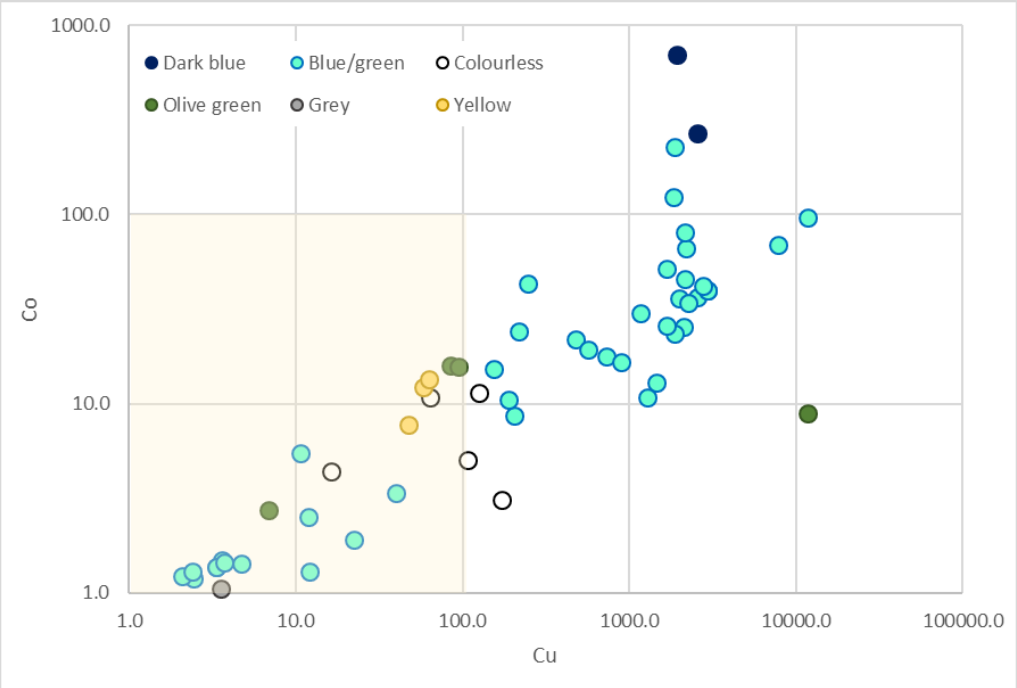


Figure 73 - Cu vs. Co concentrations in a selected group of samples from Comacchio glass dataset, divided by colour. The scale on both axes is logarithmic. The area coloured in faint yellow suggests glass with low values of colourants, which may indicate no or very limited recycling practices.

The same pattern shown in Figure 70 is repeated when recycling markers are plotted according groups. I included an example with Cu vs. Pb (Figure 71), but the same pattern repeats when other pairings are explored. It is worth noticing how group 1C tightly clusters around high values of both Cu and Pb, which indicates that it was made with one source of recycled glass, and that limited mixing with other sources occurred. On the other hand, 1B and 2B are well distributed across the whole plot area which indicates different cycles of recycling and potentially mixing with other sources of glasses. A small 2B sub-group also falls within the non-recycled area (Com06, 14, 18, 29, 85, and 91).

If colour is considered, mostly blue-green is part of the second group with high colourant content, together with dark blue samples. Yellow, mostly

olive green, and part colourless glass are included instead in the first supposedly non-recycled group. What seems most likely is that mosaic tesserae have been added to fresh glass to produce most blue-green glass in Comacchio.

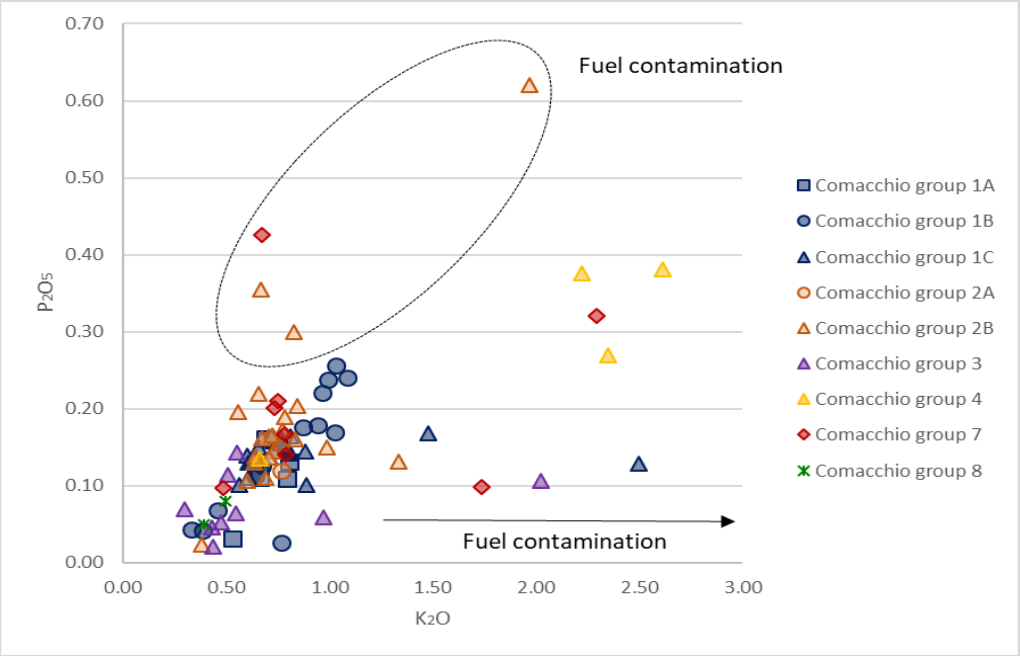


Figure 74 – K_2O and P_2O_5 contents in glass from Comacchio divided by groups according to cluster analysis. Samples included in the area delimited with a striped line might be contaminated by fuel ashes.

Some samples in Comacchio glass dataset show signs of contamination, both from fuel ash and crucible. In Figure 61, all samples from group 7 show higher values of magnesium or potassium oxide, together with a small number of samples from group 1, 2, and 3. Such increments in both oxides could be connected to fuel ash or crucible contamination on one hand or mixing to the other. When potassium and phosphorus oxides contents are paired (Figure 74), most of the natron glass group is focused within expected potassium and phosphorus oxide values, respectively c. 0.1wt% and 0.2wt%: such values have been registered in other coeval datasets such as Verita' and colleagues work on Venetian lagoon glass (2002, fig. 1, 364). Group 1 shows overall a progressive increase of P_2O_5,

while group 2 show tighter values, albeit still included in the known K_2O values for natron glass.

A small group of samples shows instead higher values in one or both oxides. Com40 has both oxide values close to group 4 - plant ash (c. 030 P_2O_5); together with high K_2O and MgO values (Figure 61), it might indicate that Com40 is a mix of both natron and plant ash recipe. Four samples from 1B (Com63), 3 (Com76), 2B (Com79), and 1C (Com48) group positively correlate with Com 40: such correlation could indicate that such samples are the result of mixing a base natron glass with variable quantities of plant ash glass.

Three samples (Com 95, 89, and 55, top) show increasing values in phosphorus oxide potentially from settling fuel ashes (Paynter, 2008). The same can be hypothesised for five samples which show increase of potassium oxide (Com 79, 36, 80, 53, and 24, bottom), all waster or crucible layers minus Com24, which is a fragment from a vessel. Com14 has considerably higher values in both oxides (respectively 1.97wt% and 0.62wt%), with P_2O_5 way over the values for registered for the plant ash group (0.27wt% - 0.38wt%), which lead me to consider the possibility that It might be not only a mix between natron and plant ash, but it might also have been heavily contaminated by fuel ash during re-melting.

Group 3 and 8 show overall lower values of both oxides, which makes them the less contaminated of all groups in Comacchio glass dataset. Group 7 though shows excess of both MgO, Fe_2O_3, and Al_2O_3 (Figure 61 and Figure 63) when compared with the other natron groups. Increasing values of the afore mentioned oxides have been connect with crucible contamination: because sample were in direct contact with the crucible wall, contaminants migrated from the crucible body to the layer of glass (Paynter, 2008, Jackson and Paynter, 2016).

5.1.1.4 Trace elements

62 samples have been analysed for 47 trace elements by LA-ICP-MS.

A recent article by Ceglia and colleagues (Ceglia et al., 2017) explores the potential of trace elements in discriminating between major glass recipes. More specifically, Zr/SiO_2 is plotted with Ce/La and Sr/CaO. Zr tends to be associated with heavy mineral fractions in the sand source, and it has proved to be discriminating when associated with other trace elements, like Ti (Aerts et al., 2003; Shortland et al., 2007). Ce and La are amongst the most abundant REEs; Sr and CaO ratios are indicative of the carbonaceous fraction of the sand (Ceglia et al., 2017). Investigating the combination of these ratios will not only help in defining the geochemistry of the sand source of the glass types, but potentially will discriminate between them, as they did in Ceglia and colleagues work. In Figure 75 and Figure 76 these ratios have been plotted for Comacchio glass too, together with Levantine and HIMT unrecycled reference material (Ceglia et al., 2017).

Zr/SiO_2, Ce/La, and Sr/CaO ratios are only partially discriminating for Comacchio glass. It is evident from both plots (Figure 75 and Figure 76) that only a restricted number of samples fall within expected and non-recycled Levantine and HIMT materials: group 3, group 1A, group 2A, plant ash group 4, HIMT group 8, and a small group of samples from group 2B (Com06, 18, 29, 85). Most of Comacchio samples fall within a positive array in Zr/SiO_2 vs. Sr/CaO between Levantine and Foy 2 groups using Ceglia and co-workers reference material. In addition, in Figure 76 two arrays seem to start from the Levantine end: one array positively correlated with the Foy 2 end-member in the previous graph, and another sub-group of samples from group 1 tends to higher Zr/SiO_2 ratios values associated with the HIMT recipe. This might indicate further mixing with a stronger HIMT recipe of part of Comacchio glass.

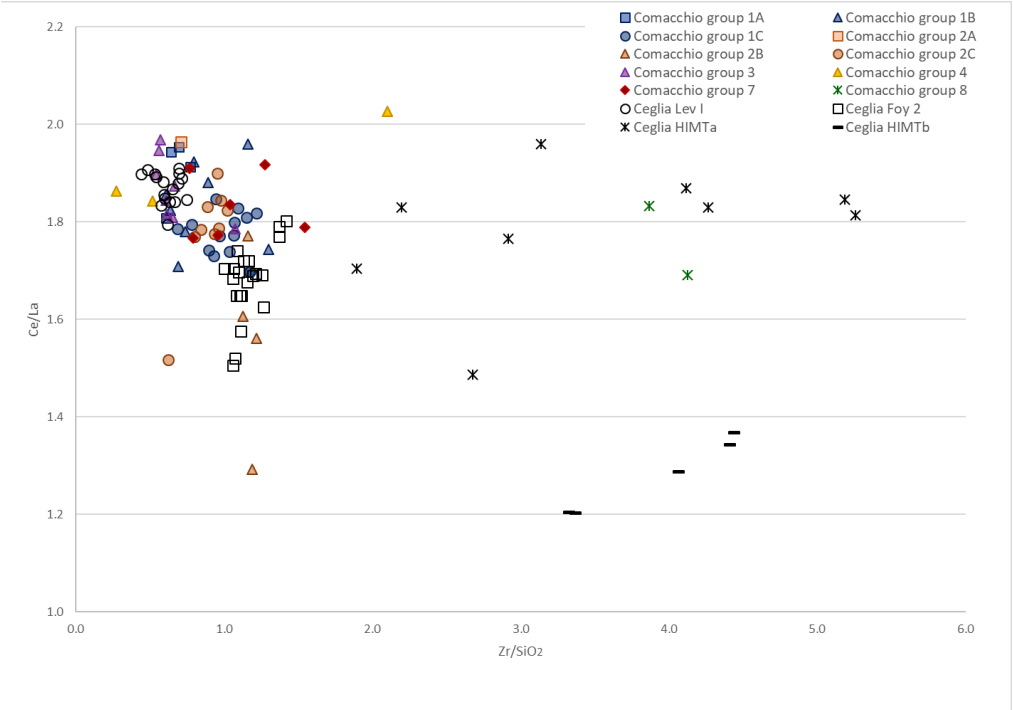


Figure 75 –Zr/SiO_2 and Ce/La ratios of Comacchio glass groups dataset. Levantine I, Foy 2, HIMTa, and HIMTb comparison materials (non-recycled) are plotted after Ceglia et al., 2017.

Mixing is less evident using Zr/SiO_2, Ce/La because the array becomes blurred at its lower end (higher Zr/SiO_2 ratio). If we take the area covered by Ceglia and colleagues' reference materials for our array, a potential end-member might be found in Foy 2 Ceglia et al.data.

Com91 (white opaque tessera) plots within the suggested Foy 2 area, but I would exclude it from such a group given it diverges using Al_2O_3 and Fe_2O_3 and is closer to group 4 - plant ash with higher MgO values (3.83wt%). Higher MgO contents in white mosaic tesserae is not unusual, but it has been suggested that plant ash could have been used to make the base glass, or potentially the addition of plant ash to natron glass (Boschetti et al., 2016, 307; 308). Therefore, it cannot be considered as pure "Foy 2" glass.

Group 8 plots within the area of influence of Ceglia HIMTa group, with a high Zr/SiO_2 ratio and higher Ce/La ratio when compared to both HIMTb and Foy2 variants of HIMT.

I cannot classify with confidence group 7 made of red samples (mosaic tessera, chunk of glass, and crucible layer), crucibles layers, and wasters, since its trace elements do not show a clear pattern, excluding the fact that they all plot in the middle area with the majority of mixed material.

Com 22 and 23 cluster within the Levantine area. Com21 instead does not adhere to the same patterns, and plots towards the HIMT area, with a higher Zr/SiO_2 ratio when compare to the rest of group 4, which agrees with already hypothesised mixed nature.

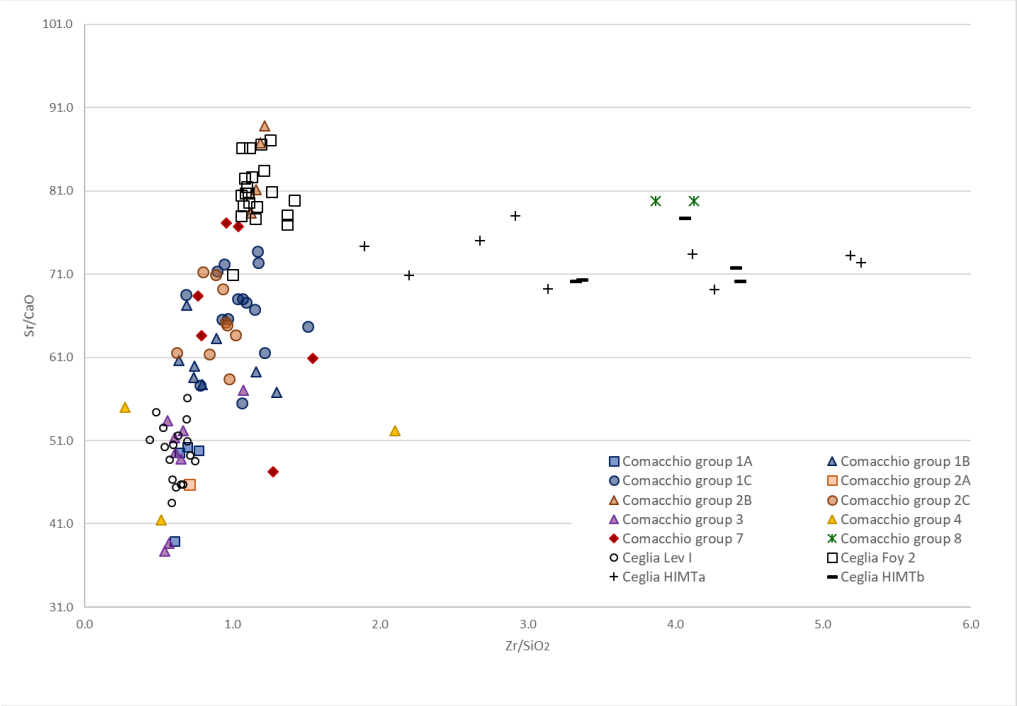


Figure 76 - Zr/SiO_2 and Sr/CaO ratios of Comacchio glass groups dataset. Levantine I, Foy 2, HIMTa, and HIMTb comparison materials (non-recycled) are plotted after Ceglia et al., 2017.

The most probable hypothesis for this compositional behaviour is that mixing practices were occurring at Comacchio between potential end members of Levantine Comacchio (groups 1A, 2A, and 3) and HIMT groups (2B and 8). When considering potential end members, we need to remember that plant ash group 4 has been dated to the 10th – 11th

centuries, later than most of Comacchio samples and the workshop supposedly active period (late 7th century - early 8th century AD). Therefore, either we need to assume that they were not available at the time of manufacture of most Comacchio glass, or a compositionally similar recipe was available at the time, or plant ash in Comacchio was made much earlier than its given chronology. Given the limited amount of both K_2O and MgO registered in most of Comacchio natron glass (Figure 61), I would exclude group 4 as an end member, or its contribution to mixing must have been minimal.

I will now describe REE (Rare earth elements) patterns for the Comacchio glass groups.

Group 3 (minus Com25, supposedly recycled given its recycling markers values over 100ppm) plots as expected within the Levantine area with higher Ce/La compared to Foy 2 recipe and the same can be said for group 1A and 2A, which supports the hypothesis of these two groups belonging to the Levantine recipe. The REE patterns (Figure 77) are higher overall in group 1A and 2B when compared to group 3, especially concerning Li and Zr and with the overall lighter REE pattern, which suggests a different mix of raw materials (sand) for all these Levantine groups. Nonetheless, when the REE patterns of different published Levantine glass are compared (Figure 78 - Comacchio Levantine groups overall agree overall with non-recycled Levantine I from Cyprus, while they shows lower REE levels when compared with Israeli material published by Phelps, which might indicate that a sand with a different REE content was used to make Comacchio glass.

Comacchio group 2 (Com 06, 18, 29, 85) -Foy 2 and group 8 - HIMT REE patterns do not coincide perfectly with Ceglia Foy 2 and HIMTa material. In Figure 79, Group 8 follows HIMTa heavy REE patterns (high Ba, Sr, and Zr), but shows overall higher values of light REE. Group 2B has similarly lower Zr, Ba, and Hf as in Foy 2, but is overall more similar in light REE patterns to HIMTa. Overall, both groups 2A and 8 seem therefore to belong to the HIMT type.

REE patterns for potentially recycled materials are described in Figure 80 and Figure 81. Group 1B and 1C have quite similar patterns, while 1C and 2C show increasing heavy and light REEs, which suggest the use of a less pure sand or it might be connected to more recycling practices. than in Levantine glasses, as showed in reference material in Figure 78 and Figure 79. Moreover, HIMT has usually a light REE pattern closer to Levantine glasses with higher absolute concentrations (Freestone et al., 2005), as showed in reference material in Figure 78 and Figure 79.

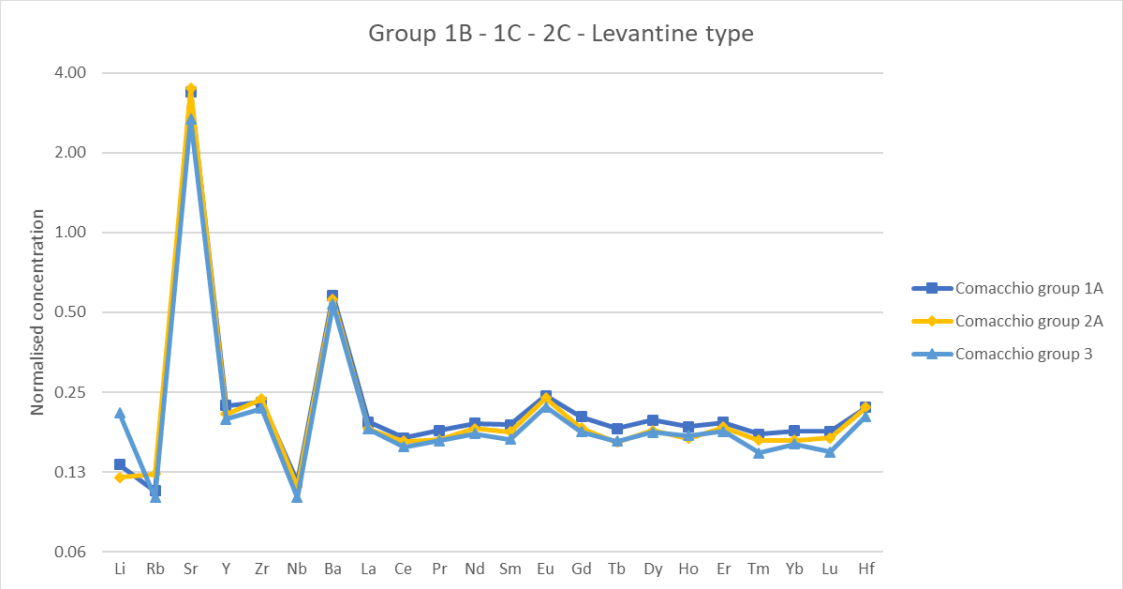


Figure 77 - Concentration of trace elements normalized to the upper continental crust (Kamber et al. 2005) for a selection of elements in group 1A, 2A, and 3 of Comacchio glass, which have been classified as Levantine I composition.

If we observe the pattern of heavy minerals, overall 1C and 2C groups both seem to be closer to HIMT parameters, with an increase of both Zr and Ba (Figure 81). Group 1B instead is closer to the Levantine I pattern for both heavy and light REE elements. I cannot separate with confidence these mixed groups from Comacchio into more defined recipes. Nonetheless, both trace elements ratios and REE patterns would suggest that groups 1B, 1C, and 2C are the results of heavy mixing between different parts of a source of HIMT glass (Foy 2) and Levantine

I, or of recycling within the same compositional group, which would produce a composition richer in impurities (such as iron oxide), and heavy minerals (for example Zr or Ba) when compared to the base glass composition.

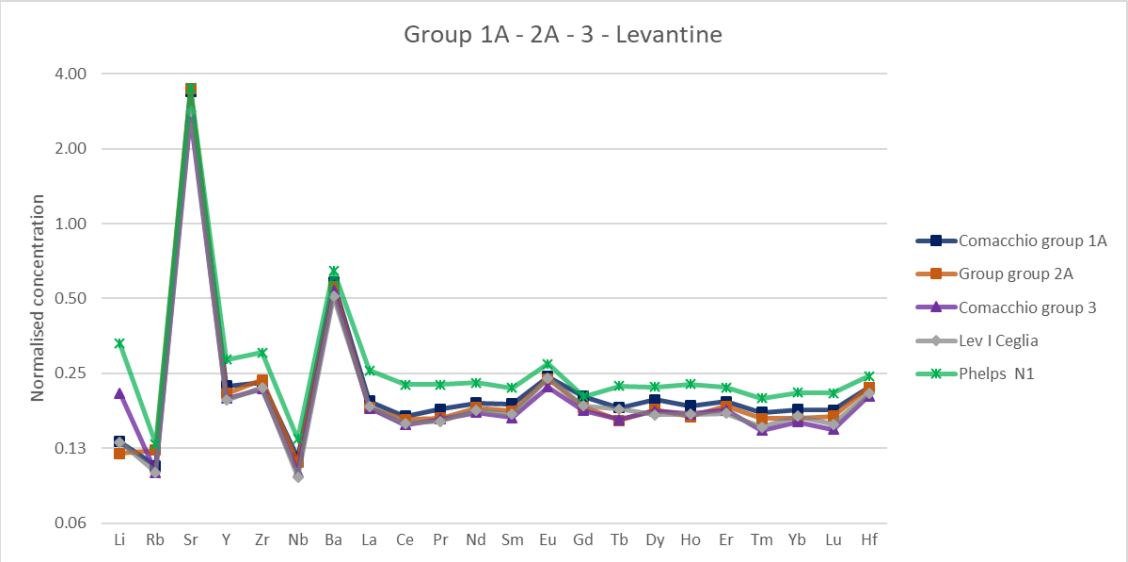


Figure 78 - Concentration of trace elements normalized to the upper continental crust (Kamber et al. 2005) for a selection of elements in group 1A, 2A, and 3 of Comacchio glass. Comparison Levantine material after Ceglia et al., 2017 and Phelps et al., 2016.

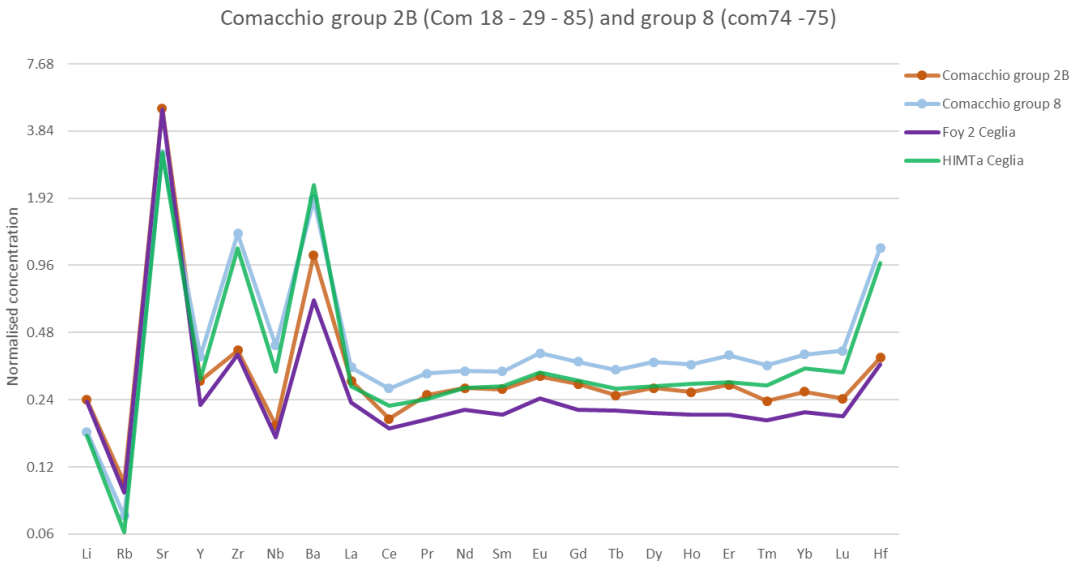


Figure 79 - Concentration of trace elements normalized to the upper continental crust (Kamber et al. 2005) for a selection of elements in Comacchio group 2B and 8. Comparison HIMT material after Ceglia et al., 2017.

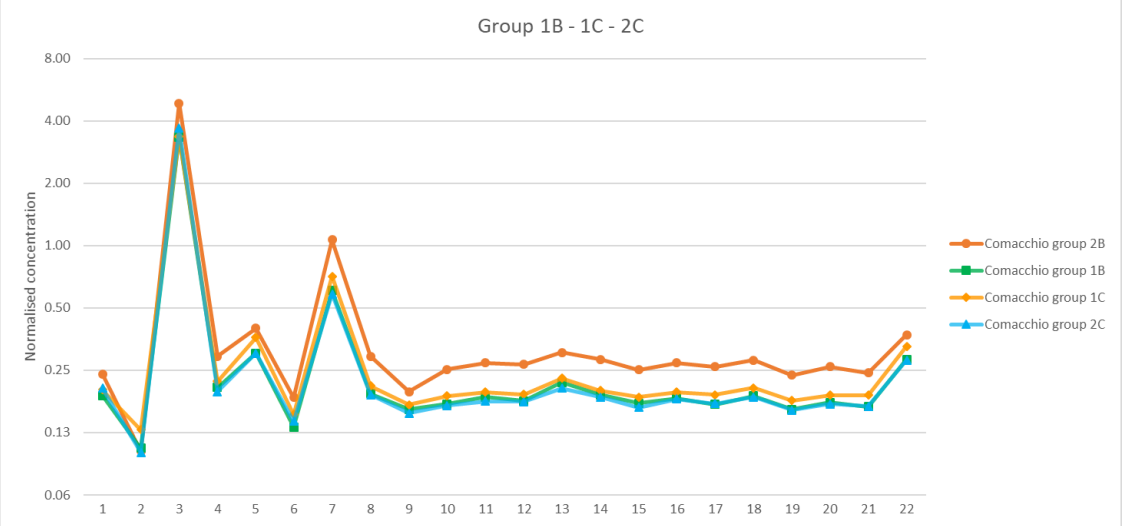


Figure 80 - Concentration of trace elements normalized to the upper continental crust (Kamber et al. 2005) for a selection of elements in Comacchio group Foy 2 (2B) and suggested mixed samples (group 1B, 1C, 2C).

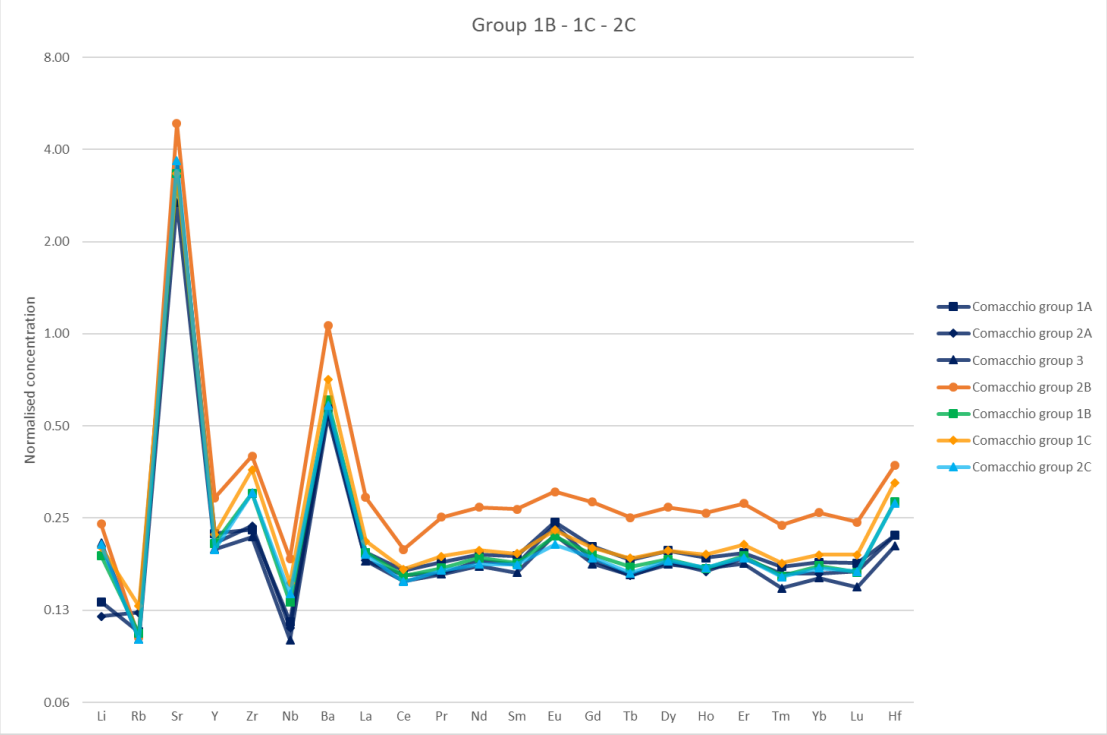


Figure 81 - Concentration of trace elements normalized to the upper continental crust (Kamber et al. 2005) for a selection of elements in Comacchio Levantine groups (1A, 2A, and 3), group Foy 2 (2B) and suggested mixed samples (group 1B, 1C, 2C).

Finally, I would like to address the area of production of Comacchio plant ash glass. Trace elements have been used recently to address the area of production of Islamic plant ash glasses from different regional production zones in the Levant, northern Syria and in Iraq/Iran (Henderson et al., 2016). Henderson and colleagues clearly demonstrated not only the existence of a differences in raw materials use and production from Western - Levant area (Cairo, Damascus, Beirut, and Khirbat-al-Minya) from Eastern glasses (Samarra, Ctesiphon, Nishapur).

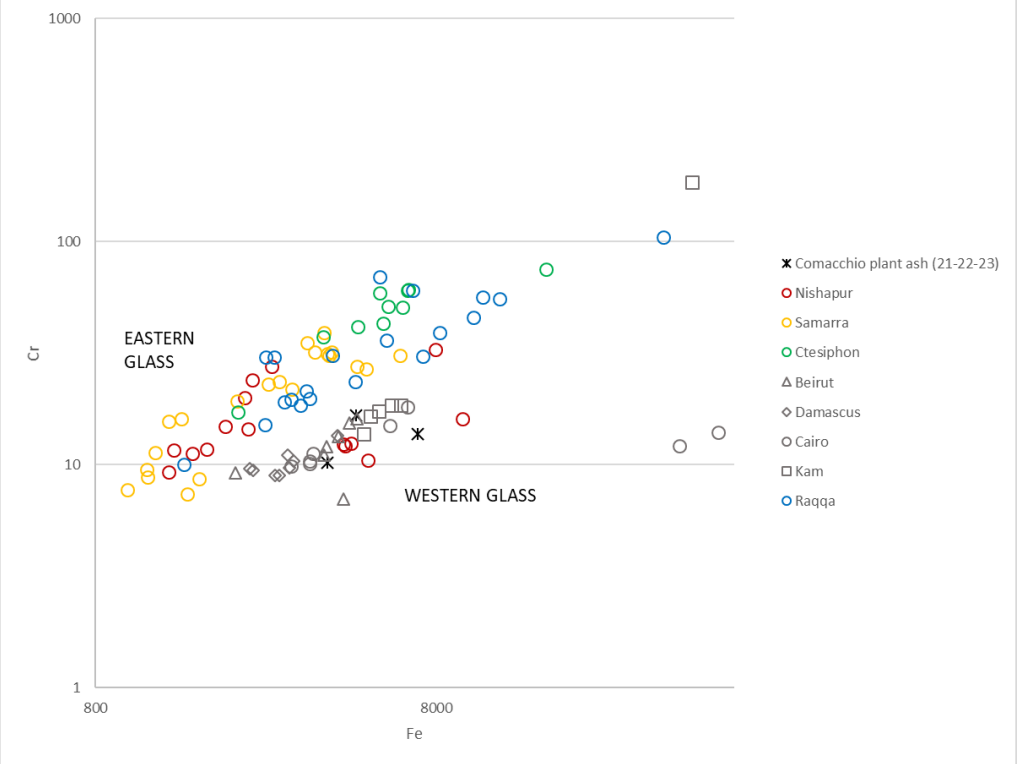


Figure 82 - Fe versus Cr concentrations (mg/kg) in Comacchio group 4 – plant ash (logarithmic scale). Comparison material after Henderson et al., 2016.

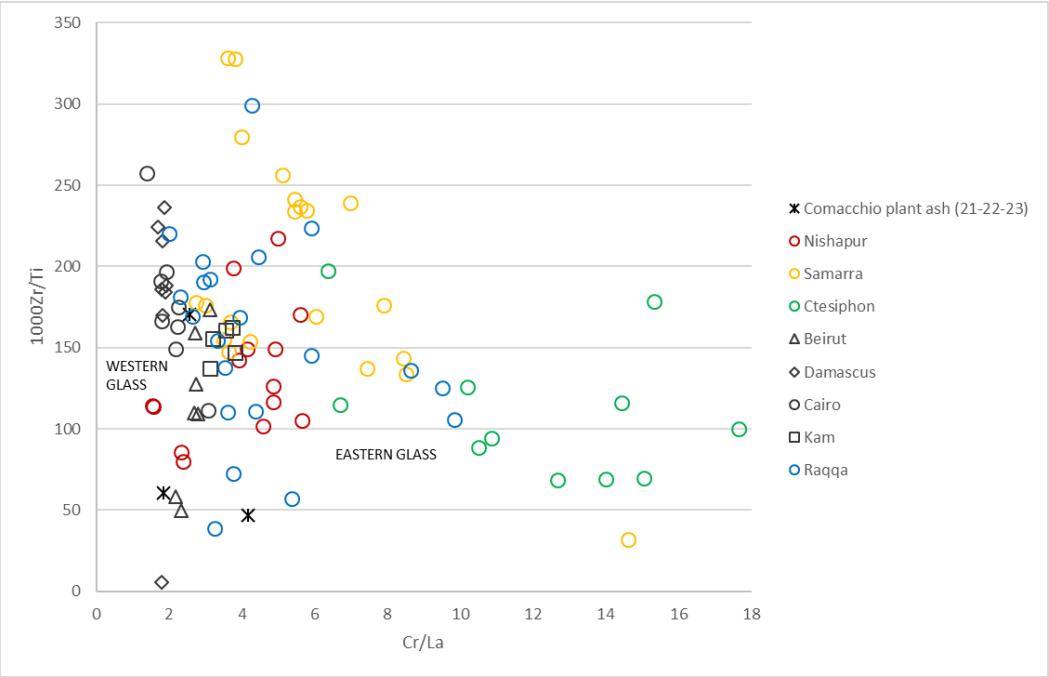


Figure 83 - Cr/La versus 1000Zr/Ti ratios in Comacchio group 4 – plant ash (logarithmic scale). Comparison material after Henderson et al., 2016.

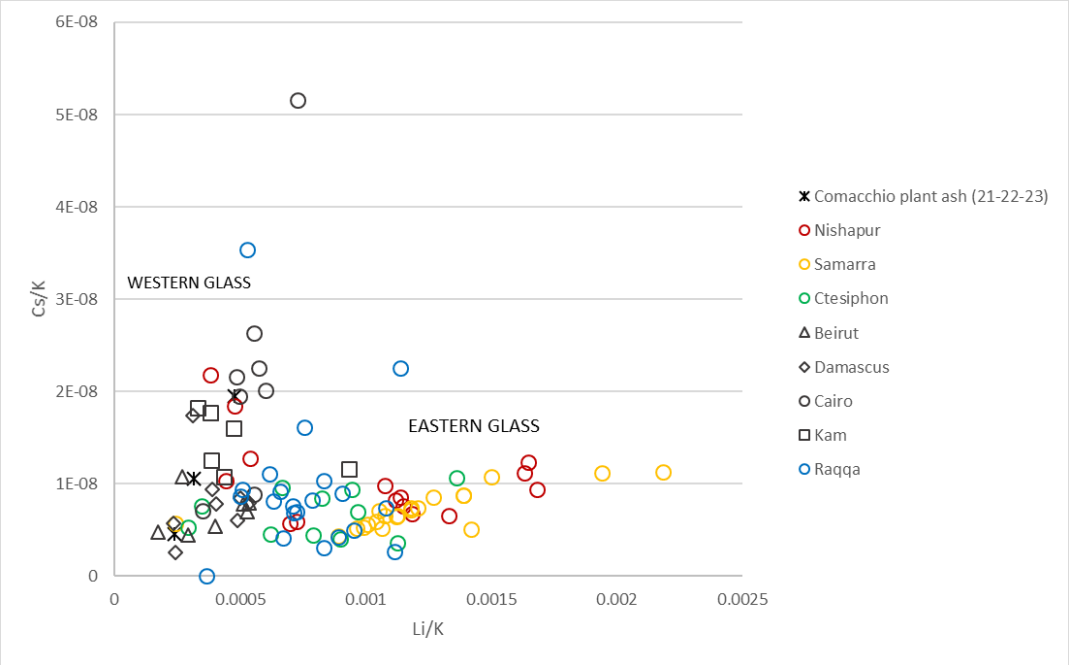


Figure 84 – Li/K versus Cs/K ratios in Comacchio group 4 – plant ash. Comparison material after Henderson et al., 2016.

Other than entering with the silica sand source as contaminant heavy minerals, trace elements can enter via the plant ash source, as substitute for K and Na as Li, Rb, and Cs (Henderson et al., 2016, 139). Cr/La vs. Zr/Ti has been already proved successful in discriminating LBA Mesopotamian from Egyptian material (Shortland et al., 2007).

Comacchio plant ash glass plot consistently in the Western plant ash area: it shows higher Fe concentration compared to its values of Cr together with all the other Western plant ash (Figure 82). A lower Ce/La ratio but paired to a lower Zr/Ti ratio (Figure 83), in opposition with the majority of other Western glasses, that overall show for the same ratio values over 100.

Finally, the Comacchio plant ash glasses overall show a lower Li/K ratio paired with variable Cs/K, consistent with the Western plant ash samples (Figure 84). Such compositional similarities in trace elements suggests that Comacchio plant ash is consistent with Western materials from Cairo, Damascus, Beirut, and Khirbat-al-Minya, and could therefore have been produced at the same primary production centres, potentially at Raqqa, Syria (Henderson et al., 2004) or Tyre, Lebanon (Aldsworth et al., 2002; Freestone, 2002).

5.1.1.5 Summary Comacchio glass types

The Comacchio glass dataset is made up by a majority of natron-based glass, including Levantine I glass and HIMT (weak and strong), plus a small group of plant ash–based glasses.

Cluster analysis proved to be only partially discriminating in Comacchio glass. Soda (Na_2O) and silica (SiO_2) together with impurities and feldspar content (Al_2O3 and Fe_2O_3) separate the Levantine (group 3) and from HIMT (group 2B and 8) in Comacchio glass, while K_2O and MgO discriminate natron-based from plant ash glass as expected. The latter

elements were also able to separate a sub-group (group 7) with increasing MgO content containing crucibles, wasters and red opaque coloured samples, associated with increasing iron oxide and titania levels. Other signs of contamination were underlined by increasing potassium oxide levels paired with increasing P_2O_5 levels in most of glasses from macro group 1 and 2, all of which can be traceable to fuel ash and crucible contamination from glass-working practices.

Cluster analysis did not help in discriminating base glass groups (3, 4, and 8) from mixed compositions (1B, 1C, 2C), neither from a variant of Levantine glass with Na_2O content closer to HIMT glass (1A and 2A), which finds parallels with AQ2 from Aquileia (Gallo et al., 2014).

On the other hand, trace elements have proved to be discriminating in the case of Comacchio, for both base and non-mixed compositions, albeit at different levels. Increasing levels of known recycling markers such Cu, Co, Pb, and Sn (>100ppm) suggest the overly recycled status of 1B, 1C, and 2C groups. Group 3 (Levantine I, minus Com25) and 4 (plant ash, minus Com21) contains fewer contaminants (in the form of colourant markers and de-colouriser), and therefore supposedly did not go through re-melting or potentially only through very limited recycling cycles.

The combination of Zr/SiO_2 and Sr/CaO ratios in particular was able to pull apart end-members from both group 1A, 2A, 2B and group 3: not only group 3 and four samples from group 2B (Com 06, 18, 29, and 85) falls within Zr/SiO_2, Ce/La, and Sr/CaO ratios of respectively Levantine I type and Foy 2 analysed by Ceglia and co-workers (2017), but most of the remaining samples from group 1 and 2 samples have for the same ratios and fallon a positive array, with the previously mentioned base groups as potential end-members, proving that mixing of Levantine and HIMT – Foy 2 glass types could have indeed occurred.

REE patterns of mixed groups plot closer to either Levantine (1B and 2C) or HIMT weak – Foy 2 (1C), which might give indication which glass is prevalent in their original compositional make up.

Group 2B are all translucent glasses, three yellow vessels and one colourless tessera; the yellow glasses do match the typical HIMT colour and they date before and within the workshop active phase (late 6th – early 8th century AD)[87]. The tessera (Com06) is dated to a much later period (10th -11th century AD).

Group 3 (6th – 8th century AD) includes only blue-green glasses, mostly vessels with one window and two chunks of glass. REE patterns matches with Ceglia - Levantine I type of glass, which suggest the Levantine I primary workshops were their primary manufacturing centres (such as 4th – 7th century Apollonia, Israel). Group 1A and 2A REE patterns match closely group 3, but they show higher Na_2O and minor content of silica: similar Levantine compositions have been registered in Aquileia glass (group AQ2, drinking vessels) dated to the late 3rd to the 6th century AD (Gallo et al., 2014, 11). On the other hand, Comacchio glass has been assigned a more recent chronology based on stratigraphy (late 6th – 7th century AD), which might indicate that such Levantine glass could have been in circulation for a long period of time.

The presence of un-recycled plant ash material (group 4) in Comacchio is limited to only two 11th century dated samples (Com22 and 23), which showed a common Fe and Cr concentration, Zr/Ti, Cr/La, Cs/K and Li/K ratios to Levantine made material from l12th – 14th century AD Damascus and Beirut glass, 8th century AD Khirbat-al-Minya glass, and finally with 14th – 15th century AD Egyptian material from Cairo analysed by Henderson and co-workers (2016). This suggests that Comacchio plant ash glass was produced with raw materials sourced in the Western area of the Middle East. The Comacchio plant ash glass does not match with 9th century AD Raqqa glass dataset ratio values, one of the primary production centres known for plant ash glass for the Early Medieval

[87] We need to consider that samples have been dated stratigraphically within a range of dates, and therefore some samples might appear older than the workshop, such as these from group 2B.

period. (Tyre would be closer in date (10-11th century AD) but no trace elements are available for that site at the moment).

Mixing practices did not involve only Levantine and HIMT recipes but also plant ash glass. Com21 – group 4 and Com14 – group 2 are a perfect example of such a practice: given their lower soda, higher silica, potash, and magnesia values (when compared to group 1 and 2), the first can be considered a base plant ash glass with the addition of some natron-based glass (potentially of the Levantine type). Com14 instead plots consistently with 2C group concerning the soda, silica, alumina, and iron oxide values, but shows a positive correlation between its potash and magnesium oxides values, which suggests a HIMT natron-based glass with the addition of small quantity of plant ash. Given the Comacchio plant ash is more recent, it can be assumed that Com14 has been mixed with a compositionally similar plant ash or group 4 has been made and traded to Comacchio earlier than its deposition date.

Averaged Empa and trace results of non-mixed groups are reported respectively in Table 7 and in Table 8.

Table 7 – Mean composition for all oxides for each of the unrecycled groups of Comacchio dataset analysed in this dissertation, excluding Com20; nd= non-detected; n/a = not applicable. Please refer to Appendix 2 for group 2A (Com20) values.

	Levantine I		HIMT weak - Foy 2		Levantine I		Plant ash		HIMIT	
	Group 1A (n= 6)		Group 2B (n=4)		Group 3 (n = 8)		Group 4 (n=2)		Group 8 (n=2)	
Element	**Average**	**Sd**	**Average**	**Sd**	**Average**	**sd**	**Average**	**sd**	**Average**	**sd**
SO_3	0.22	0.06	0.32	0.04	0.19	0.07	0.2	0.08	0.26	0.03
P_2O_5	0.11	0.04	0.12	0.02	0.07	0.03	0.32	0.05	0.06	0.02
V_2O_5	0.02	0.02	0.03	0.01	0.02	0.01	0.05	0	0.02	0
As_2O_5	0.12	0.09	0.09	0.00	0.1	0.09	nd	n/a	nd	n/a
Sb_2O_5	0.09	0.15	0.03	0.00	0.01	0.01	nd	n/a	nd	n/a
SiO_2	66.55	1.12	63.53	3.02	70.96	1.7	62.69	1.1	63.69	0.19
TiO_2	0.08	0.03	0.12	0.00	0.08	0.02	0.06	0.02	0.56	0.01
SnO_2	0.01	0.01	0.02	0.00	0.02	0.01	nd	n/a	nd	n/a
Al_2O_3	3.21	0.32	2.60	0.17	3.08	0.26	1.56	0.22	3.52	0.01
Cr_2O_3	0.01	0.00	0.01	0.00	0.01	0.01	0.01	0	0.01	0
Fe_2O_3	0.48	0.04	1.26	0.33	0.46	0.14	0.74	0.23	2.25	0.15
MgO	0.82	0.10	1.31	0.14	0.65	0.17	3.01	0.2	1.54	0.09
CaO	9.63	1.75	7.89	0.60	7.89	1.51	10.29	0.29	5.19	0.42
MnO	0.12	0.23	1.57	0.22	0.03	0.04	2.03	0.66	2.26	0.18
CoO	0.01	0.00	0.01	0.00	0.01	0.01	0.02	0	0.01	0
NiO	0.01	0.00	0.01	0.00	0.01	0	0.01	0	nd	n/a
CuO	0.19	0.34	0.04	0.01	0.02	0.02	0.02	0	0.05	0
ZnO	0.01	0.01	0.02	0.00	0.01	0.01	0.02	0	0.02	0
BaO	0.03	0.01	0.06	0.00	0.03	0.02	nd	n/a	0.05	0
PbO	0.40	0.74	0.04	0.01	0.02	0.01	nd	n/a	nd	n/a
Na_2O	17.14	0.68	17.33	1.05	14.74	0.76	11.74	0.73	18.84	0.62
K_2O	0.71	0.09	0.68	0.05	0.71	0.53	2.29	0.06	0.44	0.05
Cl	0.87	0.16	0.80	0.06	0.73	0.14	0.69	0.09	0.93	0.13

Table 8 – Mean composition for selected trace elements for each of the 4 groups of Comacchio dataset analysed in this dissertation. Please refer to Appendix 2 for group 2A (Com20) values.

	Levantine I		HIMT weak - Foy 2		Levantine I		Plant ash		HIMT	
	Group 1A (n=4)		Group 2B (n=4)		Group 3 (n=8)		Group 4 (n=2)		Group 8 (n=2)	
Element	**Average**	**Sd**	**Average**	**Sd**	**Average**	**Sd**	**Average**	**Sd**	**Average**	**Sd**
Li	3.76	0.23	6.66	0.46	5.88	3.57	6.83	2.43	3.76	0.23
B	82.72	5.49	167.89	15.86	62.12	32.83	68.63	1.73	82.72	5.49
Ti	500.99	62.90	846.43	41.15	497.53	156.61	489.22	92.88	500.99	62.90
Cr	15.03	3.06	15.66	1.06	17.52	5.79	11.98	1.76	15.03	3.06
Mn	147.98	35.07	11452.50	1332.17	911.65	1930.94	14741.17	4608.83	147.98	35.07
Fe	3229.67	559.71	9171.17	2677.46	3362.29	1432.14	5448.67	1619.00	3229.67	559.71
Rb	8.45	1.44	7.66	0.90	8.36	2.77	13.37	3.48	8.45	1.44
Sr	480.22	68.45	696.22	45.91	394.40	52.54	541.10	98.10	480.22	68.45
Y	7.10	0.60	8.79	0.95	6.44	0.48	4.77	0.97	7.10	0.60
Zr	45.56	3.93	78.74	3.42	47.31	11.27	26.87	8.32	45.56	3.93
Nb	1.76	0.23	2.80	0.13	1.66	0.36	1.60	0.16	1.76	0.23
Cs	0.08	0.01	0.15	0.04	0.09	0.07	0.23	0.15	0.08	0.01
Ba	229.93	10.64	413.79	39.64	225.60	37.18	428.12	44.88	229.93	10.64
La	6.28	0.46	8.91	1.21	6.06	0.55	4.41	1.12	6.28	0.46
Ce	11.96	1.06	13.69	0.77	11.30	0.93	8.16	2.02	11.96	1.06
Pr	1.52	0.12	2.02	0.25	1.43	0.13	0.99	0.27	1.52	0.12
Nd	6.26	0.51	8.37	1.08	5.88	0.57	4.15	1.28	6.26	0.51
Sm	1.30	0.08	1.71	0.27	1.16	0.09	0.83	0.25	1.30	0.08
Eu	0.38	0.03	0.45	0.05	0.35	0.03	0.23	0.08	0.38	0.03
Gd	1.28	0.13	1.68	0.23	1.17	0.12	0.83	0.22	1.28	0.13
Tb	0.18	0.01	0.24	0.03	0.16	0.01	0.12	0.02	0.18	0.01
Dy	1.15	0.11	1.50	0.20	1.07	0.10	0.76	0.20	1.15	0.11
Ho	0.23	0.01	0.30	0.04	0.21	0.02	0.15	0.04	0.23	0.01
Er	0.65	0.05	0.88	0.11	0.62	0.06	0.45	0.11	0.65	0.05
Tm	0.09	0.01	0.11	0.01	0.08	0.01	0.06	0.01	0.09	0.01
Yb	0.58	0.05	0.80	0.09	0.54	0.07	0.39	0.09	0.58	0.05
Lu	0.09	0.01	0.11	0.01	0.07	0.01	0.05	0.01	0.09	0.01
Hf	1.17	0.07	1.97	0.07	1.17	0.25	0.72	0.22	1.17	0.07
Th	0.87	0.07	1.25	0.05	0.85	0.17	0.78	0.01	0.87	0.07
U	0.85	0.20	1.08	0.16	1.18	0.66	0.42	0.02	0.85	0.20

5.1.2 Barking Abbey

Based on cluster analysis (Figure 85) Barking Abbey glass falls into four main branches, which further divides in 6 groups, plus two outliers (Ba 39 and 52, respectively group 5 and 6).

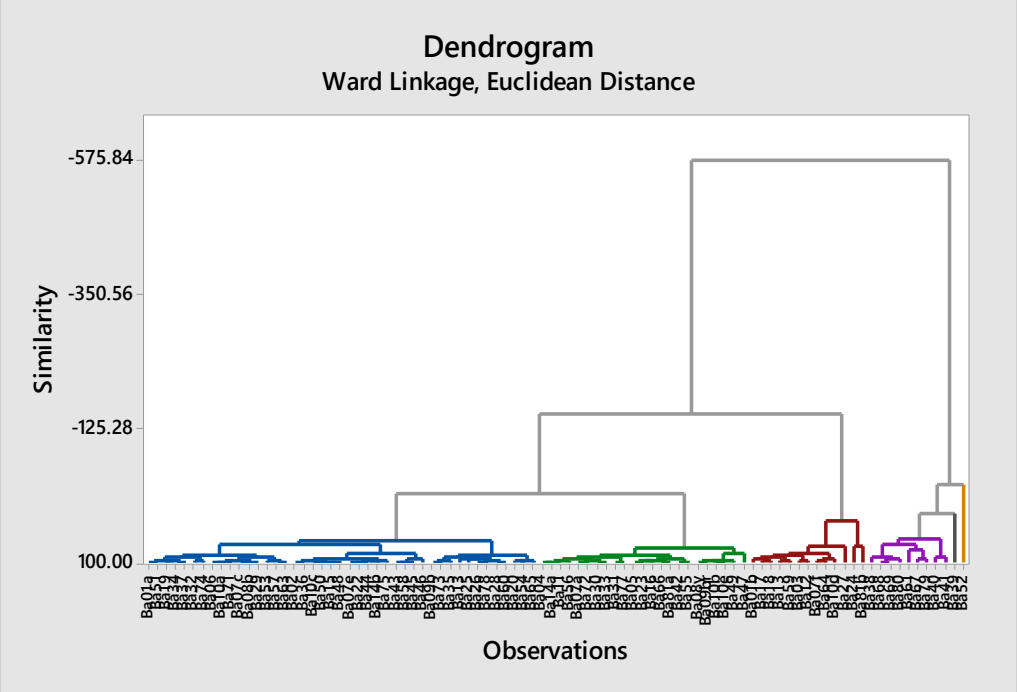


Figure 85 - Cluster analysis (Ward's method, Euclidean distance) distinguish 6 principal groupings of samples in Barking Abbey glass. Determining oxides: SiO_2, TiO_2, Al_2O_3, Fe_2O_3, CaO, and NaO_2. (N= 91; Ba39 and 52 will be removed from the following plots because outliers).

The same groups can be plotted by PCA. Based on Figure 86, principal component 1 in Comacchio glass shows positive coefficients for SiO_2, Na_2O, and CaO. On the other hand, Principal component 2 is positively correlated with Fe_2O_3 and to a lesser extent to CaO.

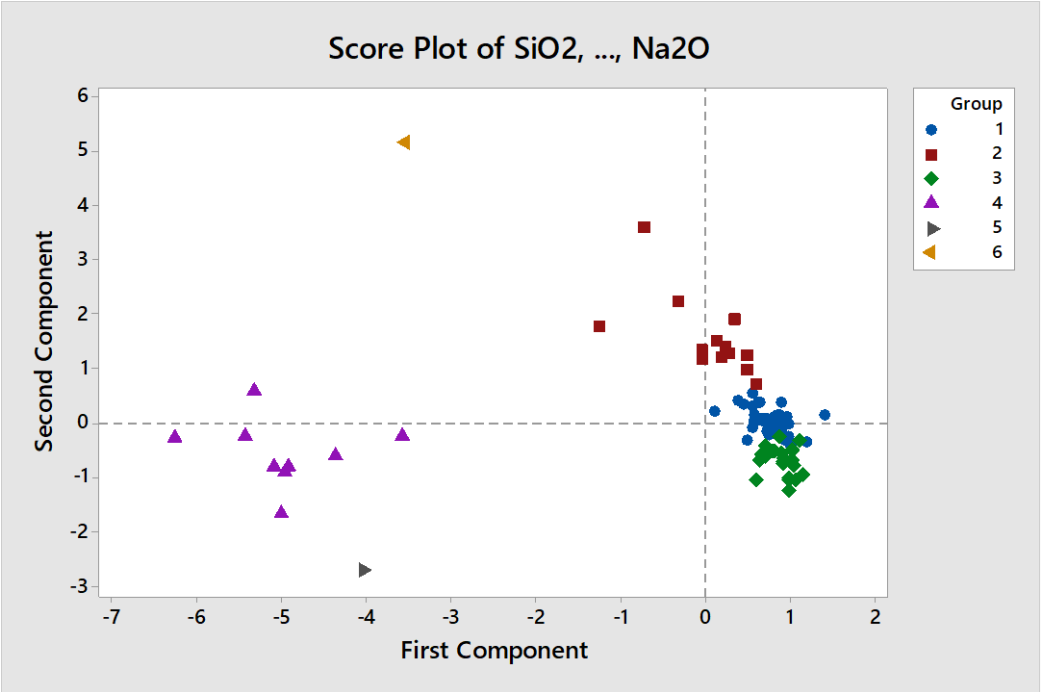


Figure 86 - PCA bi-plot of Pca 1 and Pca 2 of Barking Abbey glass dataset. Determining oxides: SiO_2, TiO_2, Al_2O_3, Fe_2O_3, CaO, and NaO_2. Group labels are based on cluster analysis (see this section, Figure 85).Figure 86 - PCA bi-plot of Pca 1 and Pca 2 of Barking Abbey glass dataset. Determining oxides: SiO2, TiO2, Al2O3, Fe2O3, CaO, and NaO2. Group labels are based on cluster analysis (see this section,

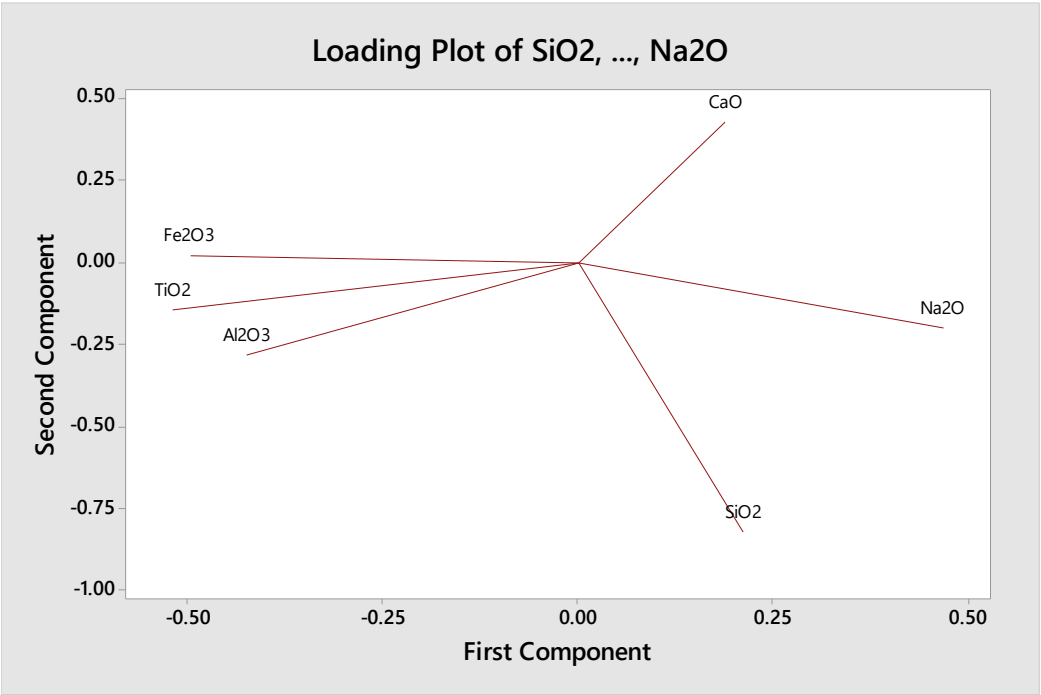


Figure 87 - The length and direction of the vectors show the contribution of each variable to the principal components 1 and 2. Principal component 1 in Barking Abbey glass has positive coefficients for SiO_2, Na_2O, and CaO. Principal component 2 is positively correlated with Fe_2O_3 and to a lesser extent to CaO.

5.1.2.1 EMPA

In Figure 86, Group 1, 2, and 3 divide based on their contents of CaO, SiO_2 and Na_2O: group 2 has potentially a higher Fe_2O_3, TiO_2, and Al_2O_3 content compared with 1 and 3. Group 4 in Barking Abbey glass cluster separately from group 1, 2, and 3 with lower values in both CaO, Na_2O, and SiO_2 to a lesser extent. On the other hand, it shows high contents of Al_2O_3, Fe_2O_3, and TiO_2 compared to the other groups.

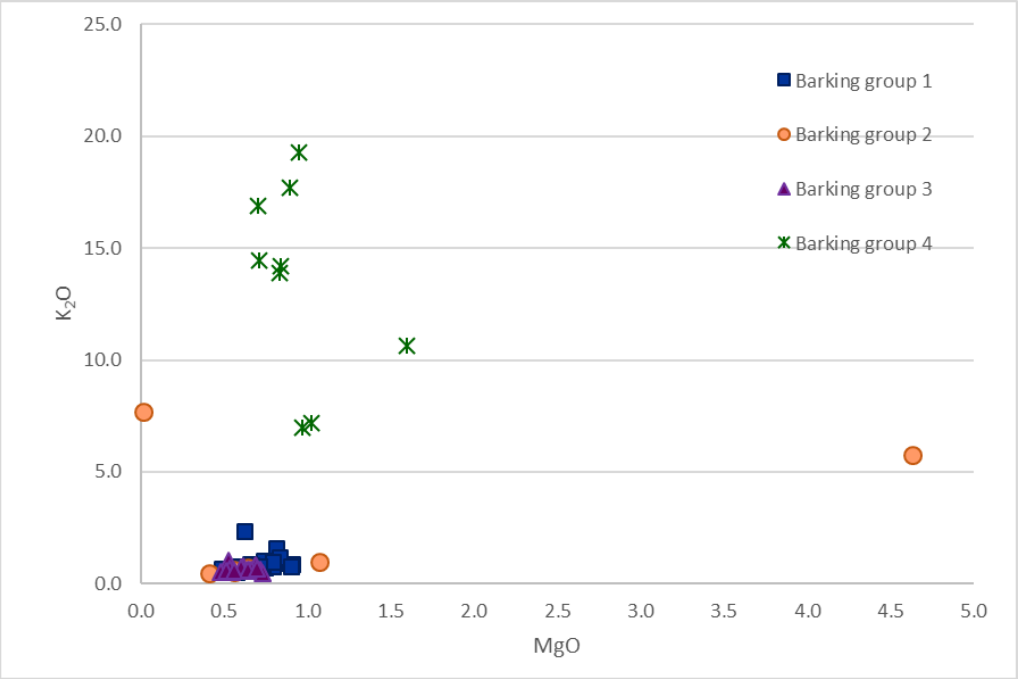


Figure 88 - MgO versus K_2O contents for glass from Barking Abbey divided by groups based on cluster analysis.

The majority of Barking Abbey glass falls within the natron glass limits (0.54wt% - 1.18wt% for K_2O; 0.48wt% - 0.96%wt for MgO), as showed in Figure 88 and Figure 89. Two samples from group 1, Ba13 and Ba43, show relatively higher potassium oxide values (respectively 1.59wt% and 2.34wt%) when compared to the major cluster.

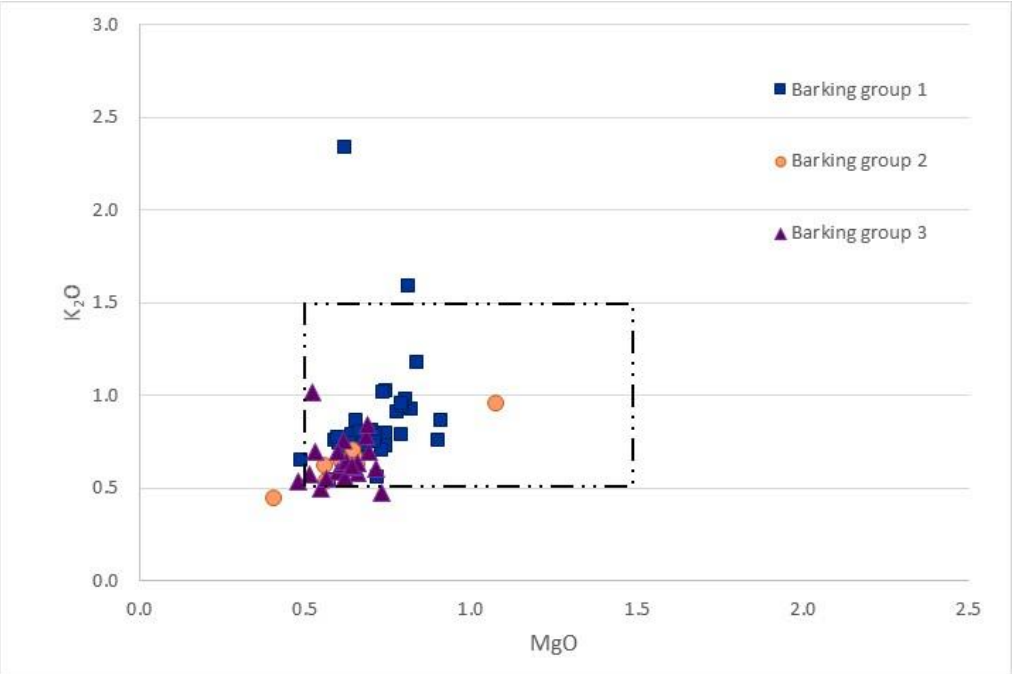


Figure 89 - MgO versus K_2O contents for glass from Barking Abbey glass divided by groups based on cluster analysis: in this picture, group 4 and two outliers (Ba24 and 27) have been taken out to underline group 1, 2, and 3 MgO and K_2O contents.

A couple of outliers in group 2 do not fit the natron glass parameters: Ba 24 has minimal MgO content (0.01wt%), while Ba27 shows instead much higher contents of both MgO (4.63wt%) and K_2O (5.74wt%).

Group 4 shows high levels of potassium oxides (> 5wt%), but MgO is still within natron parameters (0.70wt% - 1.60wt%).

SiO_2 and Na_2O contents (Figure 90) reveal a potential sand source between the three natron groups in Barking Abbey. Group 1 and 3 have the same level of Na_2O, but different silica contents, with Group 3 having over 70wt% of SiO_2. On the other hand, group 1 is stable between c. 65wt% and 70wt%. Group 2 is the one with the lowest amount of silica, with values between 58.69wt% and 64.80wt%.

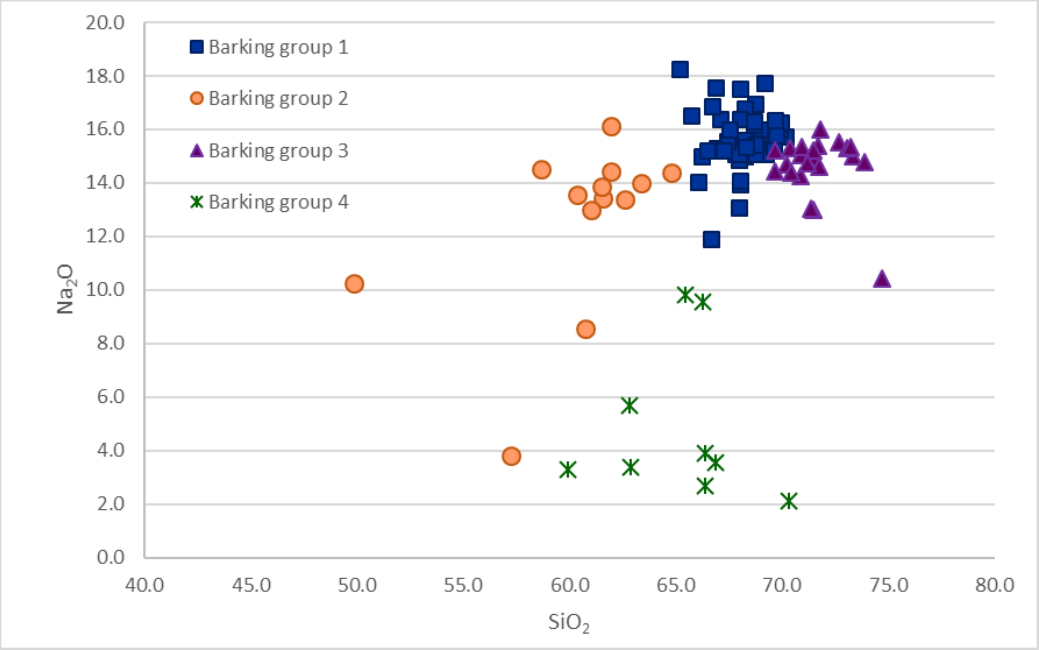


Figure 90 - SiO_2 versus Na_2O contents for glass from Barking Abbey glass divided by groups based on cluster analysis.

Group 4 plots quite separately from the other three natron groups, with the lowest values of Na_2O of all Barking glasses: the majority of them with less than 8wt%. Ba 40 and 41 from group 2 show values closer to the natron groups, with respectively 9.81wt% and 9.56wt%.

Ba24 and Ba27 plot closer to group 4, with similar Na_2O values respectively of 3.84wt% and 8.56wt%. Ba81b from group 2 plots on its own with 49.88wt% SiO_2 and 10.25wt% N_2O.

Lime and alumina content are plotted in Figure 91 and Figure 92. Group 4 has lower lime content compared to the other three groups (c. <5.0wt%), but relatively high alumina (>4.73wt%). Figure 92 allows one to discern the differences in lime and alumina contents of all three natron groups. Group 1 and 3 show similar levels of CaO (>7.0wt%) but Al_2O_3 patterns behave differently: group 3 shows a tendency towards high Al_2O_3 variation content (>2.86wt%< 3.34wt%), while group 1 overall tends towards relatively lower levels of Al_2O_3.

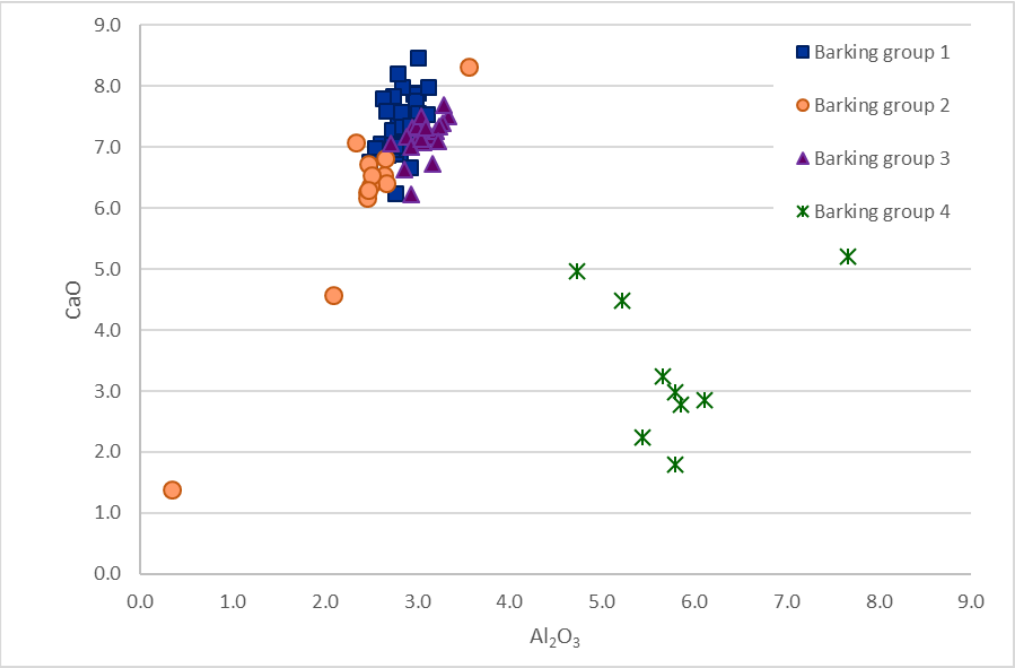


Figure 91 - Al_2O_3 versus CaO contents for glass from Barking Abbey glass divided by groups based on cluster analysis.

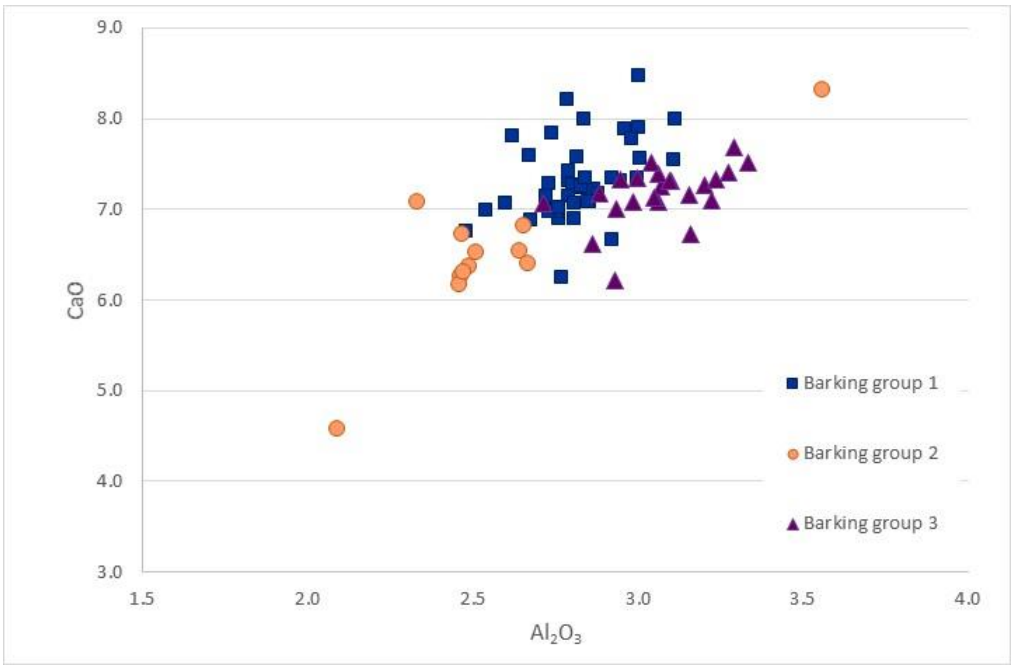


Figure 92 - Al_2O_3 versus CaO contents for glass from Barking Abbey glass divided by groups based on cluster analysis. Group 4 has been taken out to focus group 1, 2, and 3 Al_2O_3 and CaO contents.

Group 2 divides in two small groups of samples, but overall it shows a minimal variation when compared to group 1 and 3, with lower levels of both Al_2O_3 (>2.46wt%< 2.67wt%) and CaO ((>6.16wt%< 6.53wt%). Ba27 and Ba81b do not plot together with group 2 but show respectively higher levels of both CaO and Al_2O_3 (8.31wt% and 3.56wt%), and lower levels of both CaO Al_2O_3 (4.58wt% and 2.09wt%).

Finally, in Figure 93 and Figure 94 the contents of both alumina and iron oxides are plotted.

Group 4 clusters separately compared to the other natron groups, with very high levels of both Al_2O_3 (c. >4.5wt%) and Fe_2O_3 (> 2.97wt%). In Figure 94, the three natron groups are compared together.

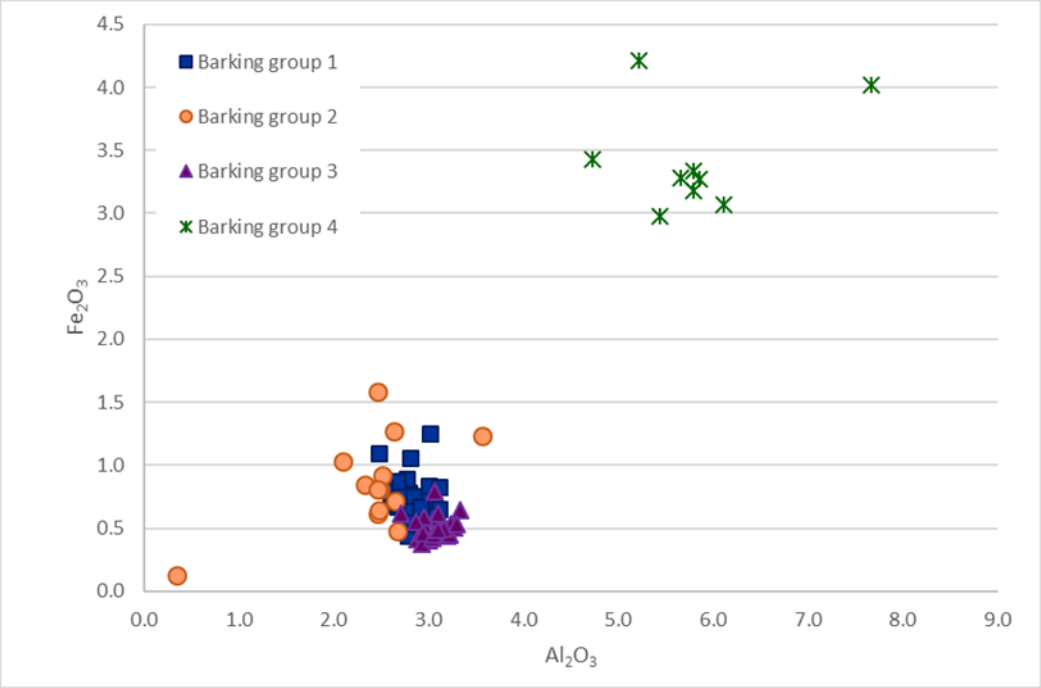


Figure 93 - Al_2O_3 versus Fe_2O_3 contents for glass from Barking Abbey glass divided by groups based on cluster analysis.

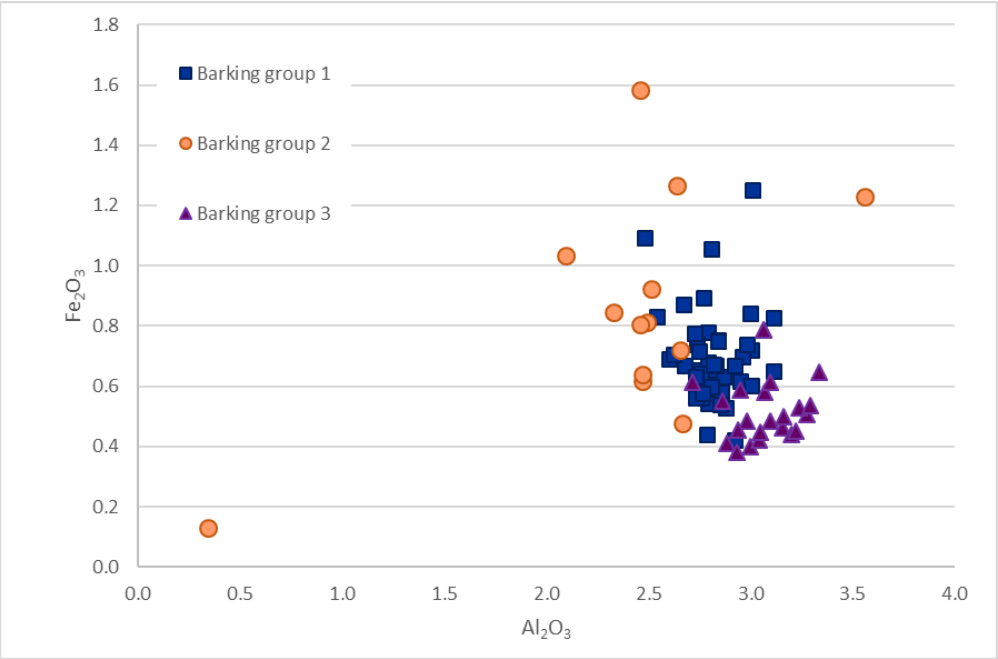


Figure 94 - Al_2O_3 versus CaO contents for glass from Barking Abbey glass divided by groups based on cluster analysis. Group 4 has been taken out to underline group 1, 2, and 3 Al_2O_3 and CaO contents.

Overall group 1 has quite tight contents of both oxides, ranging from 2.60wt% and 3.11wt% for Al_2O_3 and 0.53wt% and 0.78wt% for Fe_2O_3. On the other hand, a small sub-group of samples shows higher values of Fe2O3 (>0.8wt%) compared to the main group 1, similar to some samples from group 2.

Finally, group 3 splits in two sub-groups: the first has quite tight values of both Al_2O_3 (between 2.88wt% and 3.29wt%) and Fe_2O_3 (between 0.38wt% and 0.54wt%), while the second sub-group differ from the first one because of its higher Fe_2O_3 contents (between 0.55wt% and 0.79wt%).

Group 2 shows quite variable contents of both oxides, in particular with Fe_2O_3 contents, between 0.48wt% and 1.58wt%; Al_2O_3 contents do not show the same variation as Fe_2O_3 (between 2.09wt% and 2.64wt%).

Ba24 and Ba 27 are both clearly distinct from other sample in group 2: Ba24 with relatively low Al_2O_3 (0.34w%) and Fe_2O_3 (0.13wt%), while

Ba27 to the contrary shows much higher contents of both oxides (respectively 3.56wt% Al_2O_3 and 1.23wt% for Fe_2O_3).

Colour

When compared to the Comacchio dataset, Barking Abbey translucent samples reveal a greater variability of translucent colours: they range from amber, to blue-green, green and olive green, colourless, yellow, and blue glasses (copper- dark- cobalt blue). Blue-green glass at Barking Abbey, is limited compared to Comacchio: even in this case, their characteristic blue-green tinge is most likely the result of the interaction of iron oxide and sulphur with an oxidising atmosphere: Fe_2O_3 ranging between 0.41wt% to 3.18wt% and SO_3 from 0.01wt% to 0.26wt%.

Twelve samples show different shades (dark or bright)[88] of amber colour. Amber is the combination of ferric iron and sulphur (very little is required) in a strong reduced melt (Brill, 1988, 272). Addition of manganese oxide can counteract the Fe^{3+} action and suppress the amber colour as result, but the low MnO content in these Barking Abbey samples (0.01wt% to 0.38wt)[89] was not enough to neutralise the Fe_2O_3 (0.50wt% to 1.25wt%) and SO_3 (0.06wt% to 0.18wt%) influence on their final colour.

Oxidised copper oxide is responsible for the intense copper blue colour in thirteen samples (CuO 1.73wt% - 4.75wt%). Cobalt-bearing minerals must be responsible for the cobalt-blue colour in Ba 65, with 0.07wt% of cobalt oxide content.

The interaction between higher concentration of iron oxide (0.60wt% - 2.55wt%) and lower levels of sulphur (0.09wt% -0.10wt%) an oxidising

[88] Samples characterised by a darker shade of amber have been registered in the Appendix1 by "Amber-dark blue" definition, because their colour can only be discerned by observing it by transmitted light.

[89] Julian Henderson, personal communication.

atmosphere resulted in an olive-green colour in five samples. A combination of Fe_2O_3 (0.46wt% and 0.54wt%) and SO_3 (0.10wt% and 0.08wt%) together with oxidising atmosphere caused the yellow colour in Ba08y and Ba72 samples.

Four colourless glasses (Ba24, 29, 46 47) do not apparently show either enough Sb_2O_5 (0.01-0.02wt%) or MnO (0.02wt% - 0.22wt%) to act as decolourisers in their composition. Further analysis though shows that Ba24 and 29 have Mn contents respectively of 1170 ppm and 1755.67 ppm, leaving manganese as potentially its principal de-colouriser agent in at least these two samples.

Opaque shades of glass include white, copper blue and light blue opaque glass.

No antimony oxide is present in the white opaque samples, but instead tin compounds are used as opacifiers (1.04wt% - 6.91wt%), save Ba05, for which both opacifiers are below the detection limit. Equally, copper-blue opaque samples show no antimony oxides content, but elevated tin oxide (0.18wt – 2.32wt%), which would point to the latter being the opacifier (as suggested for the white opaque samples), paired with elevated CuO values (1.91wt% - 2.68wt%), which could be responsible for the blue colour.

The same can be said for the only blue-green opaque sample (Ba15) with Sn_2O_5 around 0.88wt and CuO around 1.90wt%.

5.1.2.2 Further considerations and comparison with published materials.

I will discuss the different types based on their average values and suggest types similarities based on their EMPA results.

Group 1 is low-alkali natron glass with relatively tighter soda values compared to group 1 (c.14-16wt% against c. 14-18wt%). It also shows lower Fe_2O_3 (c.0.40-0.60wt% compared to c.0.50-0.80wt%) and TiO_2 (<0.01wt% against c. 0.05-0.15wt%) and MnO (c. 0.20wt%) values. In addition, group 3 does not show a positive correlation between Fe_2O_3 and TiO_2 (Figure 95). The majority of group 3 has a relatively high silica (71.61wt%) and alumina around 3.07wt%, which would suggest the use of a mature high silica sand with a significant feldspar content.

On the other hand, Fe_2O_3 and TiO_2 in group 1 do positively correlate, but their correlation is still weak compared to proper HIMT glass; in addition, their content of both MnO (c. wt%), MgO (c. wt%) are too low to be considered HIMT. Group 2 constitutes a small low-alkali group formed by mostly white opaque glasses with the lowest silica (60.44wt%) values of the whole dataset paired with low Al_2O_3 (2.40wt%) and CaO (6.12wt%). In addition, their contents of Fe_2O_3 and TiO_2 are negatively correlate[90], and therefore both oxide contents have been included in the base recipes as a heavy mineral fraction from the same sand source. On the other hand, the negative correlation allows HIMT glass to be excluded as their base glass composition.

[90] Titanium oxide results from the second run of analysis as to be consider as a semi-quantitative result, as seen in section 4.2.2.1.

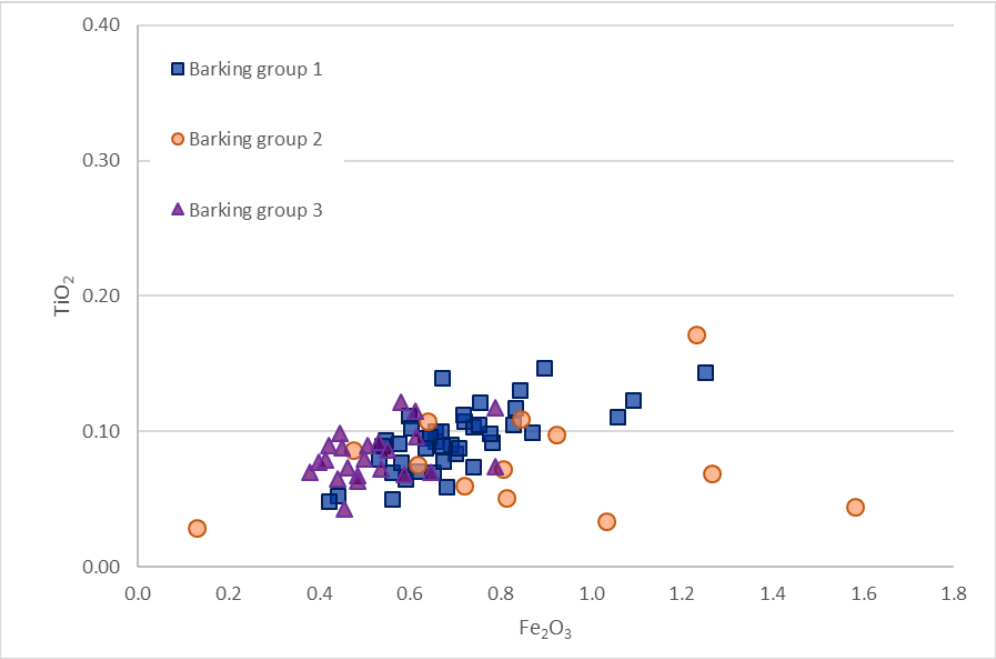


Figure 95 –Fe_2O_3 versus TiO_2 contents for Group 1, 2, and 3 from Barking Abbey.

Given that they do not adhere to the HIMT parameters, my hypothesis is that group 3 and 1 share a similar base glass which, considering their level of iron oxide and alumina, is closer to Levantine I, with group 3 being the closest of the two. The nature of group 2 glass is instead less certain, given the high content of opacifier (in form of tin compounds) and other contaminants (like PbO c. 10wt%) which modify their basic compositions.

A good portion of Barking Abbey glass is strongly coloured or opaque, with high levels of copper, tin oxide, and lead oxide in particular. Hence, when EMPA analysis are considered, the colourant and opacifier fractions included in the final recipe must have influenced the final major elements total for each group.

I think this could it be the case of Barking Abbey glass, and most specifically the colourant and opacifiers fractions would have affected the final silica percentage, as showed in Figure 90. If colourants and opacifiers influence the final Empa analysis result, it also implies that major elements are not sufficient in discriminating accurately the natron-

based groups at Barking Abbey. I will address the impact of colourants and opacifiers on the base composition in the recycling section.

Group 4 major values are the most unexpected of the whole dataset. Based on their high potassium oxide (>5.0wt%) and P_2O_5 (c. 0.20-30wt%) I would suggest some type of high alkali-based glass, such as wood ash or plant ash. When compared to the latter, group 4 has low MgO (0.95wt%) when compared to plant ash glass expected value (Figure 88). The same can be said for calcium oxide and soda contents, respectively c. 2-5wt% and c.2-10wt%wt% , while 8th – 9th century AD plant ash from Raqqa would be around 13.70wt% Na_2O and 8.51wt% CaO (Henderson et al., 2004, table 2, 453).

On the contrary alumina (c. 5-6wt%) and iron oxide (> 3.0wt%) are both much higher content when compared to the same plant ash, which would attest respectively to 1.17wt% and to 0.55wt% (Henderson et al., 2004, table 2, 453). A different source of silica (rich in impurities) might have been used, closer to sand rather than quartz, but the low manganese oxide (0.95wt%) content still needs to be explained. High levels of both Al_2O3 and Fe_2O_3 would be traceable also to crucible contamination.

Another possible interpretation would be that group 4 would belong to early wood-ash such as the one produced North of the Alps (Wedepohl, 1997, table 2, 249), but Barking samples are not comparable in most of their major oxides, especially alumina, calcium oxides, soda, phosphorus, and magnesium oxide.

Finally, it is possible that instead of plant ash, saltpetre (KNO_3) has been used as mineral source for potash, which would agree with the fairly low levels of MgO in group 4 (Brill, 1995; Li, 1999; Dussubieux, 2016), In this case, group 4 would be classified as potash glass with low lime and high alumina, which is typically found in South and South-East Asia.

In order to help further classifying these types, I decided to compare them with published literature. Group 3 can be characterised as Levantine I given its high silica values, low impurities associated to significant

feldspar content together with relatively higher alumina. I would not define group 1 as HIMT, because it lacks the characteristic high content in iron oxide, titania, and manganese oxide necessary to call it HIMT. It also does not fall within any weak HIMT values in any of the graphs that I presented. I suggest instead that group 1 should be classified as another type of Levantine I glass with overall higher values of both titania and iron oxide.

In Figure 96 and Figure 97 group 1 and 3 levels of iron oxide, alumina, silica, and soda are compared with two different types of Levantine I glass, Foy 3 (Foy et al., 2003) and N-1 type (Phelps et al., 2016). In both graphs it can be observed that both groups 1 and 3 fall overall within the values of both recipes, save for a sub-group of group 1 that shows more elevated iron oxides values (c. >0.70wt%). The Fe_2O_3 increment it is not specifically associated to any particular colour or opacifier; I suggest that it might be connected with a build-up of impurities in the recipe through repetitive recycling processes.

A similar pattern is registered when soda and silica are considered (Figure 97). Group 3 Barking glass plots within both Levantine I limits, while group 1 instead does not show the same soda-silica combination, even though it still falls within Foy 3 - Levantine parameters.

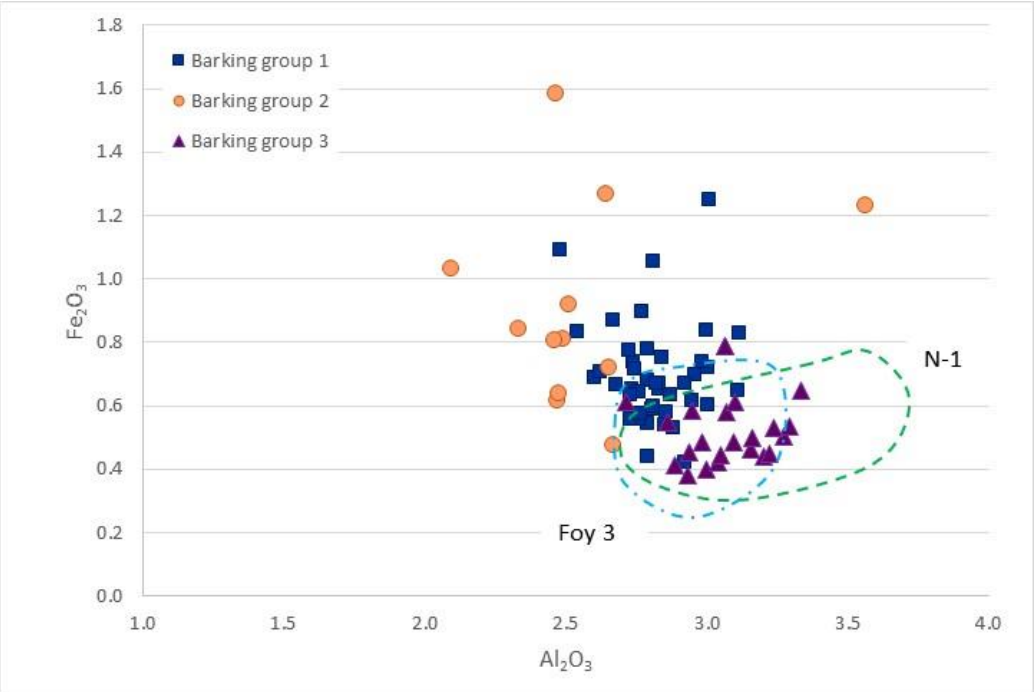


Figure 96 – Al_2O_3 versus Fe_2O_3 contents for Barking Abbey group 1 and 3. Comparable data: N-1-Levantine I from the Palestinian area (7th – 8th century AD), after Phelps et al., 2016; Foy 3 - Levantine type glass (7th – 8th century AD), after Foy et al., 2003.

Barking group 1 could indeed form a group closer to other types of Levantine glasses, like for example Foy 3 or, as suggested previously, the colourant and opacifier fractions intake from diluting group 1 with other glass (potentially strongly coloured or better opaque glass) would have affected the final silica percentage and impurities intake (such as iron oxide) together with elevated tin and lead oxides levels. Nonetheless, its base glass would remain Levantine formula, but group 1 would have been diluted with strongly coloured or opaque glass with a similar compositional major elements pattern, resulting in the heavy mixed and recycled group 1.

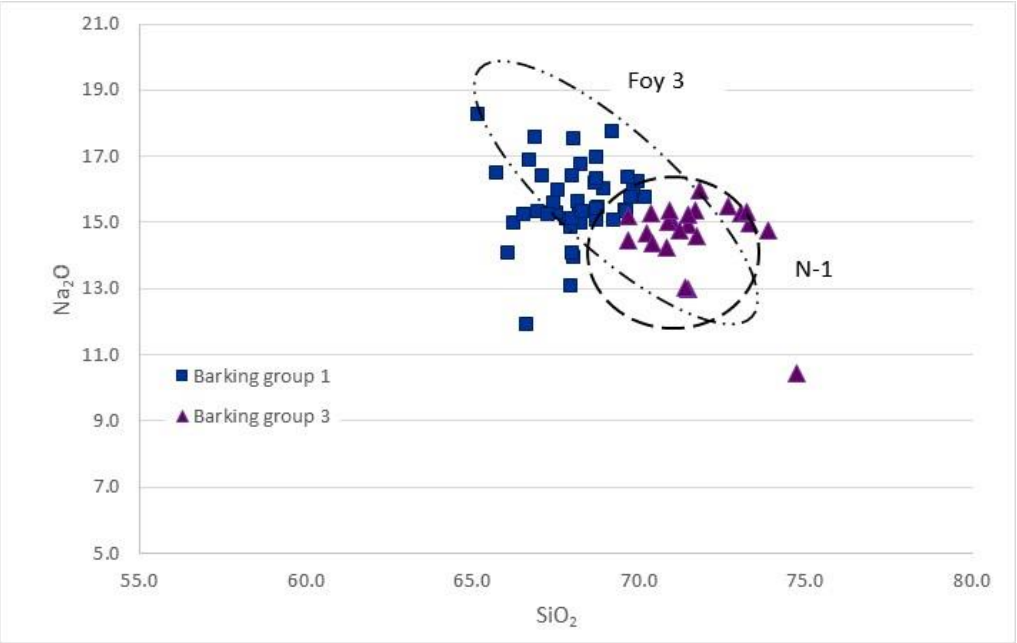


Figure 97 –SiO_2 versus Na_2O contents for Barking Abbey group 1 and 3. Comparable data: N-1-Levantine I from the Palestinian area (7th – 8th century AD), after Phelps et al., 2016; Foy 3 - Levantine type glass (late 7th – early 8th century AD), after Foy et al., 2003.

The presence of Levantine glass in Anglo-Saxon glass is not a surprise. As Willmott and Welham mention that Anglo-Saxon Glastonbury glass "the Glastonbury glass contains alumina levels that are generally higher than would be expected from the Roman vessels and fits closer with the groupings of material from the production centres of Levantine I and Bet Eli'ezer" (2015, 236), although no compositional data are included in the publication.

Barking glass is compositionally similar in silica, soda, calcium, and alumina contents with other coeval glass from Britain (Figure 98). While no compositional classification has been suggested until now for glass from Hamwic beyond confirming that is natron-based (Hunter and Heyworth, 1998, 42), Brill (2006) and Freestone with Hughes (2006) have further commented on Jarrow and Wearmouth glass. Freestone and Hughes not only hypothesised for both sites a Levantine based glass, but

they acknowledged the higher content of both titania and iron oxide[91], which could be due to the introduction of HIMT (Freestone and Hughes, 2006, 148; 153). Nonetheless, their glass does not contain elevated lead and tin oxides, in contrast to group 1 and 3 at Barking, an occurrence that would still support the dilution with opaque/strongly recycled glass hypothesis.

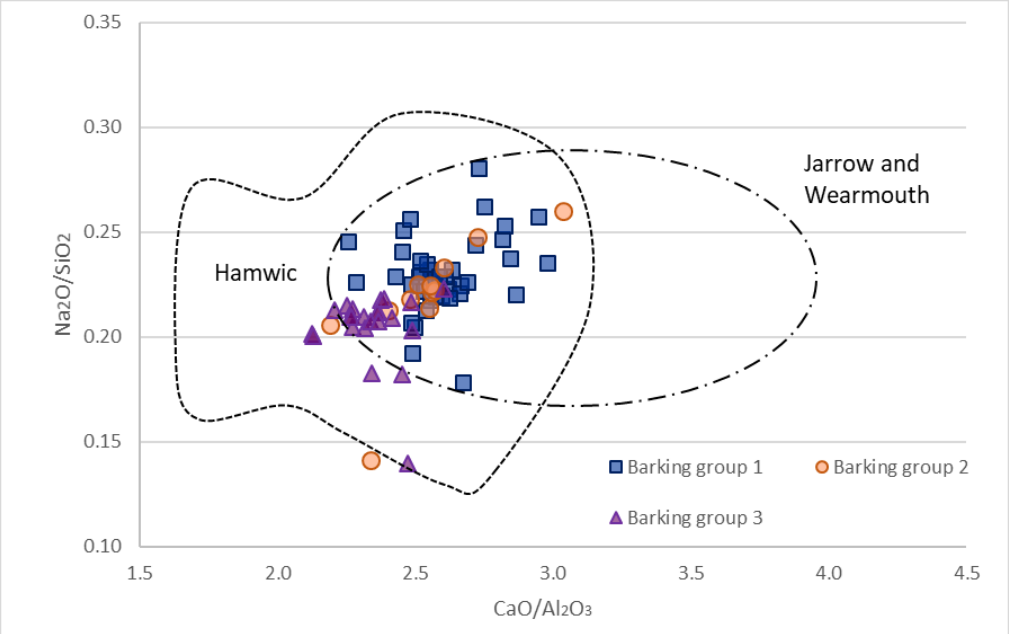


Figure 98 - CaO/Al_2O_3 versus Na_2O/SiO_2 ratios for Barking Abbey groups based on cluster analysis. Comparable data: 8th-9th century AD Hamwic after Hunter and Heyworth, 1998, 74-97; Jarrow and Wearmouth Anglo-Saxon glass after Brill, 2006, 130-1.

Finally, I would like to address the nature of group 4. If the three-hypothetical potash glasses are compared in a bi-plot of CaO/Al_2O_3 against Na_2O/SiO_2, potash-silica glass from China is the closest match for Barking Abbey high-K low lime high alumina group (Figure 99). 8th - 11th century AD plant ash glass from Raqqa does shows relatively higher values in both ratios while most of 9th -11th century wood-ash glass from

[91] An increment in iron oxide and titania levels was also previously acknowledged by Sanderson and colleagues (1984) concerning their work on early Medieval glass from Britain.

Germany is comparable for soda/silica ratios, but the carbonate and feldspar ratio results are much higher (c. 2.0 – 14.0). Early wood ash has a high variability in CaO values (Wedepohl, 1997, table 2, 249) and translates into the same high variability in CaO/Al_2O_3 ratios in Figure 99.

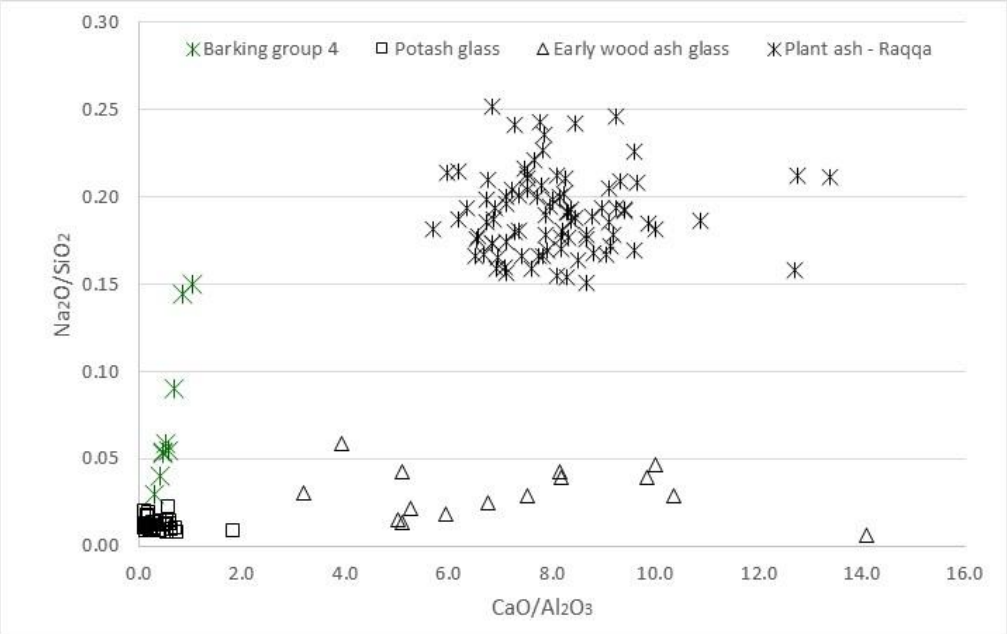


Figure 99 - CaO/Al_2O_3 vs. Na_2O/SiO_2 ratios for Barking Abbey group 4. Comparable data: Early wood ash glass from West Germany (9th – 11th century), after Wedepohl, 1997;Potash-silica glass beads from Guangxi-China (206 BC to 220 AD), after Liu et al., 2013; Plant ash glass from Raqqa-Syria (8th – 11th century AD), after Henderson et al., 2004.

.

A better compatibility is observed between group 4 and potash-silica glass from China published by Liu and colleagues (2013), even though such compatibility is not perfect. Potash-silica glass shows much clustered values in both ratios (c. <0.80 and <0.02 respectively), while Barking group 4 Na_2O/SiO_2 ratios are scattered between 0.04 and 0.15: this variability reflects the different sand sources and origin of the saltpetre mineral, and it indicates that samples in group 4 are the result of separate melts.

Alumina and calcium have been found the most diagnostic elements in potash glass-based glasses. Three major groups in potash glass have been suggested by Lankton and co-workers (2006, 326) based on their

lime and alumina contents: mKCA (moderate calcium oxide and alumina), and mKC-lowA (moderate potassium and calcium oxide, low alumina), and mKA-lowC (moderate alumina and potassium, low calcium oxide). As shown clearly in Figure 100, group 4 falls within the mKA-lowC group lime and alumina values, with a slightly increase in lime values (c. 2.0 – 3.0wt%).

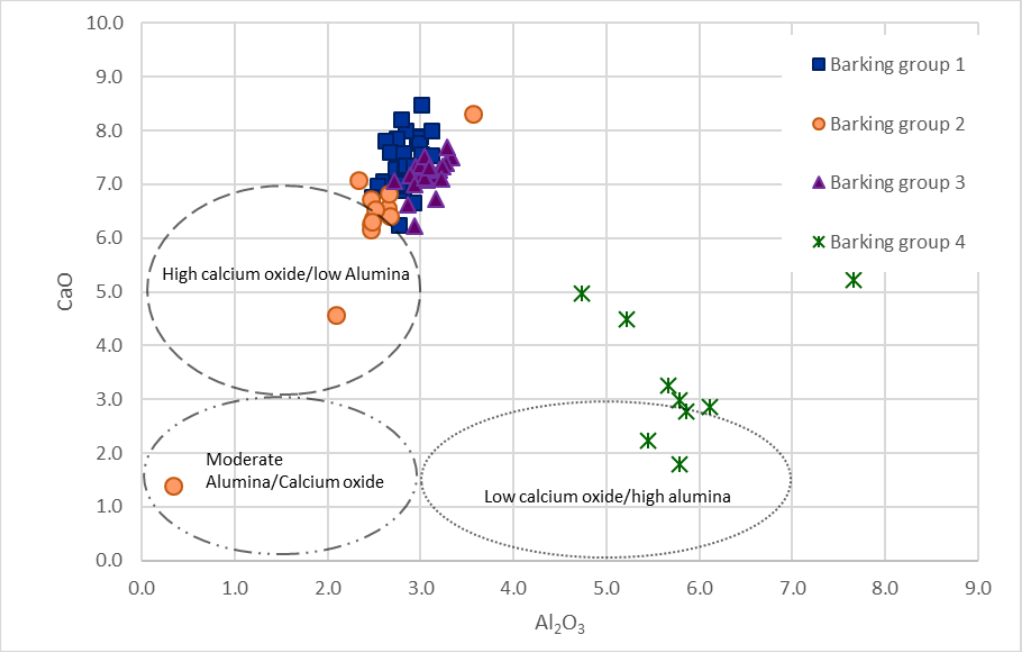


Figure 100 - Al_2O_3 vs. CaO contents for Barking Abbey groups. Three different areas are highlighted according to the three groups defined by Lakton and co-workers (2006, 326).

Ba40 and 41 show in-between calcium oxide levels (c. 5.0wt%); together with their higher levels of soda (c. 10wt%) when compared to other samples from group 4 and could have been fluxed with sodium rather than potash. Interestingly enough, Ba24 shows comparable levels of both potash and soda, and therefore might be considered as mixed-alkali potash glass, as suggested by Lankton and co-workers for some of their material (2006, 327).

5.1.2.3 Recycling

A bi-plot of manganese and antimony oxide (Figure 101) allows us to assess the presence of decolourisers in Barking Abbey glass. The concurrent presence of both decolourisers has been considered as marker of recycling, since it is not technological significant: suitable addition of one decolouriser would have been more than sufficient to counteract the blue-green glass colour caused by the natural impurities present in the sand fraction of the melt.

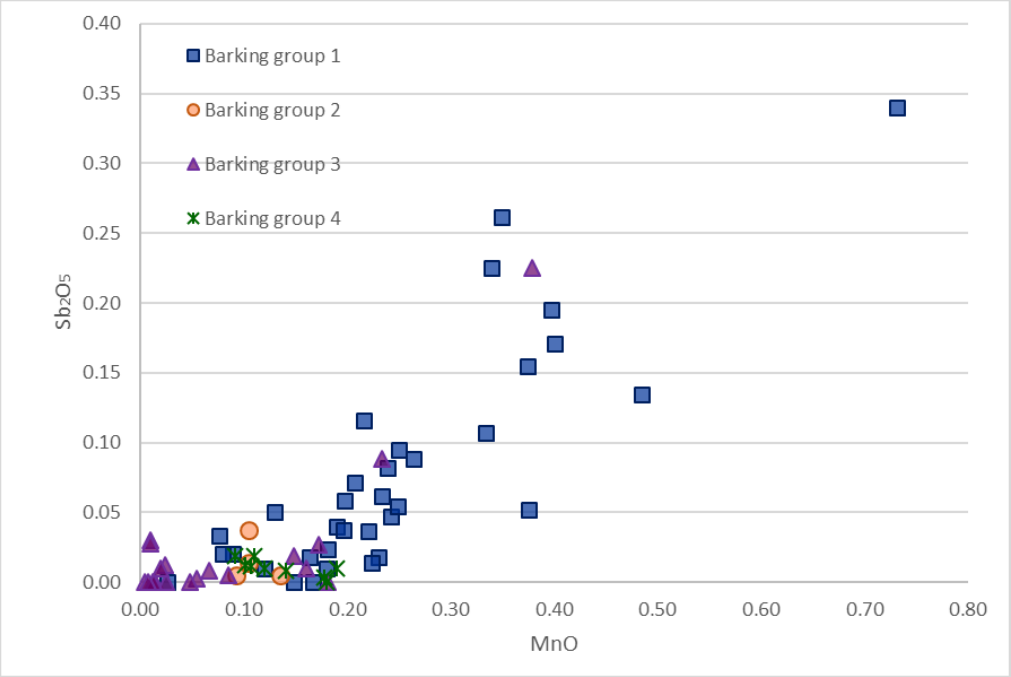


Figure 101 - MnO vs. Sb_2O_5 contents for Barking Abbey translucent glass divided by types suggested by cluster analysis.

A major nucleus of group 3 glass – Levantine I cluster between 0.10wt% of manganese oxide and 0.05wt% of antimony oxide. This suggests that most of group 3 glass potentially has not been undergoing repetitive cycles of production. The same can be said for the only three translucent samples from group 2. Potassium-silica based group 4 clusters in rather low MnO (0.10wt% and 0.20wt%) and Sb_2O_5 values (<0.05wt%), which

also lead me to suggest that they have not been through extensive recycling.

Group 1 – Foy 3 and a small group of samples from group 3 – Levantine I shows a completely different pattern of recycling, dividing in two sub-group: the first small group falls with the other non-recycled samples (c. 0.10wt% MnO), but the majority of them show a positive correlation between the two decolourisers, which indicates that both elements have been added together to the melt. Therefore, that most of group 1 has been through repetitive recycling processes.

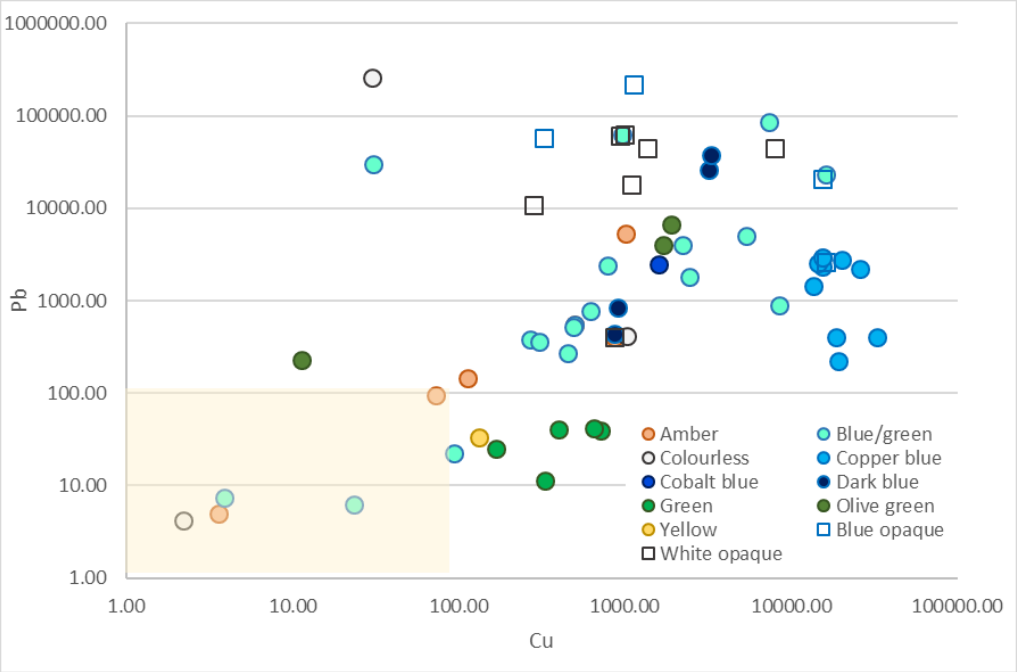


Figure 102 –Cu vs. Pb concentrations in a selected group of samples from Barking Abbey glass dataset, divided by colour and appearance (translucent or opaque). The scale on both axes is logarithmic. The area coloured in faint yellow suggests glass with low values of colourants, which may indicate no or very limited recycling practices.

Group 4 stays with low values of both de-colourisers (c. 0.10wt% - 0.20wt% of MnO and < 0.05wt% of Sb_2O_5). To investigate the degree of recycling present in Barking Abbey glass samples, a selection of bi-plots assessing the amount of colourant markers analysed in trace for each colour is presented.

Given the substantial presence of opaque coloured glass at Barking, I decided to include opaque glass too in order to assess the relationship between it and the translucent glass. In Figure 102, a bi-plot of Cu and Pb (ppm) of selected Barking Abbey samples is presented. As previously stated for Comacchio samples, 100ppm has been established as the limit under which most glass can be considered as not undergoing a repetitive cycle of re-melting, but such a limit has always to be considered more of a suggestion to be reviewed for each plot.

When colour is considered, a very limited number of samples fall below 100 ppm limit of both Cu and Pb (yellow faint area in Figure 103 and Figure 105). On the other hand, in the majority of samples Cu and Pb contents are relatively high and way over the 100ppm threshold: blue-green glasses in particular, where an elevated amount of both Cu and Pb has no technological significance. This occurs even when other markers are paired together (Figure 103 and Figure 105).

Elevated amounts of Cu are expected in copper-blue glass, being the major source of colourant of such glasses. Paynter and colleagues (2014, 40) suggest that it is not uncommon for glass opacified with tin oxide (such as this case) to contain a substantial amount of lead oxide as well: lead would have been in solution in the glass rather than as part of the opacifying crystals.

A positive correlation between the whole dataset can be observed when such colourant markers (Pb, Sb, Sb, Co, and Cu) are plotted together (Figure 103 and Figure 105) between faintly coloured glasses. The same cannot be observed in white opaque and strongly coloured copper-blue samples, which show increasing values (respectively of Sn, Pb on one hand, and Cu of the other). Increasing values of the afore-mentioned markers are connected to their coloration and opacification technologies.

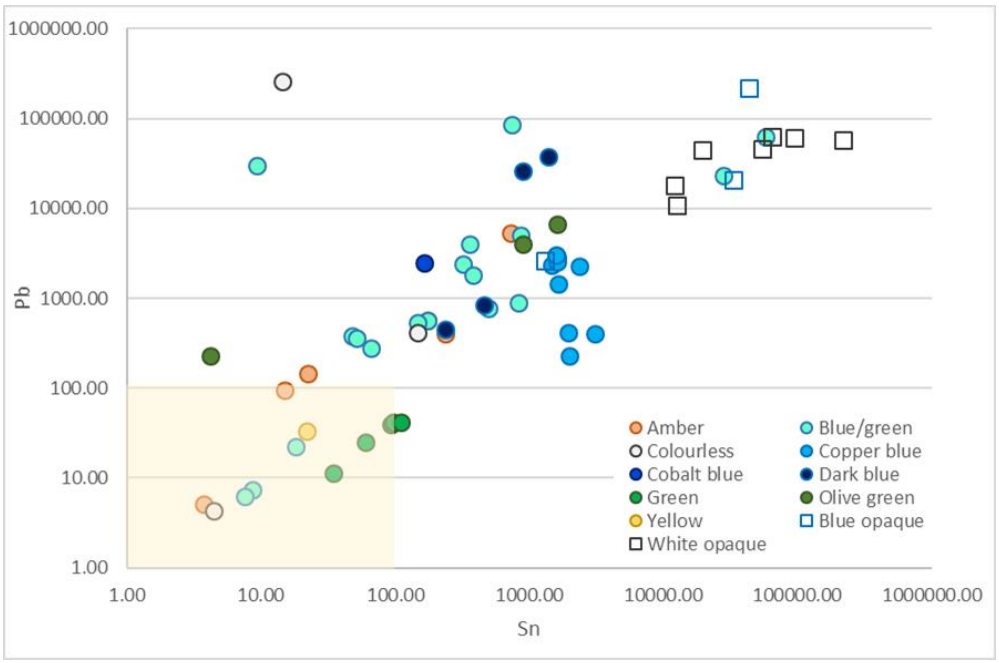


Figure 103 - Sn vs. Pb concentrations in a selected group of samples from Barking Abbey glass dataset, divided by colour and appearance (translucent or opaque). The scale on both axes is logarithmic. The area coloured in faint yellow suggests glass with low values of colourants, which may indicate no or very limited recycling practices.

The positive correlation is seen when Sn and Pb concentration are plotted together (Figure 103). This would suggest that Pb and Sn are introduced in the recipe through the same raw material.

If we consider the totality of Barking Abbey samples, we can observe how the same correlation is maintained for EMPA results (Figure 104). In addition, most of group 3 samples have low or null levels of both markers, while group 2 shows elevated amount of the same oxides (respectively >3.0wt% PbO and >2.0wt% SnO_2). Group 1 shows a different pattern: a small group displays very low PbO and Sn_2O (<0.1wt%)[92], while the rest of group 1 shows a progressive increasing amount of both markers together with a positive array towards group 2 white opaque glass.

[92] SnO_2 results from the second run of analysis as to be consider as a semi-quantitative result for both EMPA and LA-ICP-MS analysis, as seen in section 4.2.2.1.

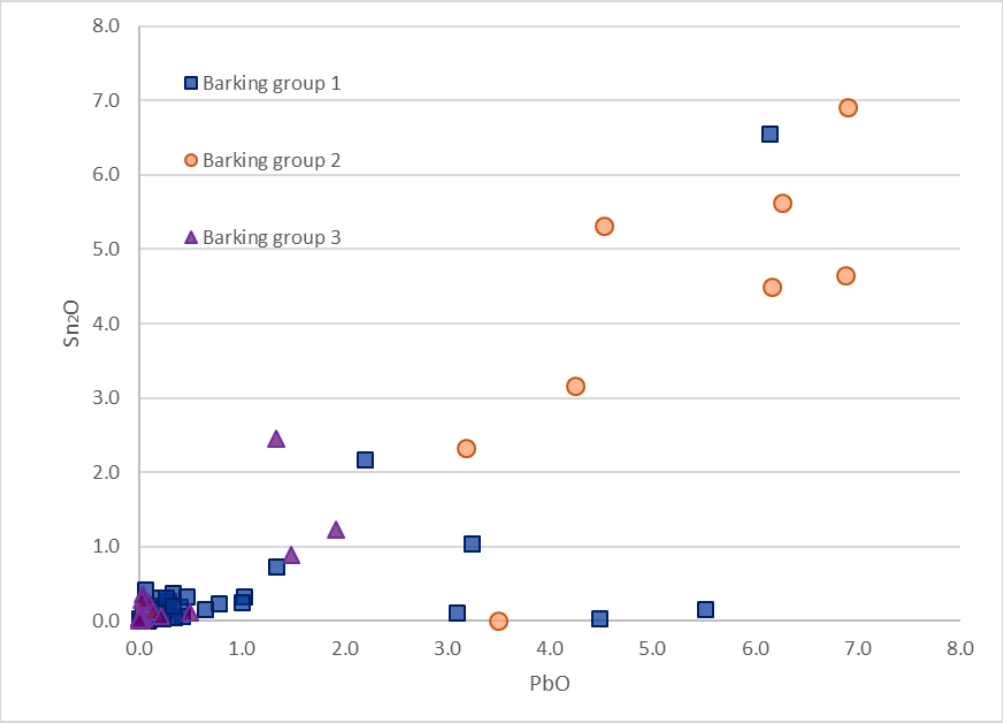


Figure 104 –PbO vs. Sn_2O contents in Barking Abbey glass divided according cluster analysis groups.

Given such a positive correlation, my first suggestion would be that the glass with increasing amount of Pb and Sn must have been diluted opacified glass, that in this case might as well be white opaque glass of group 2: in fact, only Sn_2O and PbO correlate between each other, which would suggest the addiction of some kind of opaque glass opacified through tin compounds and high lead content, such as in group 2. At the same time, the influence over the minor total of some group 1 major elements (such as SiO_2 content) would be explained with the replacement of opacifiers (tin oxide) and other additives, such as lead.

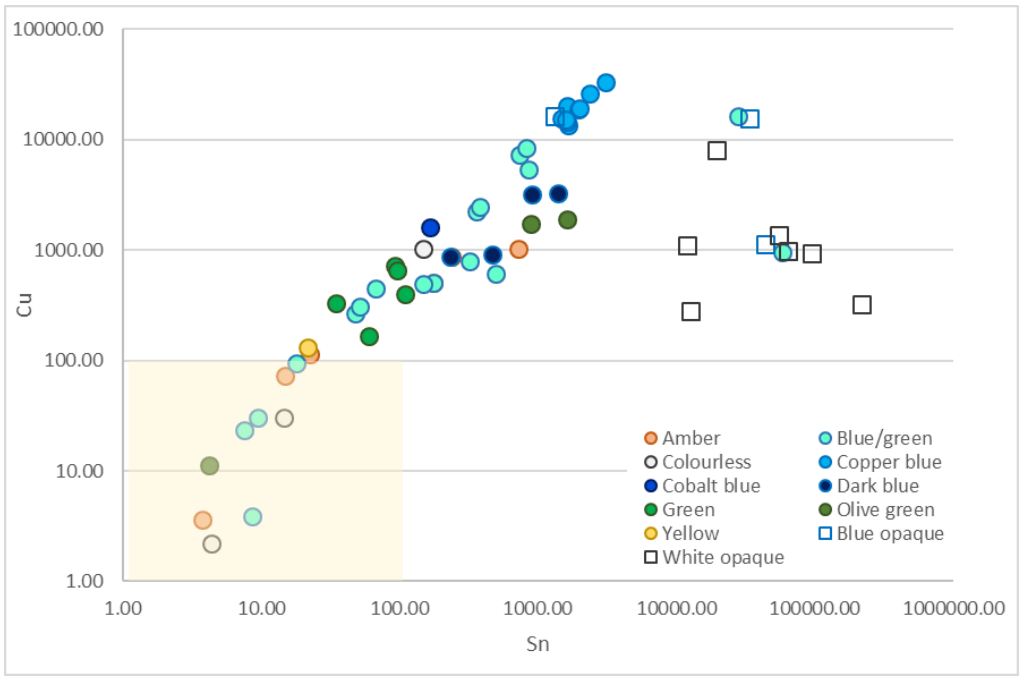


Figure 105 - Sn vs. Cu concentrations in a selected group of samples from Barking Abbey glass dataset, divided by colour and appearance (translucent or opaque). The scale on both axes is logarithmic.

Finally, the association between blue-green, copper-blue, and white opaque glass is particularly interesting (Figure 105). Concerning its Pb, Cu, and Sn levels, opaque blue glass pairs white opaque levels (Ba14b and Ba07e) and blue-green (Ba18 and Ba15) on one side and copper-blue samples the other (Ba22). Therefore, it is possible that at least in two of this samples (Ba14b and Ba07e), opaque blue results could have been obtained by mixing a base of blue-green or copper-blue base glass and opaque white (even in small quantities), as previously suggested by (Mass et al., 2002, 75).

5.1.2.4 Trace elements

A selection of 61 samples from Barking Abbey have been analysed for 47 trace elements by LA-ICP-MS. I decided to use the same bi-plots combination adopted for Comacchio to classify the Barking Abbey glass.

In Figure 106 and Figure 107, heavy mineral and carbonaceous sand fractions are plotted according to Barking Abbey glass groups. Trace elements cannot further discriminate Barking Abbey glass: the two supposed Levantine group (group 1 and 3) do plot within the same Zr/SiO_2 (0.25-0.87), Ce/La (c. 1.8- 2.0), and Sr/CaO (c. 40-60) ratios, while group 4 shows much higher SiO_2 (0.25-0.87) and Ce/La (c. 1.8- 2.0) ratios. and its Sr/CaO cluster around the other Barking groups.

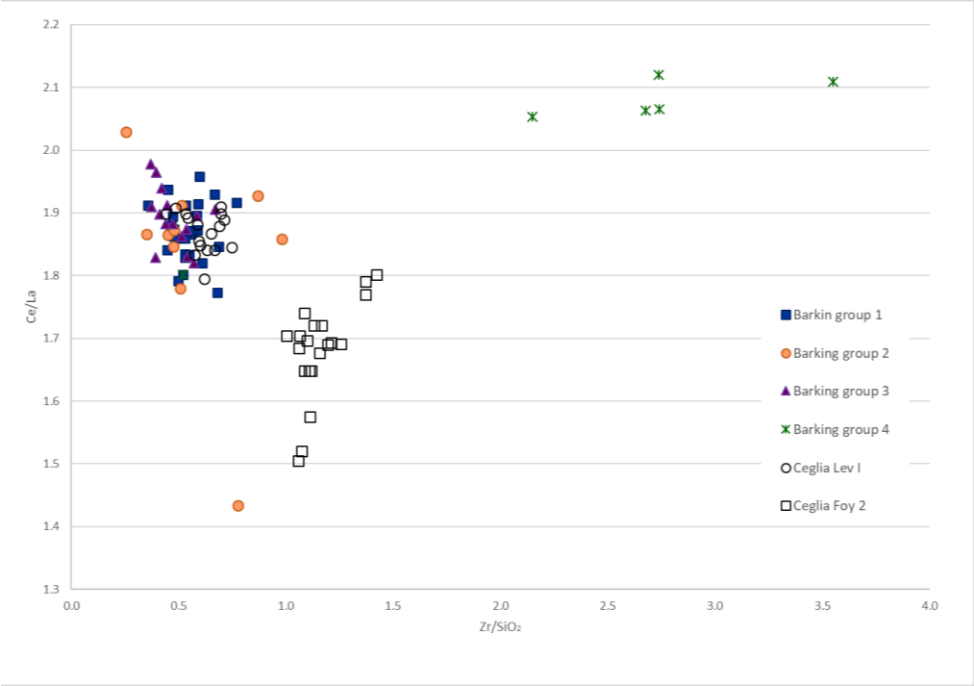


Figure 106 - Zr/SiO_2 and Ce/La ratios of Barking Abbey glass groups dataset. Levantine I and Foy 2, comparison materials (non-recycled) are plotted after Ceglia et al., 2017.

Nonetheless, group 1, 2, and 3 do fall within the Levantine limits proposed by the non-recycled material published by Ceglia and confirms the nature of the three natron-based groups. The fact that trace elements cannot discriminate further group 1, 2, and 3 even when silica values have been normalised (and therefore the influence of opacifiers and colourants has been nullified) must be considered as further proof that the three groups share a similar base glass, in this case Levantine.

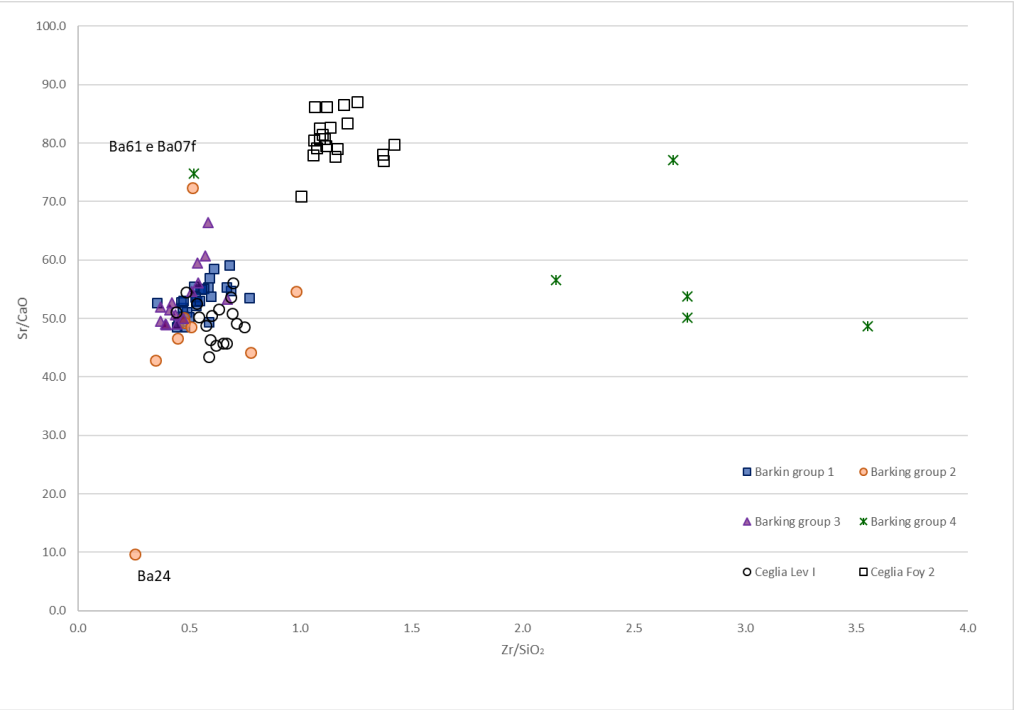


Figure 107 - Zr/SiO_2 and Sr/CaO ratios of Barking Abbey glass groups dataset. Levantine I and Foy 2, comparison materials (non-recycled) are plotted after Ceglia et al., 2017.

Group 2 shows an overall lower Sr/CaO, while instead group 1 instead positively correlated with group 2 around Zr/SiO_2 and Sr/CaO ratios, which reinforce even more the idea that these two groups are connected between them in addition to group 1 being the result of basic Levantine glass with the addition of strongly opacified glass from group 2. Two samples from group 2, Ba01b and Ba21 (both white opaque samples) do show higher Zr/SiO_2, and therefore might have been made with a different sand source than the rest of group 2. A small sub-group tends to have higher Sr/CaO for two samples, one from group 2 (Ba7f) and one from group 4 (Ba61). Ba61 also plots within the Levantine Zr/SiO_2 and Ce/La ratios values.

REE patterns (Figure 108) do confirm that group 1, 2, and 3 are compositionally similar to Levantine glass since they plot around Ceglia Levantine I values, while they show a different lighter REE pattern when compared with N1-Levantine material (Phelps et al., 2016). Phelps and co-worker's material do not come specifically from primary glass

workshops as the Ceglia Levantine samples does, and both assemblages definitely represent two different melts with raw materials gathered from the same area of production. Barking group 1, 2, and 3 share the same Levantine I base but closer to Ceglia and co-workers' assemblage, given their similar lighter element patterns.

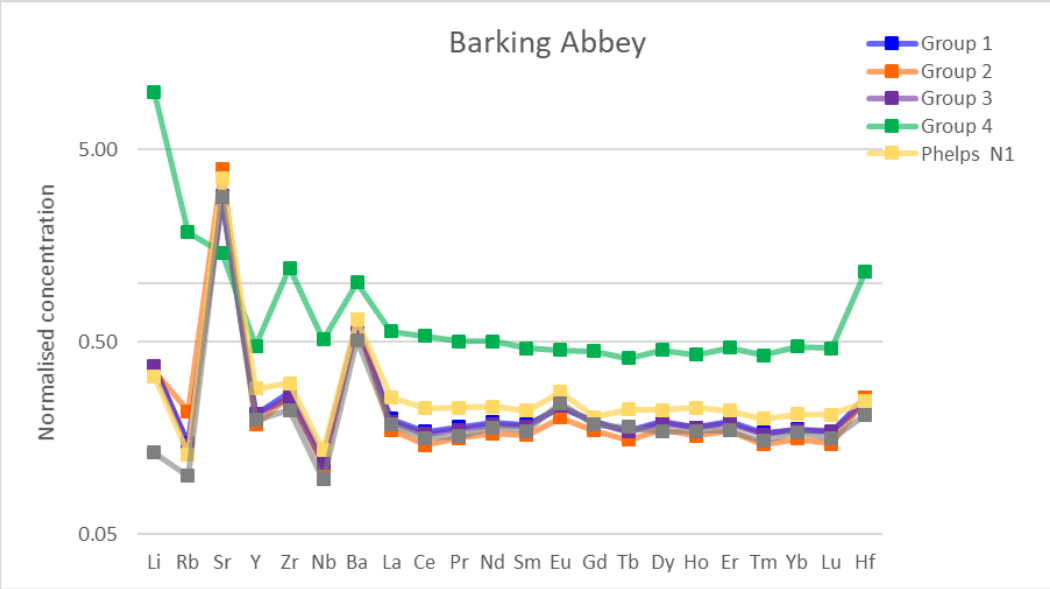


Figure 108 - Concentration of trace elements normalized to the upper continental crust (Kamber et al. 2005) for a selection of elements in group 1,2,3 and 4 of Barking Abbey glass. Comparison Levantine material after Ceglia et al., 2017 and Phelps et al., 2016.

Finally, I would like to address further the nature of potash glass group 4. REE profile of group 4 (Figure 108) confirms the diverse origin of such glass groups: their profile a general increase in all REE, with particularly high concentration of Li, Rb, Zr, Ba, and Hf. Concerning Rb, the latter REE has been paired with Sr by Liu and co-workers (2013) to address differences in potash glass groups. The bulk of Rb and Sr in glasses is incorporated with the raw materials containing potassium and calcium, respectively (Liu et al. 2013, 475). If Rb and Sr are paired together, Liu and co-workers distinguish two groups: a low Rb and higher Sr (group 1) and a higher Rb and low Sr (group 2).

In Figure 109, Rb and Sr are plotted for all groups found at Barking Abbey. First, it is clear how group 1, 2, and 3 displays much lower Rb concentration when compared with group 4, which instead is over 150ppm: these higher values are compatible with potash glass not only analysed by Liu and co-workers (2013), but they also match with some of Indian and South-eastern Asian potash glass presented by Dussubieux (2016, fig. 5.2, 101).

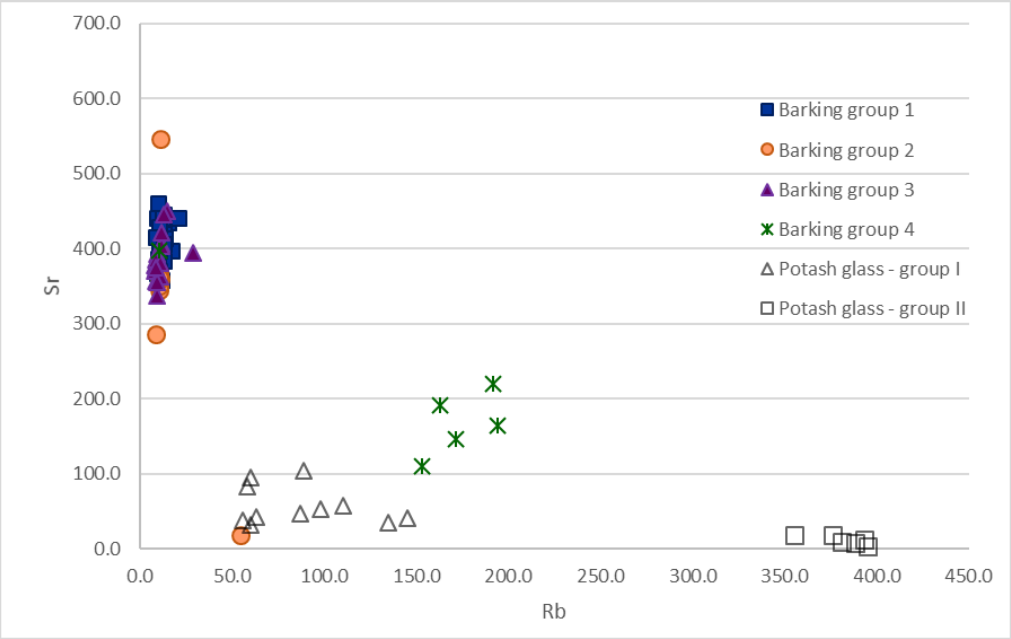


Figure 109 –Rb and Sr concentrations of glass from Barking Abbey. Comparison material: potash glass group I and II after Liu et al., 2013.

Moreover, group 4 positively correlates with Al but not with K, which therefore excludes the possibility of potassium coming from a combination of saltpetre and some other potassium aluminosilicate mineral (like potassium feldspar and mica) as instead proposed for by Liu and colleagues' group 2.

Finally, Ba61 still plots within the other Levantine groups when Rb and Sr concentrations are paired together (Figure 109): if we consider similar Zr/SiO_2, Ce/La, and Sr/CaO ratios to the other Barking groups, my

conclusion is that Ba61 must have been made by mixing a base Levantine glass with a small quantity of potash glass from group 4. This latter occurrence opens up a whole new mixing practices scenario between natron and potash glass at Barking Abbey.

5.1.2.5 Summary of Barking Abbey glass types

The Barking Abbey glass dataset is made up mostly by natron-based – Levantine I type (group 1, 2, and 3). Cluster analysis proved to be discriminating, with silica and soda content proves to be discriminant in Group 1, 2, and 3, together with iron oxide and alumina: group 3 falls within major oxide levels of Levantine I glass, while group 1 shows increased levels of iron oxides, and decreasing levels of silica.

Colour or object type do not prove to be discriminating in group 1 and group 3. On the other hand, group 2 is mostly made by white opaque glass. Moreover, as suggested by both recycling markers (Sn, Pb, and Cu in particular) group 3, 1, and 2 show increasing levels of contaminants from colourants and opacifiers.

My hypothesis is that group 3 represents glass with a base of Levantine I recipe, since it shows the lowest levels of impurities and colourant markers; group 1, falls within Levantine glass major oxide contents, falls in-between group 3 and 2 soda and silica values, while its iron content is still higher that group 3, but it does not agree with HIMT compositions.

The increasing levels of both tin and lead oxide in group 1 are not connected necessarily to their colour (and therefore not just technologically justifiable as opacification processes).Given that both oxides correlate positively and that group 2 and 3 act as at the end members, not only both oxides must have been introduced by the same raw material, but group 1 must have been the result from a basic natron glass (most probably Levantine) plus the addition of a material rich in tin-

based compounds and lead oxide. The addition of mosaic tesserae or glass from group 2 (which consist mostly by opaque white glass) are the most probable hypotheses.

Trace elements and REE patterns not only confirm the group suggested by cluster and EMPA analysis, but they support the use of a common base of Levantine glass for all three natron-based groups. In this case, normalising the EMPA results was fundamental to underline common patterns between the three compositional groups and was essential to counteract the influence that the colourant and opacifiers (lead and tin oxide fraction in particular) have over the total percentage of the major elements.

Groups 1, 2, and 3 falls within the expected Zr/SiO_2, Ce/La, and Sr/CaO ratios and REE patters follow the expected values for Levantine I (Ceglia et al., 2017) with no apparent discrepancies between all three groups, therefore confirming that all three natron-based group share the same base glass: the majority of group 2 plots together with group 3 – Levantine glass, while instead group 1 show a spread of values of all three ratios.

A small group (group 4) of potash glass has been instead fluxed with saltpetre mineral (KNO_3) together with high levels of potash (>5.0wt%) and alumina (4.73 – 7.66wt%) together with low levels of lime (5.21-1.79wt%) and soda (2-10wt%). As suggested by Lankton and co-workers (2006), alumina and calcium oxide proved to be discriminant for potash-based glass in group 4, which not only plots distinctively from group 1, 2, and 3, but resembles closely soda, lime, and alumina content in other potash glass beads from China (Liu et al. 2013) and South Asia (Dussubieux and Gratuze 2003; Lankton and Dussubieux 2006; Dussubieux 2016). In particular, group 4 resemble the mKAl (low lime – high alumina) group. Group 4 REE show a different pattern when compared to the other Levantine groups present at Barking Abbey, with general increment of both heavy and light REE, with positive anomalies with Li, Zr, Ba, and Hf concentrations.

High levels of Rb in group 4 finds correspondence with potash glass analysed by Dussubieux and colleagues (2016) and Liu and co-workers (2013). Concerning the latter work, group 4 glasses do match group 1 low Rb – high Sr - potash group described in Liu and co-worker's publication (2013), also in their lack of correlation between Rb and K_2O, which would dismiss the combined used of potassium nitrate and some other potassium-aluminosilicate mineral (like potassium feldspar and mica) as flux. Averaged EMPA and trace results are reported respectively in Table 9 and Table 10 .

Table 9 - Mean composition for all oxides for each of the 4 groups of Barking Abbey dataset analysed in this dissertation.

	Levantine 1		Levantine 1		Levantine 1		Potash glass	
	Group 1 (n=43)		Group 2 (n=13)		Group 3 (n=23)		Group 4 (n=8)	
Element	**Average**	**Sd**	**Average**	**Sd**	**Average**	**Sd**	**Average**	**Sd**
SO_3	0.15	0.05	0.1	0.04	0.11	0.04	0.03	0.03
P_2O_5	0.12	0.05	0.14	0.23	0.06	0.15	0.31	0.07
V_2O_5	0.02	0.01	0.01	0.01	0.01	0.01	0.02	0.01
As_2O_5	0.15	0.14	0.1	0.13	0.12	0.11	0.21	0.09
Sb_2O_5	0.1	0.21	0	0.01	0.01	0.02	0.01	0.01
SiO_2	68.08	1.19	60.44	3.56	71.61	11.76	65.56	2.85
TiO_2	0.09	0.02	0.08	0.04	0.08	0.03	0.43	0.04
SnO_2	0.24	0.37	3.34	2.39	0.23	2.09	0.03	0.03
Al_2O_3	2.82	0.14	2.4	0.67	3.07	0.63	5.58	0.41
Cr_2O_3	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Fe_2O_3	0.7	0.16	0.85	0.36	0.52	0.28	3.34	0.35
MgO	0.7	0.09	0.9	1.1	0.61	0.66	0.86	0.11
CaO	7.31	0.44	6.12	1.57	7.18	1.36	3.17	1
MnO	0.24	0.13	0.15	0.06	0.07	0.07	0.13	0.03
CoO	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0
NiO	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
CuO	1.1	1.18	0.38	0.7	0.46	0.84	0.24	0.33
ZnO	0.05	0.06	0.01	0.01	0.01	0.01	0.1	0.04
BaO	0.03	0.02	0.04	0.02	0.04	0.02	0.07	0.02
PbO	0.72	1.2	9.31	7.41	0.18	6.19	0.07	0.11
Na_2O	15.63	1.17	12.56	3.13	14.65	2.84	4.79	2.88
K_2O	0.85	0.29	1.58	2.22	0.65	1.39	13.81	4.28
Ag_2O	0	0.01	0	0.01	0.01	0.01	0.01	0.01
Cl	0.82	0.1	0.69	0.17	0.85	0.17	0.03	0.05

Table 10 - Mean composition for selected trace elements for each of the 4 groups of Barking Abbey dataset analysed in this dissertation.

	Levantine 1		Levantine 1		Levantine 1		Potash glass	
	Group 1 (n=43)		Group 2 (n=13)		Group 3 (n=23)		Group 4 (n=6)	
Element	Average	sd	Average	sd	Average	sd	Average	sd
Li	10.25	4.19	7.71	3.35	10.51	7.73	277.82	168.14
B	98.5	30.69	68.26	12.64	70.9	27.26	28.97	27.85
Ti	587.74	128.85	513.5	112.02	522.28	134.73	2388.66	832.80
Cr	14.87	2.2	37.49	57.95	15	2.37	12.84	5.85
Mn	1949.16	1108.31	936.14	399.98	899.25	965.41	953.62	107.17
Fe	4839.21	1062.59	5454.67	1956.36	4009.56	1407.76	19016.11	6743.25
Rb	11.73	2.52	10.32	0.8	11.48	4.85	147.30	62.81
Sr	403.89	28.95	373.77	74.9	388.59	30.45	205.07	92.48
Y	6.69	0.95	6.19	0.76	6.68	0.64	15.15	3.74
Zr	54.11	8.52	50.73	12.1	50.75	14.82	239.63	93.31
Nb	1.9	0.3	1.65	0.2	1.79	0.44	7.84	2.72
Cs	0.29	0.32	0.23	0.1	0.19	0.14	0.90	0.67
Ba	249.76	36.49	241.56	69.96	240.23	23.05	402.82	132.20
La	6.46	1.52	5.74	0.71	6.21	0.81	18.34	5.59
Ce	12.09	3.06	10.25	1.16	11.73	1.4	37.89	12.20
Pr	1.52	0.37	1.36	0.19	1.47	0.18	4.24	1.28
Nd	6.26	1.46	5.66	0.77	6.11	0.59	16.48	4.74
Sm	1.27	0.31	1.16	0.18	1.24	0.13	3.18	0.94
Eu	0.36	0.08	0.34	0.05	0.36	0.03	0.71	0.17
Gd	1.22	0.19	1.14	0.18	1.21	0.14	2.83	0.73
Tb	0.17	0.03	0.16	0.02	0.17	0.02	0.40	0.11
Dy	1.13	0.17	1.06	0.17	1.1	0.09	2.67	0.69
Ho	0.22	0.03	0.21	0.04	0.22	0.02	0.52	0.13
Er	0.65	0.08	0.6	0.1	0.63	0.06	1.57	0.40
Tm	0.09	0.01	0.08	0.01	0.08	0.01	0.22	0.06
Yb	0.57	0.07	0.52	0.06	0.57	0.08	1.53	0.45
Lu	0.08	0.01	0.07	0.01	0.08	0.01	0.23	0.06
Hf	1.36	0.21	1.33	0.38	1.29	0.38	6.16	2.44
Th	1.02	0.16	0.96	0.28	0.94	0.28	4.82	1.71
U	0.83	0.13	0.71	0.21	0.73	0.17	1.26	0.23

5.1.3 Ribe

Based on cluster analysis, Ribe glass samples fall into two main branches, which further divides into five groups, plus one outlier (Rib35, group 3).

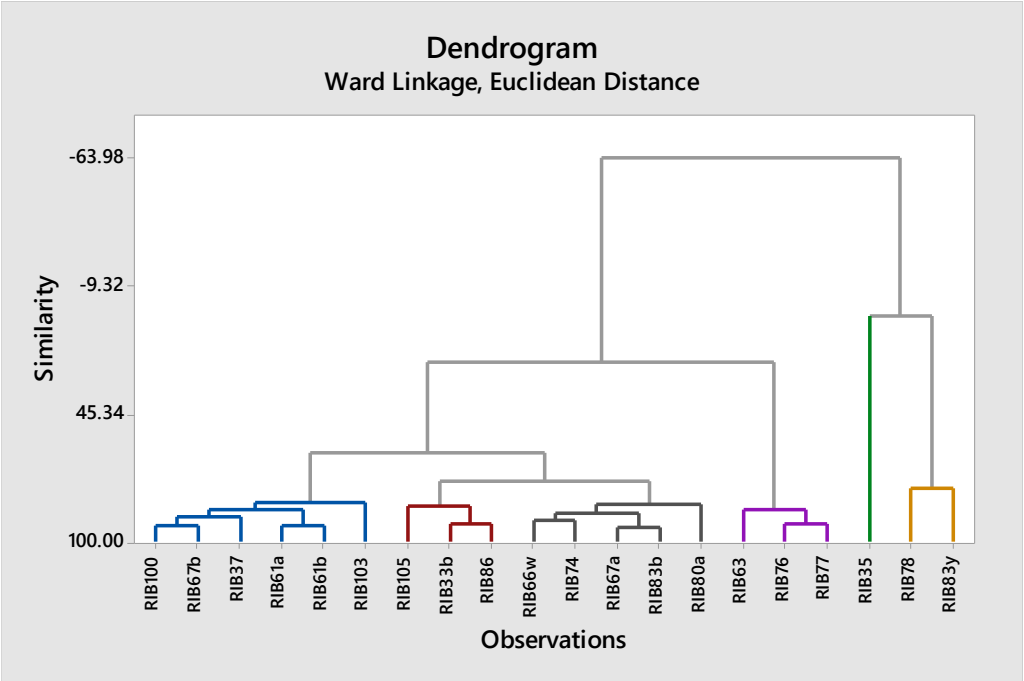


Figure 110 - Cluster analysis (Ward's method, Euclidean distance) distinguish 6 principal groupings of samples. Determining oxides: SiO_2, TiO_2, Al_2O_3, Fe_2O_3, CaO, and NaO_2. (N= 20; Rib35 is removed from the following plots because it is an outlier).

The same groups can be plotted by PCA. Based on Figure 110 and Figure 111, principal component 1 in Ribe glass positively correlates with Na_2O, SiO_2, TiO_2, and CaO, while Principal component 2 is positively correlated only with Na_2O and SiO_2. Group 1 separates from group 2, 4, and 5. The latter groups cluster together, with a potential increase in both CaO (lime content) and TiO_2 when compared to group 1 and 6. Group 6 plots on its own, showing a negative correlation with all the chosen variables. Group 3 (Rib35) has been excluded from the following plots because cluster analysis indicates it as an outlier.

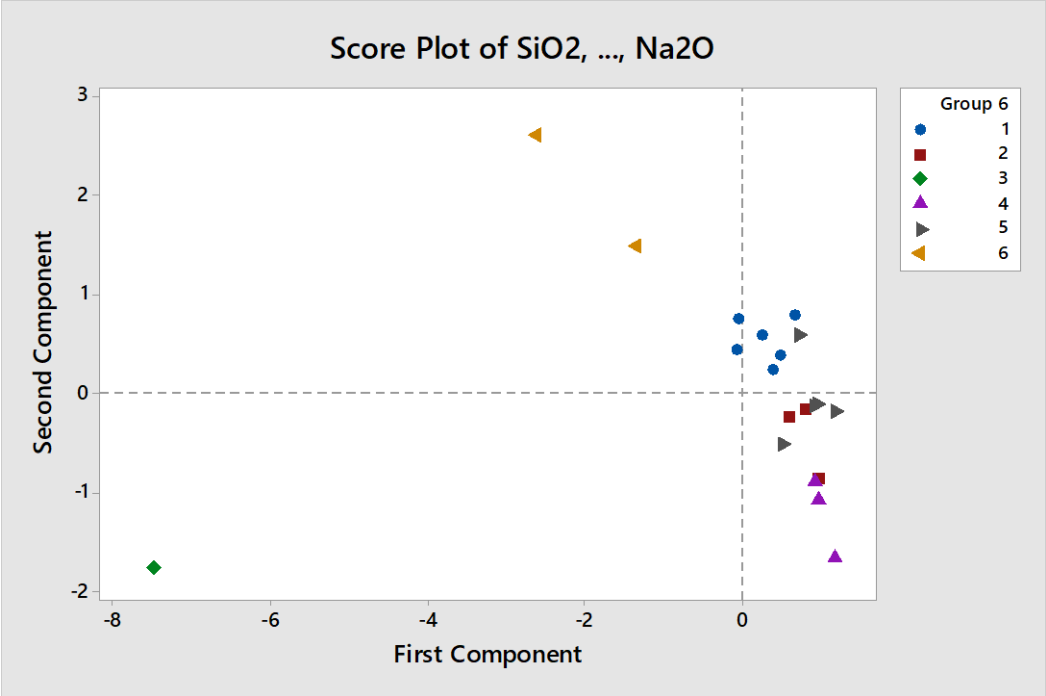


Figure 111 - PCA bi-plot of Pca 1 and Pca 2 of Ribe glass dataset. Determining oxides: SiO_2, TiO_2, Al_2O_3, Fe_2O_3, CaO, and NaO_2. Group labels are based on cluster analysis (see this section, Figure 110).

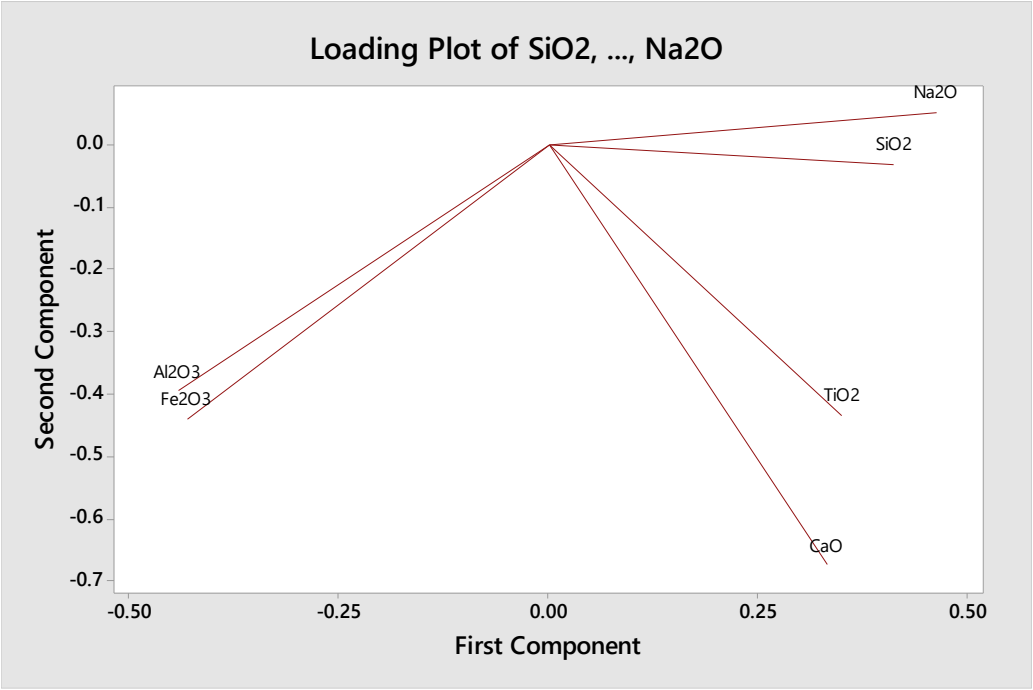


Figure 112 - The length and direction of the vectors show the contribution of each variable to the principal components 1 and 2 in Ribe glass dataset. Principal component 1 has positive coefficients for Na_2O, SiO_2, TiO_2, and CaO. Principal component 2 is positively correlated with Na_2O and SiO_2.

5.1.3.1 EMPA

In Figure 113, K_2O and MgO contents. The majority of Ribe glasses (group 1, 2, 5) cluster tightly within the known natron glass limits, as showed in Figure 113. Two samples show relatively higher K_2O values (c. 1wt%), but still within natron limits. Group 6 shows lower values of both MgO and K_2O (<0.5wt%) when compared to the rest of the natron glasses. Group 4 instead show an overall increase of both oxides (c. >2.5wt% for MgO and between 1.0wt% and 2.42wt% for K_2O). Rib77 in particular falls within the plant ash known area.

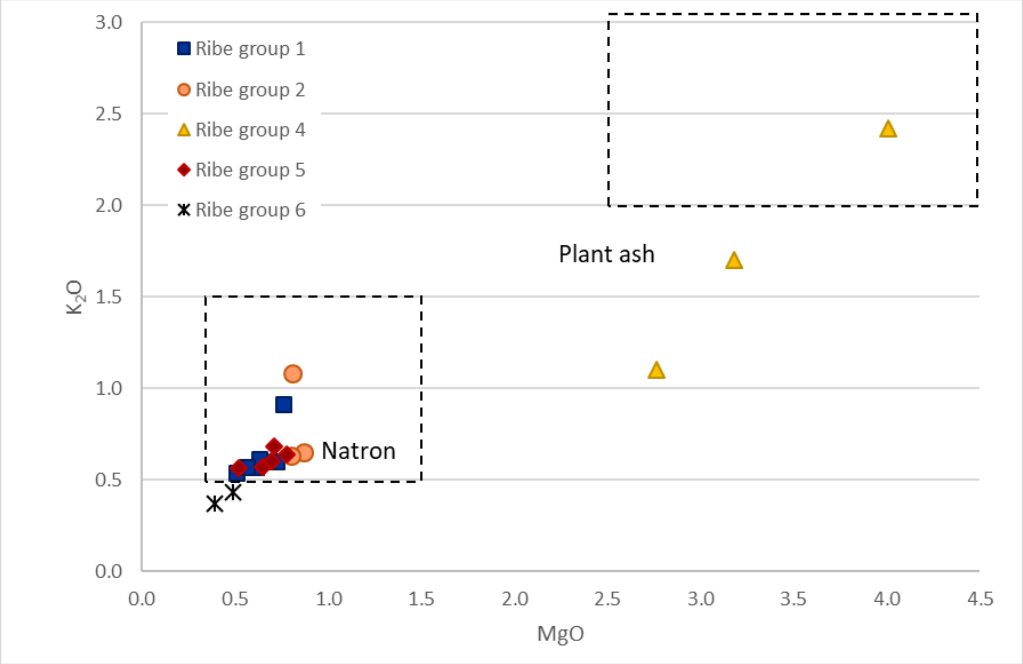


Figure 113- MgO versus K_2O contents for glass from Ribe divided by groups based on cluster analysis.

Ribe group 1, group 2, and group 5 overall cluster together throughout major elements plots, save for variation in CaO and Fe_2O_3 contents (Figure 115, Figure 116, and Figure 117).

In the SiO_2 and Na_2O plot (Figure 114), Group 4 and 6 have overall a lower SiO_2 content when compared to group 1, 2 and 5, which on the other hand cluster with the same range of values for both oxides. Group 6 also contains significantly lower Na_2O when compared to the other groups (c. <48%wt).

The alumina and iron oxide plot (Figure 115) is not diagnostic in discriminating sand and its heavy minerals component fraction. Group 1 and 5 both fall within the same range of both oxides, even though group 5 has slightly higher Fe_2O_3 (c. 1.0wt%). Group 2 shows instead a relatively higher Al_2O_3 content (2.69wt% and 2.75wt%) when compared to group 1 and 5.

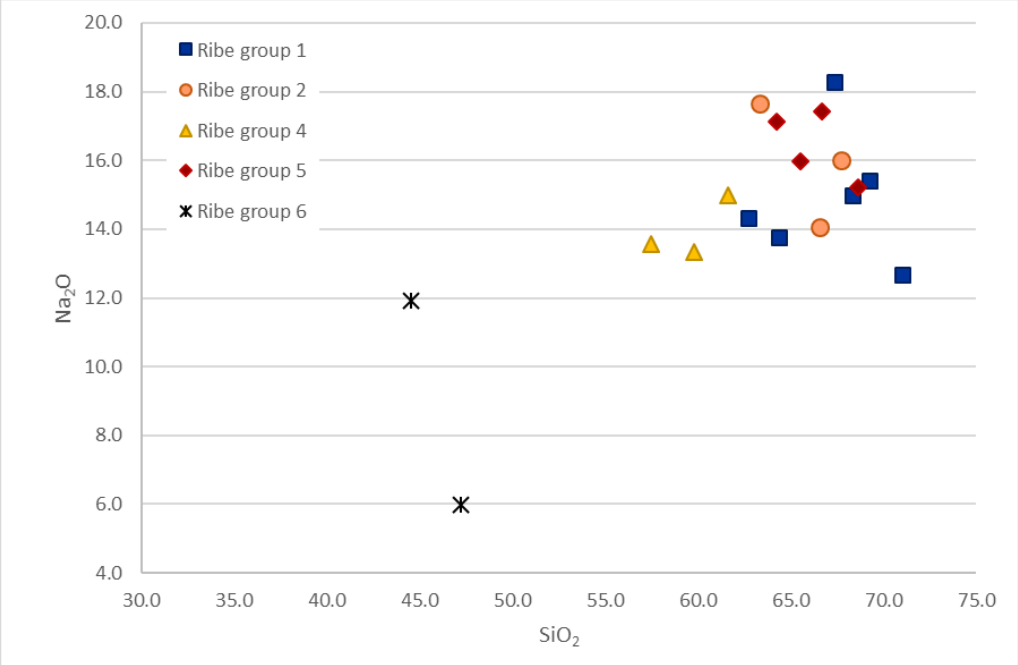


Figure 114 - SiO_2 versus Na_2O contents for glass from Ribe divided by groups based on cluster analysis.

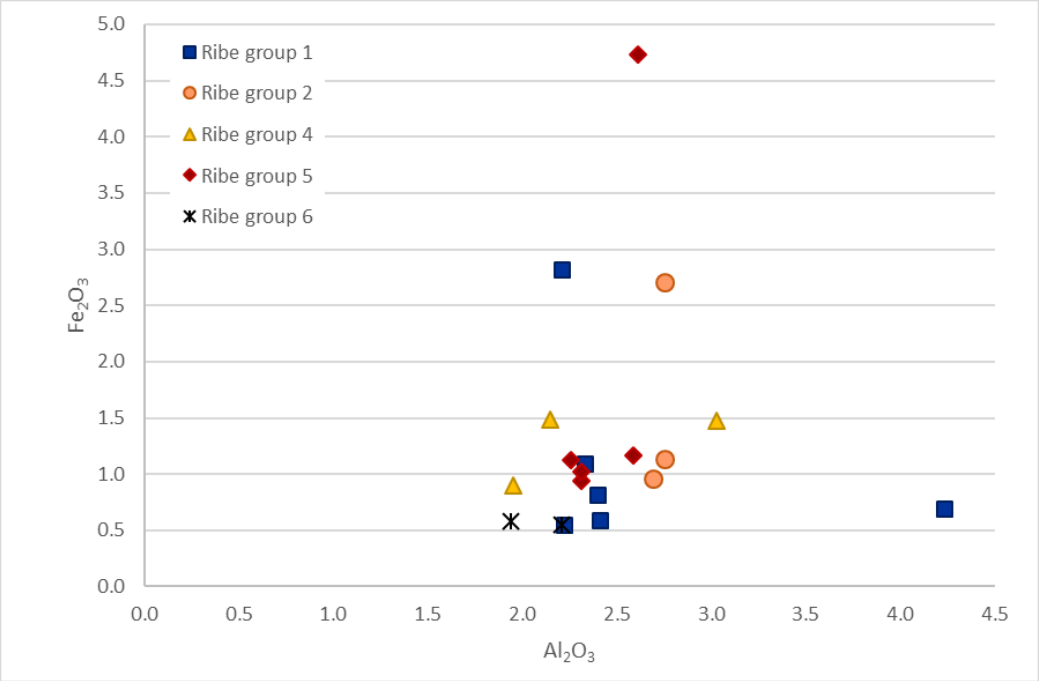


Figure 115 - Al_2O_3 versus Fe_2O_3 contents for glass from Ribe divided by groups based on cluster analysis.

Two samples from group 4 have Al_2O_3 contents closer to 2.0wt%, (1.95 wt% and 2.15wt%), while another one (Rib76) has a much higher value, closer to group 2. Rib67b from group 1 plots on its own with over 4.0wt% of Al_2O_3. Finally, three samples (Rib 33b; Rib61a, and Rib74), all red opaque, show higher iron oxide contents (c. >2.5wt%).

Fe_2O_3 paired with TiO_2 seems to discriminate the groups better (Figure 116). Groups 1 and 6 have lower TiO_2 content, plotting respectively between 0.06wt%-0.07wt% and 0.05wt%-0.07wt%. Group 4 and 5 instead show slightly higher Fe_2O_3 and TiO_2 contents. Group 5 plots quite tightly around 0.09wt%, while group 4 is spread more broadly around c. 0.10wt%. Group 2 overall does not adhere to a fixed pattern, since all three samples cluster separately with other groups.

In Figure 117, the lime content versus alumina is plotted. Group 2 separates from group 1 and group 5 according to both CaO and Al_2O_3 contents, while group 4 shows similar higher CaO values to group 2 (c.

>7.0wt%). Finally, group 6 plots distinctively on its own with much lower CaO values (2.77wt% and 4.34wt%).

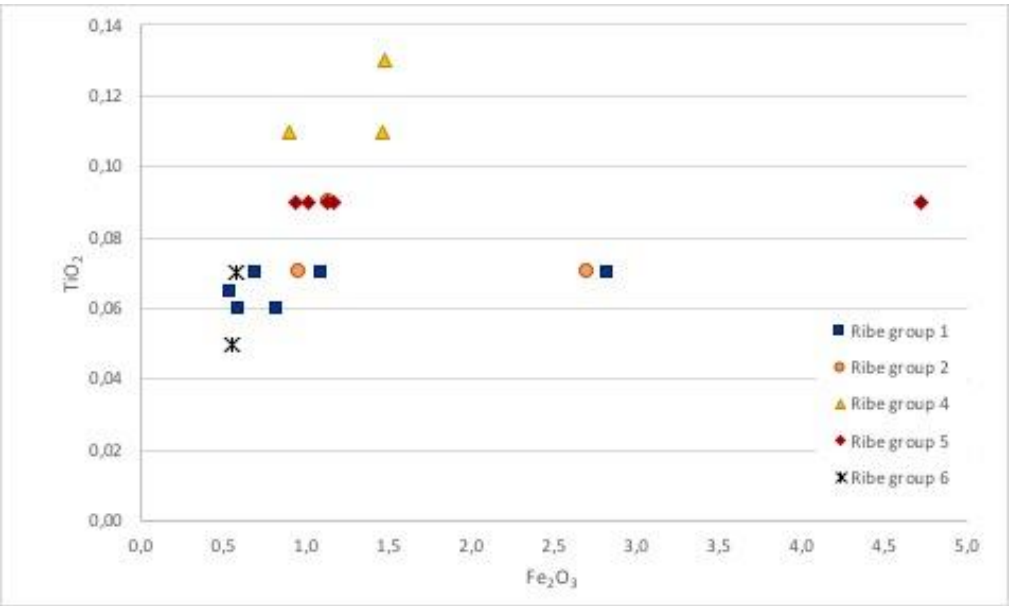


Figure 116 - Fe_2O_3 versus TiO_2 contents for glass from Ribe glass divided by groups based on cluster analysis.

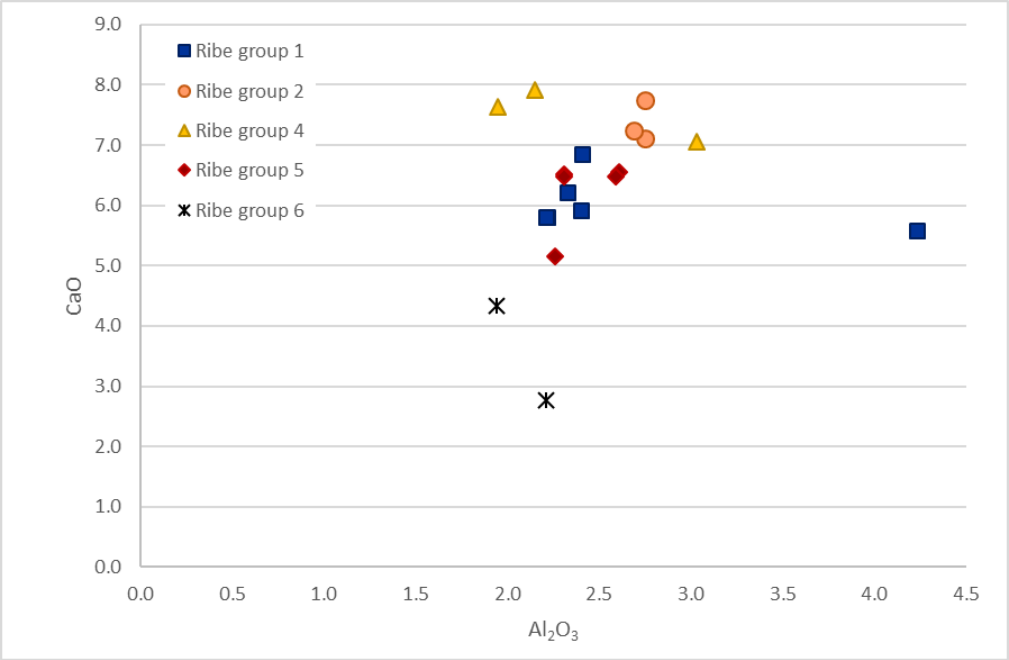


Figure 117 - Al_2O_3 versus CaO contents for glass from Ribe divided by groups based on cluster analysis

Colour

The majority of analysed samples from Ribe include a small range of opaque colours: white, red, blue, and yellow. The remaining samples are translucent: blue/green, and one grey sample.

Given its high levels of SnO_2 (5.49wt%), Rib66w is potentially coloured by tin oxide crystals. Another green opaque sample does not show elevated contents of antimony or tin oxides, but instead high Fe_2O_3 (1.47wt%) and PbO (3.53wt%). Still, both opacifiers have potentially been added to the melt 0.22wt% and 0.55wt%: the colour could have been the result of mixing a yellow opaque glass with blue glass by adding lead antimonate to preformed blue glass or even by adding copper to preformed yellow glass (Duckworth, 2011, 54). Given its high levels of CuO (2.02wt%), The second hypothesis is more probable.

Rib78 and 83y yellow opaque samples paired high levels of PbO (36.84wt% and 32.00wt%) have higher levels of SnO_2 (4.81wt% and 2.55wt%). Rib61b and 77 have also high lead in their compositions (respectively 10.45wt% and 7.24wt%) but are paired with moderate tin oxide when compared to the others (0.89wt% and 0.44wt%). Faint yellow opaque Rib86 does not show elevated levels of neither PbO, Sn_2O_5, Sb_2O_5.

Five out of six red opaque samples falls within the “dullish red” category, with relatively high values of CuO as main colourant (0.61 – 1.92wt%) produced in a reducing atmosphere plus high levels of Fe_2O_3 (1.14 – 4.73wt%) as reducing agent helping the development of cuprite crystals, and elevated levels of PbO (0.35 – 6.38wt%), which would have increased the solubility of copper at high temperatures (Brill, 1963; Freestone, 1987). Rib67b does not adhere to such parameters, with considerably lower levels of all the afore mentioned oxides (c. <0.70%).

The “natural” blue-green translucent colour of Rib100, 103, and 80a is potentially due to the results of the interaction between iron and sulphur and the reducing atmosphere that the melt is exposed to in the furnace (Brill, 1988): in Rib100 and 80a Fe_2O_3 is respectively 1.09wt% and 1.13wt%, while SO_3 is 0.39wt% and 0.21wt%. Rib103 has considerably less iron oxide (0.59wt%), but more sulphur (0.48wt%). Ribe67a and 83b are coloured in a more intense semi-opaque blue by Fe_2O_3 (1.02wt% - 1.17wt% and opacified by high levels of antimony oxide (1.46wt% – 1.71wt%wt%).

One translucent grey sample, Rib37, shows both MnO and Sb_2O_5 oxides, both at 0.51wt% levels. Finally, the outlier Rib35 is a purple translucent sample, with high levels of manganese oxide (1.33wt%) as expected.

5.1.3.2 Further considerations and comparison with published materials.

Even though multivariate analyses underline a distinction according to chosen variables across Ribe glass dataset (n=20), the limited number of samples included in each group makes it arduous to categorise such small groups into known recipes, in particular for groups 1, 2, and 5. These groups separate by titania and calcium oxide contents (Figure 117 and Figure 116) but tend instead to cluster when other oxides are involved, which suggests that Ribe materials are compositionally similar for most of theirs major components,; the sub-classification suggested by cluster analysis is not as diagnostic as it has been for Comacchio and Barking Abbey samples.

If we consider group 1, 2, and 5 three different sub-groups belonging to one main group we can make some additional consideration.

The main group (coloured in blue, Figure 118) shows a positive correlation for alumina and iron oxide, with alumina around c. 2.5wt% and iron oxide between 0.55wt% and 1.14wt%. If we consider titanium oxide

(0.006wt% - 0.09wt%) and CaO (5.16wt% – 7.7wt%) contents we could consider the three groups as potentially belonging to the so-called “weak” variant of the HIMT recipe. MnO (0.18wt% - 1.24wt%), SiO_2 (62.72wt% - 73.65) and Na_2O (12.68wt% - 18.27wt%) range are quite variable. It is worth noting that one sample from group 4 groups together with the main supposed HIMT group.

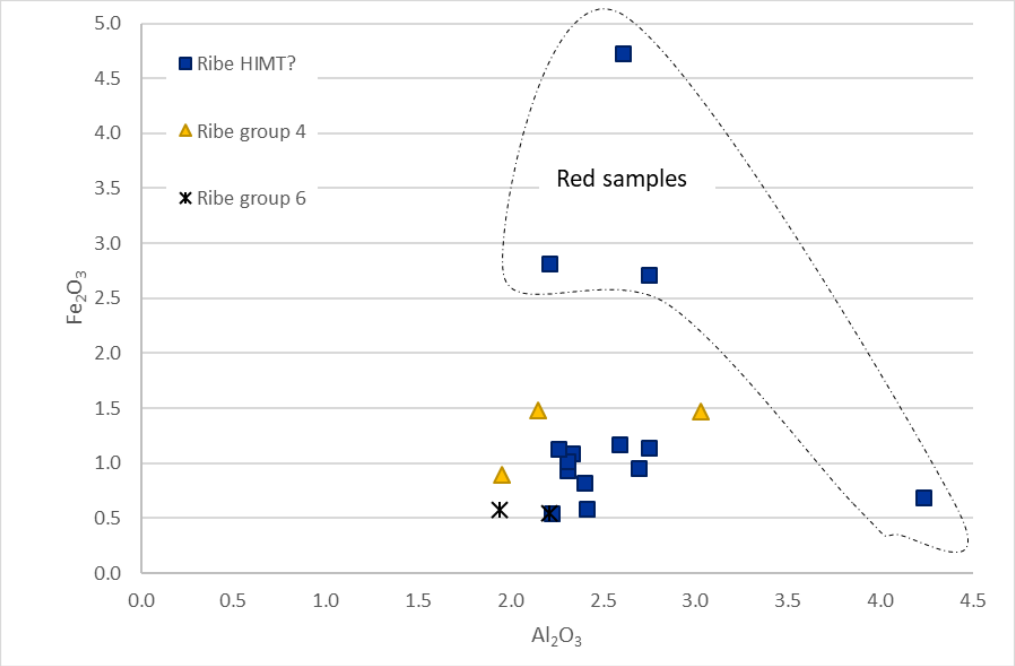


Figure 118 - Al_2O_3 versus Fe_2O_3 contents for glass from Ribe; group 1, 2, and 5 have been grouped together; the striped line includes only red samples from such group.

I would not classify group 4 as plant ash. Rib77 is the only sample out of the three with the necessary high potassium and magnesium oxides to be considered as high-alkali glass. The K_2O content in the other two samples (Rib76 and 63) is lower (1.10wt% - 1.70wt%). More so, its feldspar content is more elevated than the content known in plant ash (2.38wt% against 1.17wt% and 1.24wt% in plant ash from Raqqa), and its phosphorus oxide too low (0.13wt% against 0.29wt% and 0.27wt% in plant ash from Raqqa).

Given the positive correlation observed between K_2O and MgO (Figure 113), I suggest that group 4 is consider as natron-based glass mixed with a minimum amount of plant ash glass.

I characterise group 6 as lead glass, with low SiO_2 (45.87wt%), low alkali (K_2O 0.40wt% and MgO 0.44wt%) and lime (CaO 3.56wt%) paired to elevated lead oxide levels (34.42wt%).

Outlier Rib35 has relatively low values of SiO_2 (38.86wt%) and high Al_2O_3 (23.43wt%), Fe_2O_3 (22.77wt%), and MgO (7.89wt%) but no K_2O or Na_2O were detected. I shown in the previous section, the groups suggested by cluster analysis in the Ribe glass dataset do not cluster together save for calcium oxide and titania values. Therefore, lime and impurities in sand are discriminant between these groups, but the overall impression is that (aside group 6, which is a variation of lead glass) glass from Ribe is of the HIMT recipe, and most precisely the Foy 2 variety.

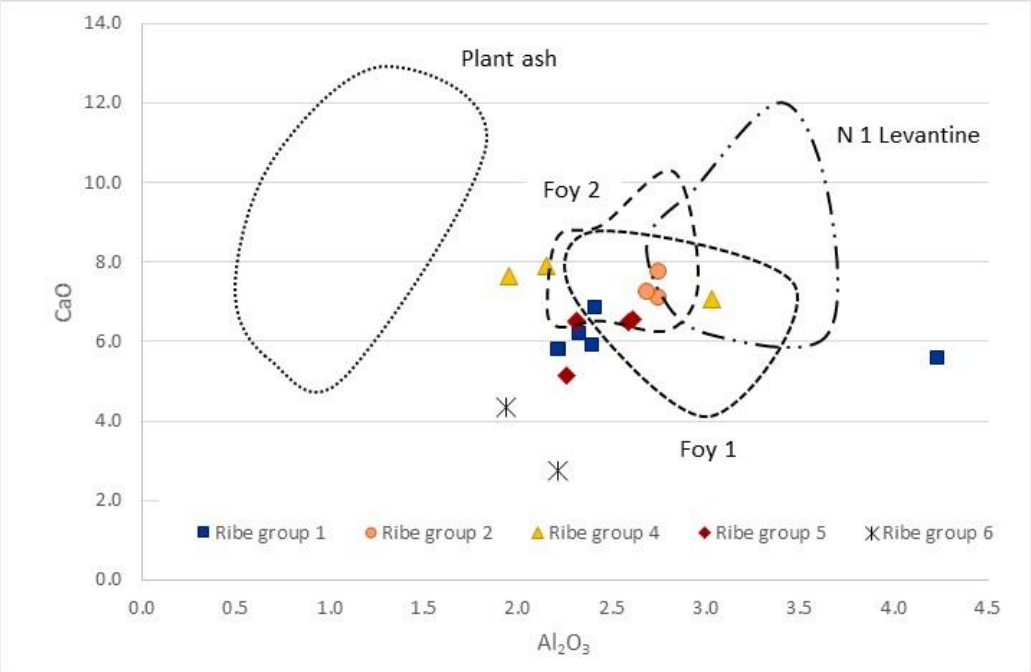


Figure 119 –CaO vs. Al_2O_3 contents for Ribe glass groups based on cluster analysis. Comparable data: Foy 1 and Foy 2 data (5th – late 8th century AD) after Foy et al., 2003, Levantine I - Apollonia type glass after Phelps et al., 2016, Plant ash glass from Raqqa- Syria (8th – 11th century AD), after Henderson et al., 2004.

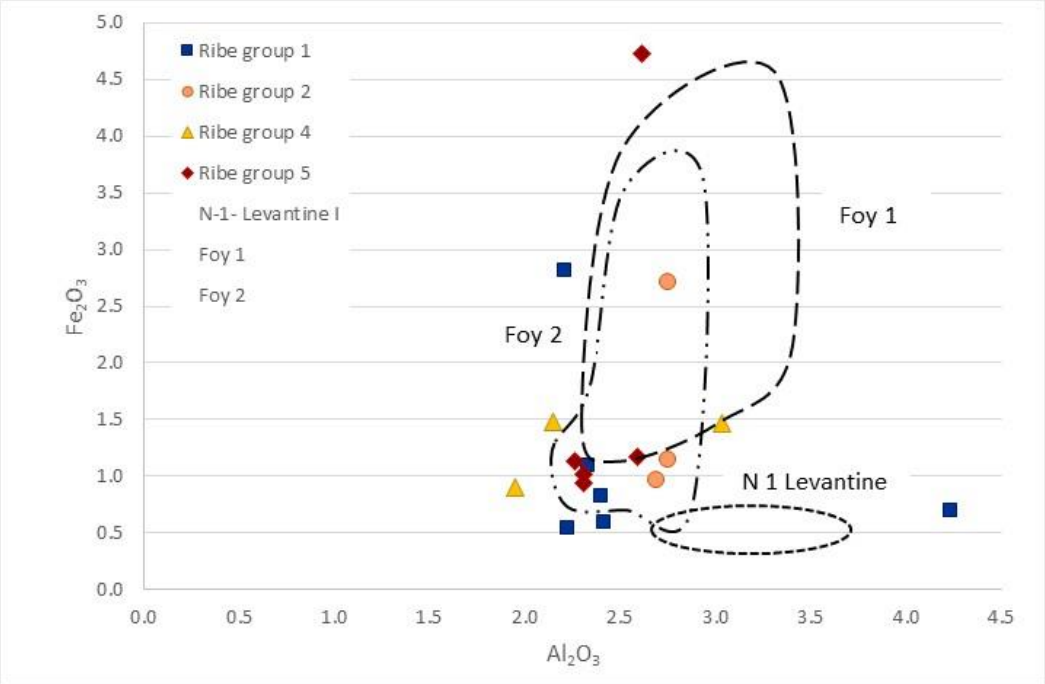


Figure 120 –Al_2O_3 vs Fe_2O_3 comparison for Ribe glass groups based on cluster analysis. Comparable data: Foy 1 and Foy 2 data (5th – late 8th century AD) after Foy et al., 2003, Levantine I - Apollonia type glass after Phelps et al.,, 2016.

If compared with published material, Ribe falls within the Foy 1 and 2 compositional areas. Such overlaps are it explainable as being both of the HIMT recipe, and therefore with similar values. Ribe samples though do not show adequate levels of iron oxide, titania, and manganese oxide to belong to the “stronger” variety of HIMT. Moreover, the positive correlation is weak. In Figure 120, higher values of Fe_2O_3 are connected to red samples, while all the other group within lower iron oxide values (0.5wt% - 1.5wt%), within the iron and alumina limits of Foy 2 group. In Figure 119, the correspondence is less clear, but all Ribe groups (save group 6 - lead glass and one sample from group 1, Rib67b) pull towards the Foy 1 and 2 alumina and lime contents.

Group 4 is characterised by higher potassium and manganese oxides in the previous plot (Figure 113): the same group does not cluster within or closer to the plant ash area (Figure 119), but it groups closer to natron-based area in both plots, supporting the hypothesis that this glass cannot

be characterised as plant ash but most probably as natron-based glass (potentially HIMT) diluted with a small quantity of plant ash glass.

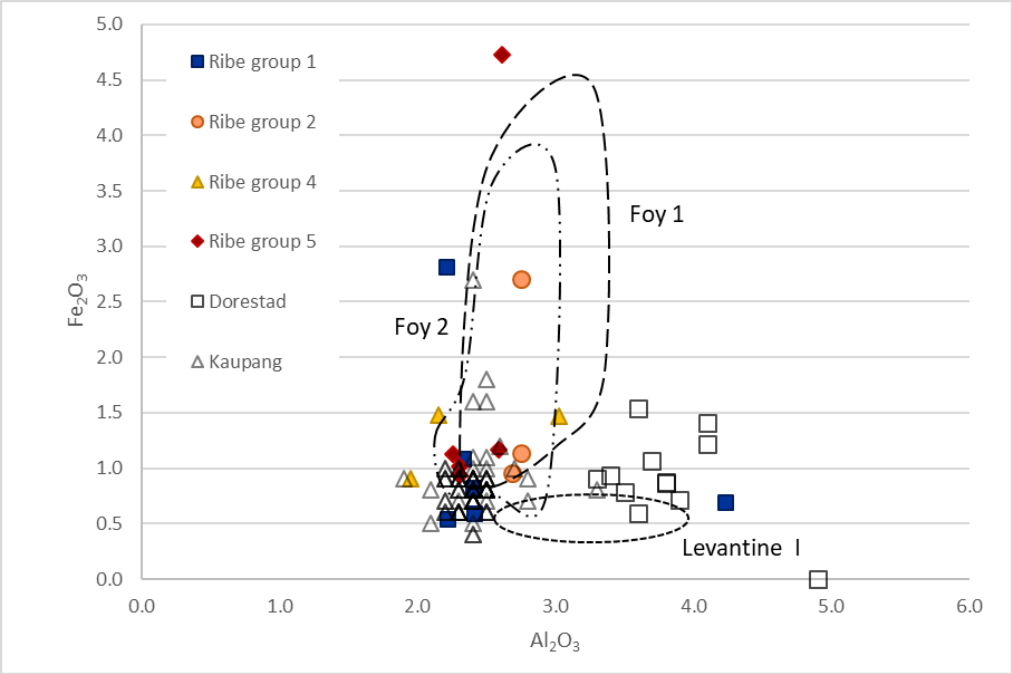


Figure 121 - Al_2O_3 vs Fe_2O_3 comparison for Ribe glass groups based on cluster analysis. Comparable data: Foy 1 and Foy 2 data (5th – late 8th century AD) after Foy et al., 2003, Levantine I - Apollonia type glass after Phelps et al., 2016; 8th – 9th century AD Dorestad glass dataset after Sanderson et al.,1984; 9th century AD Kaupang natron glass dataset after Gaut, 2011.

If the same plots are compared with coeval Scandinavian material, some differences in major elements can be observed. In Figure 121, Ribe materials is compared to 8th – 9th century AD Dorestad glass and 9th century AD (Sanderson et al., 1984) and Kaupang natron glass datasets (Gaut and Skre, 2011): Dorestad material clusters closer to Levantine alumina levels, while Ribe and Kaupang rest closer to the HIMT area in both alumina and iron oxide contents. The same correspondence can be observed when calcium oxide and alumina are plotted together (Figure 122). The diverse content of alumina and calcium between Dorestad and Ribe glass implies that they differ in both lime and feldspar sources, which suggests that two different sets of raw materials where used to make them in the first place.

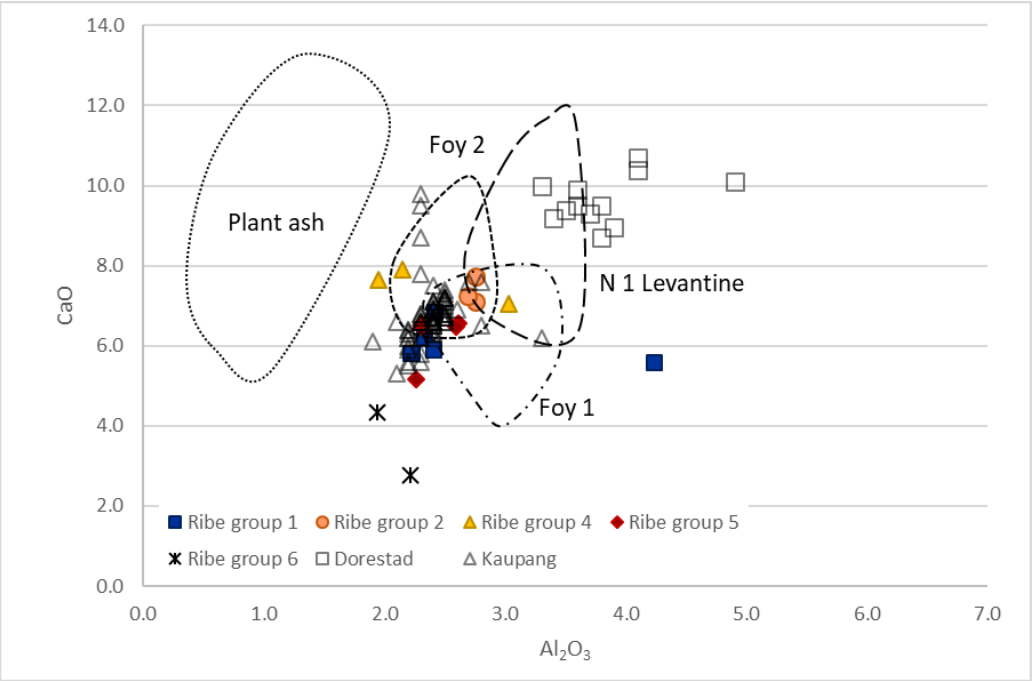


Figure 122 - Al_2O_3 vs. CaO contents for Ribe glass groups based on cluster analysis. Comparable data: Foy 1 and Foy 2 data (5th – late 8th century AD) after Foy et al., 2003, Levantine I - Apollonia type glass after Phelps et al., 2016; 8th – 9th century AD Dorestad glass dataset after Sanderson et al., 1984; 9th century AD Kaupang natron glass dataset after Gaut, 2011.

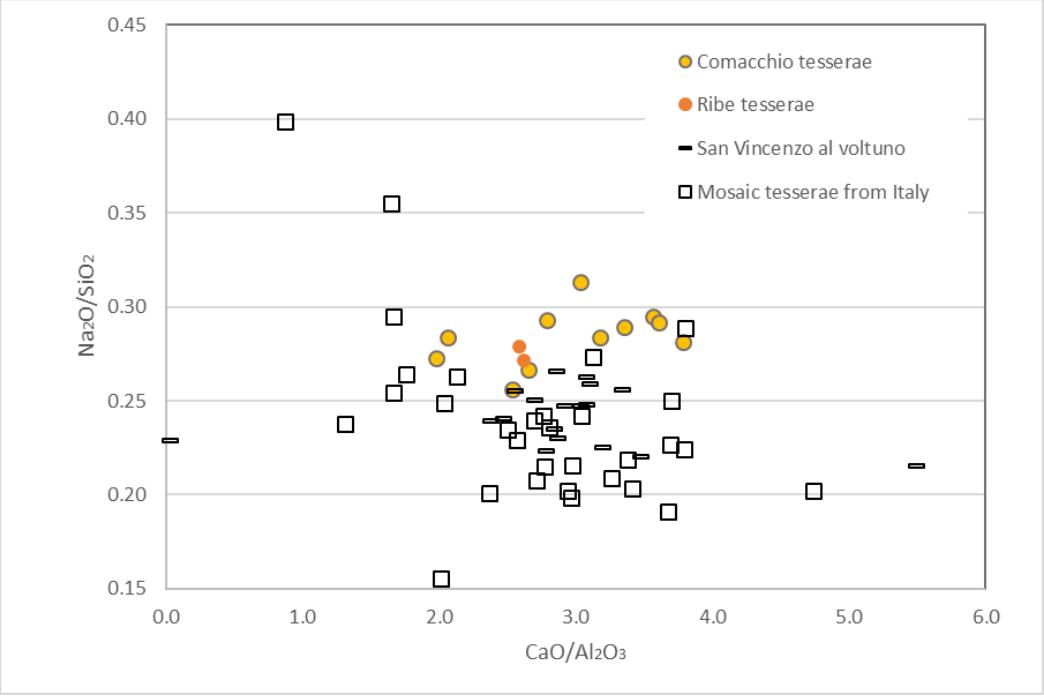


Figure 123 – CaO/Al_2O_3 vs. Na_2O/SiO_2 ratios for translucent and opaque mosaic tesserae from Ribe and Comacchio (overall half 7th century AD - 11th century AD). Comparative data: San Vincenzo al Volturno (9th century AD), after (Schibille and Freestone, 2013, table 1, 4); Roman mosaic tesserae from Italy (3rd century AD – 4th century AD), after Boschetti et al., 2016, table 2, 306.

Kaupang and Ribe similarities instead suggests the opposite, that the two datasets potentially share the area of production.

Lastly, I would like to address the origin of Ribe mosaic tesserae. It has been suggested already that mosaic tesserae from Ribe were imported from Northern Italy (Feveile, 2012, 115), but this affirmation has never been supported by compositional data.

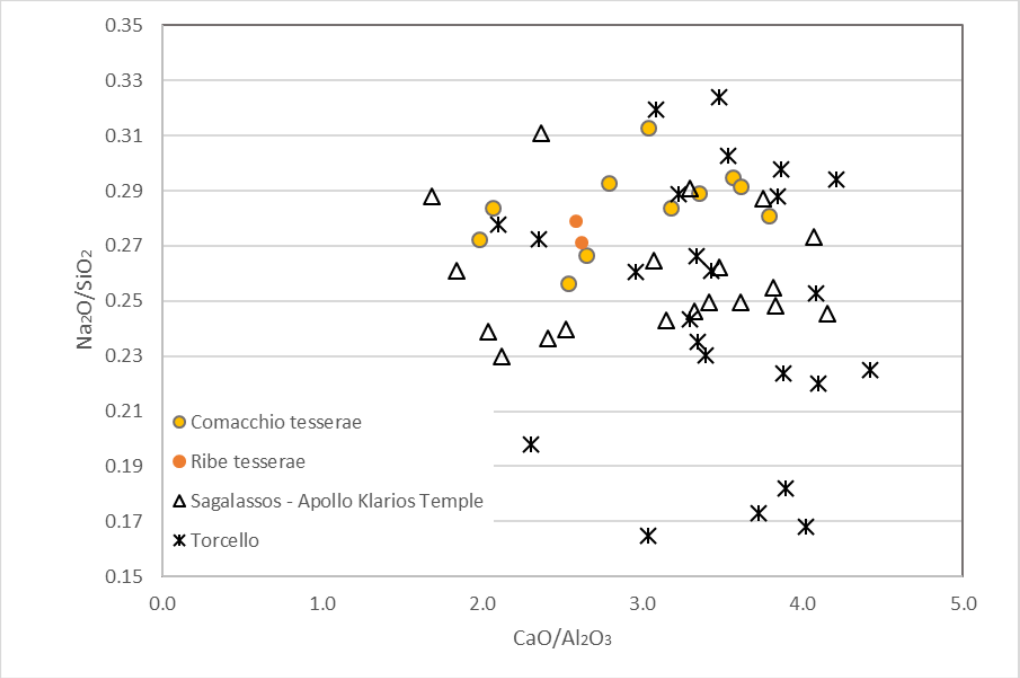


Figure 124 - CaO/Al_2O_3 vs. Na_2O/SiO_2 ratios for translucent and opaque mosaic tesserae from Ribe and Comacchio (overall half 7th century AD - 11th century AD). Comparative data: Late Byzantine mosaic tesserae from Sagalassos - Apollo Klarios Temple (6th century AD); Mosaic tesserae from Basilica Santa Maria Assunta in Torcello, Venice (11th – 12th century AD), after Andreescu-Treadgold et al.,, 2006, table 1, 123.

I decided therefore to compare mosaic tesserae from Ribe and Comacchio for silica, soda, feldspar, and lime content by plotting CaO/Al_2O_3 and Na_2O/SiO_2 ratios together. In Figure 123, the plot shows Comacchio and Ribe tesserae compared with Roman mosaic tesserae (3rd century AC - 4th century AD) and San Vincenzo al Volturno (9th century AD), which are considered of Roman origin. The two tesserae from Ribe fall within Comacchio higher Na_2O/SiO_2 ratios (>0.25), while

Roman and San Vincenzo tesserae overall show lower ratios (<0.25), save two samples from Boschetti and colleagues work.

Figure 124 reveals a different situation. If Comacchio and Ribe are compared with Byzantine material from 6th century AD Sagalassos-Apollo Klarios temple material (Schibille et al., 2012) and 11th- 12th century AD Santa Maria Assunta – Torcello mosaic tesserae, there is a partial overlapping, primarily with Torcello samples.

First, the compositional similarity between Comacchio (and therefore, Northern Italian samples) and Ribe tesserae was never proved until now. Secondly, the partial overlapping between Ribe, Comacchio, Torcello, and Sagalassos tesserae means that they have common raw materials.

This evidence does not imply that Ribe tesserae were made in Comacchio, or that such materials have been made at the same workshop. Nonetheless, the compositional similarity makes plausible to theorise the use of similar raw materials for the samples from Ribe, Comacchio and part of Sagalassos, and Torcello one, and therefore a common glass-making technology and, potentially, a common primary workshop for all these samples.

5.1.3.3 Trace elements

A selection of 18 samples from Ribe have been analysed for 47 trace elements by LA-ICP-MS. In Figure 125 and Figure 126, heavy mineral and carbonaceous sand fraction are plotted according to Ribe glass groups. In Figure 125, Ribe material plots within the refence Levantine and HIMT datasets, which might suggest mixing practices between two defined end-member similar to the plots illustrated for Comacchio dataset. On the other hand, Ribe materials do not show any potential end-member as instead hypothesised for Comacchio glass. The absence

of end-members suggests that Ribe glass might have been through repetitive cycles of indiscriminating recycling.

The majority of Ribe samples plot within the Foy 2 Zr/SiO_2 and Sr/CaO ratio (Figure 126). Sr/CaO content could then suggest that the carbonaceous fraction of the sand source in natron glass from Ribe is similar to Foy 2, which suggests that Ribe glass falls within the limits of a weak HIMT formula, as showed by the Empa analysis.

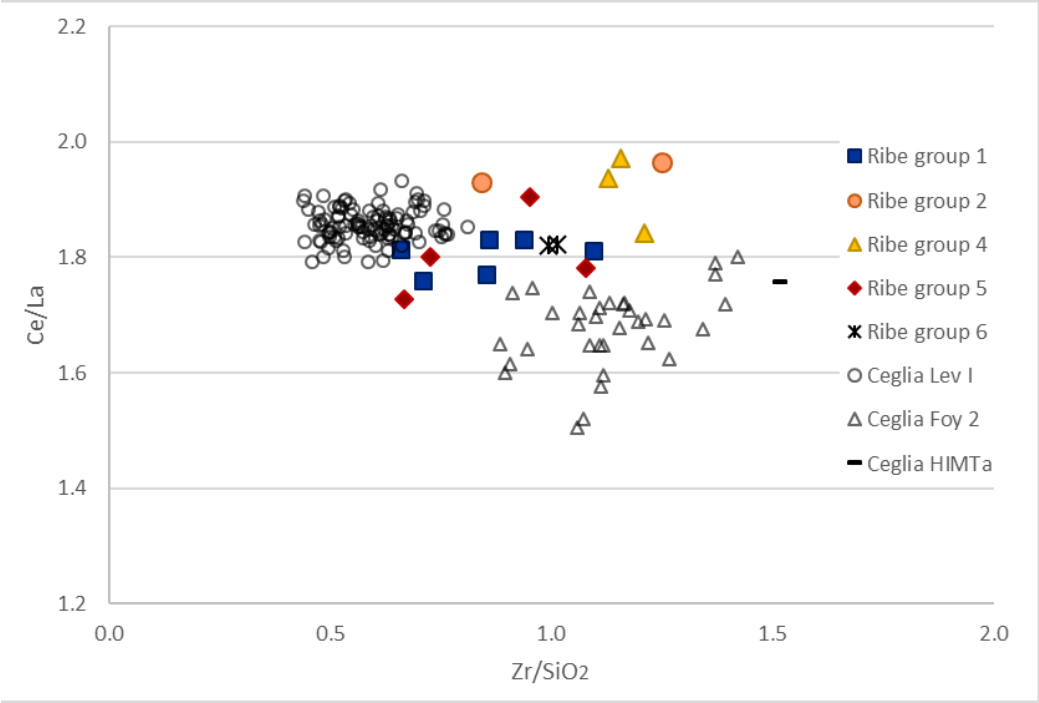


Figure 125 - Zr/SiO_2 and Ce/La ratios of Ribe glass groups. Levantine I, Foy 2, HIMTa comparison materials (non-recycled) are plotted after Ceglia et al., 2017

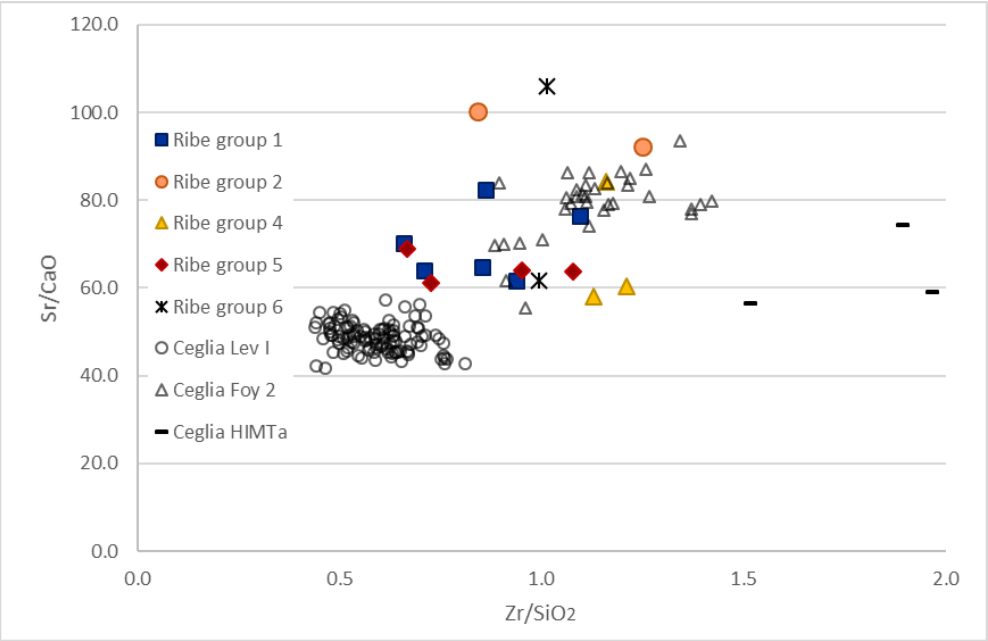


Figure 126 - Zr/SiO_2 and Sr/CaO ratios of Ribe glass groups. Levantine I, Foy 2, HIMTa comparison materials (non-recycled) are plotted after Ceglia et al., 2017.

The REE profile does not help in discriminating Ribe glass (Figure 127). Ribe group 1, 2, 4, and 5 show profiles falling in-between both Levantine and Foy 2 – weak HIMT recipes. Similar Zr content are found in groups 1 and 5, and the same can be said for groups 2 and 4. The barium normalised concentrations fall within the limits of HIMT glasses (c. 0.70). Nb concentrations seem to be discriminating, with different concentration values in all four group (0.13 -0.24). Lighter REE elements show instead different patterns in all 4 groups.

Given the similar Sr/CaO ratios, I am inclined to suggest that the basic glass for Ribe must have been HIMT in its weak form. If Sr/CaO ratios and the REE are considered, two hypotheses are potentially correct: Ribe glass could have undergone repetitive cycles of recycling using the same formula, or it could be the mixing of Levantine and weak HIMT recipes, with the latter of being the base for the glass.

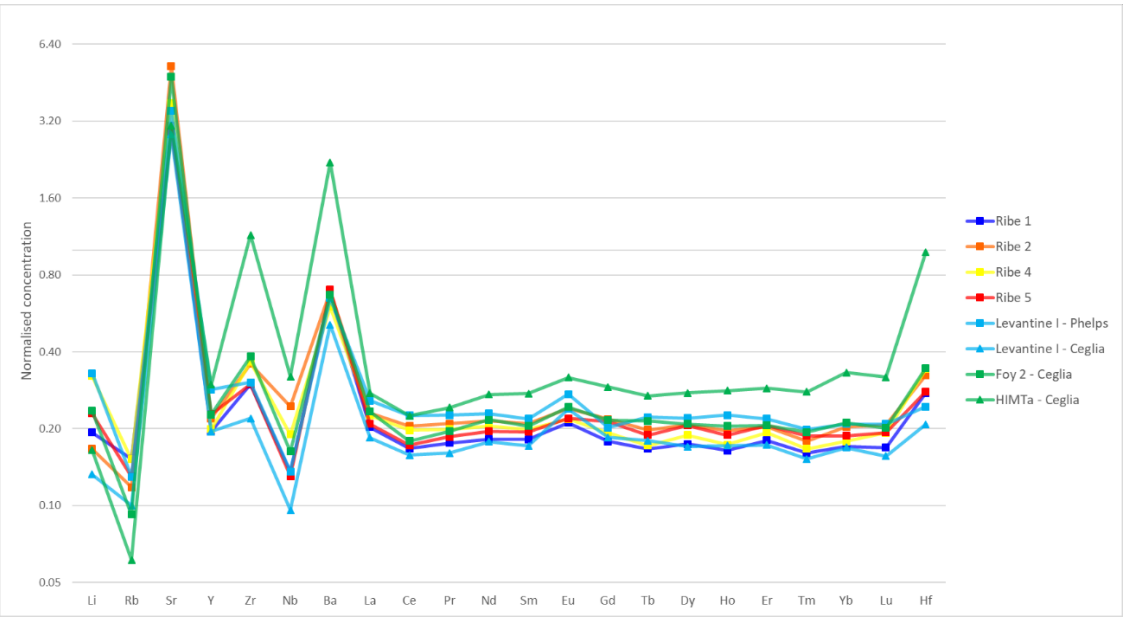


Figure 127 - Concentration of trace elements normalized to the upper continental crust (Kamber et al. 2005) for a selection of elements in Ribe glass groups based on cluster analysis. Comparison Levantine material after Phelps et al., 2016 and Ceglia et al., 2017; comparison HIMT material after Ceglia et al., 2017.

An interesting pattern emerges when the same Zr/SiO_2, Ce/La, and Sr/CaO ratios are plotted according to colour (Figure 128 and Figure 129): red, yellow, white, and green opaque samples plot with overall higher values in all three ratios; transparent and semi-opaque blue and green samples on the contrary, show lower values in all three ratios.

This subdivision cannot be considered the result of random mixing in my opinion. At this point of the research, I cannot indicate with confidence if the material treated in this dissertation was re-melted in Ribe or if this material is the result of gathering cullet waiting to be remelted. If the local secondary production and re-melting in Ribe is assumed, such correspondence between colours and recipes indicates that Ribe artisans operated a careful selection of raw material (cullet), and secondly they would pair certain colours in that specific cullet/recipe, practice potentially connected to bead-making production.

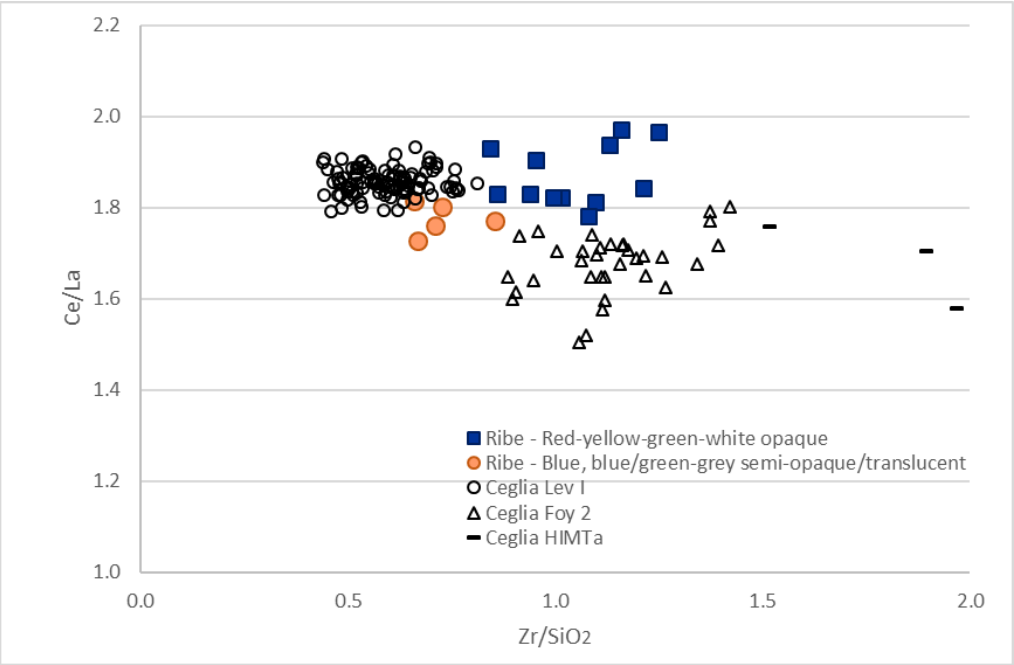


Figure 128 - Zr/SiO_2 and Ce/La ratios of Ribe glass divided by colour. Levantine I, Foy 2, HIMTa comparison materials (non-recycled) are plotted after Ceglia et al., 2017.

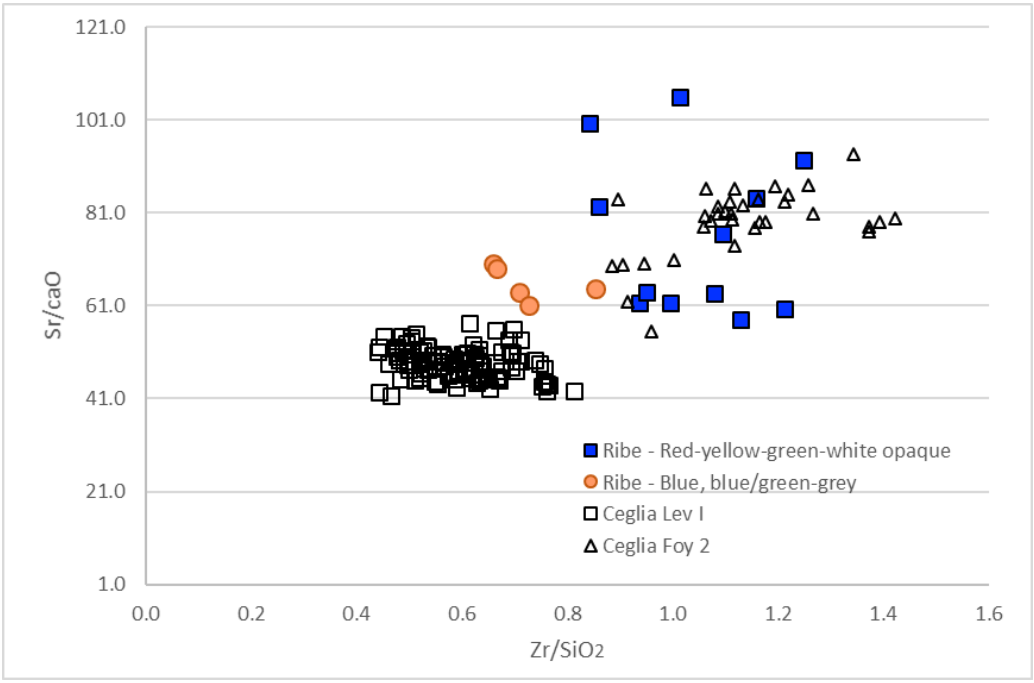


Figure 129 Zr/SiO_2 and Sr/CaO ratios of Ribe glass divided by colour. Levantine I, Foy 2, HIMTa comparison materials (non-recycled) are plotted after Ceglia et al., 2017.

The same careful selection of raw material was nevertheless in place if this dataset belongs to material that was waiting to be remelted. In both cases, this level indicates a strong control of the secondary technological process, both in the actual manufacture of the glass and in the organisation and storage of the same material.

5.1.3.4 Summary Ribe glass types

Ribe glass, as in Comacchio and Barking Abbey datasets, is formed by mostly natron-based low potash- magnesia glass, save one group (group 6) which shows elevated PbO contents (>32.00wt%). Cluster analysis in this case proved to be a poor discriminant of the Ribe groups: CaO and TiO_2 are the most discriminant elements in all natron-based groups (group 1, 2, and 5), but overall, they all show similar contents in all major oxides similar to HIMT – Foy 2 recipe. Trace elements proved to be a poor discriminant for the Ribe glass dataset, even if normalised SiO_2 is paired with Zr as suggested for Comacchio and Barking Abbey datasets.

In both plots (Zr/SiO_2 vs. Ce/La and vs. Sr/CaO) Ribe glass falls in-between Levantine I and Foy 2 non-recycled limits, suggesting that Ribe glass might have gone through repetitive recycling cycle but no clear end-members where identified, as occurred for Comacchio glass: unfortunately, I cannot support this hypothesis with confidence given the current state of research.

Magnesium and potassium oxide contents in group 4 paired with lower alumina content (c. 2wt%) might suggests that group 4 is made with plant ash as major source of alkali. Nonetheless, other major oxides values do not match a plant ash basic recipe.

Moreover, when trace elements are considered, group 4 plots closer to HIMT – Foy 2 high Zr/SiO_2 (1.13 -1.21) rather than lower ratios registered in group 4 plant ash from Comacchio (0.27-0.52). Two samples supposedly of plant ash glass plot within Levantine and HIMT – Foy 2 values for Sr/CaO non recycled group suggested by Ceglia and co-workers (2017): Rib76 instead plots together very few samples within the area of Foy 2 Sr/CaO. Therefore, a different sand richer in Zr content could have been used for the plant ash glass from Ribe, or it could be the result of mixing a base natron glass with a small quantity of plant ash glass.

Red, green, white, and yellow opaque samples show a distinctive higher Ce/La (1.8 – 2.0) and Zr/SiO_2 (0.84 – 1.25) ratios when compared to semi-opaque blue or blue-green and grey translucent glass, which might indicate that the main criterion of selection and recycling at Ribe was colour and not its basic recipe. Therefore, a careful selection of material through colour would have allowed recycling using only such colours. Unfortunately, the undiagnostic character of Ribe glass compositions does not allowed at the moment to carry on the research further.

Averaged Empa and trace results are reported respectively in Table 11 and Table 12.

Table 11 - Mean composition for all oxides for each of the 5 groups of Ribe dataset analysed in this dissertation; n/a = not applicable.

	Ribe group 1 (n= 6)		Ribe group 2 (n=3)		Ribe group 4 (n=3)		Ribe group 5 (n=5)		Ribe group 6 (n=2)	
Element	**Average**	**Sd**	**Average**	**Sd**	**Average**	**Sd**	**Average**	**Sd**	**Average**	**Sd**
SO_3	0.26	0.13	0.22	0.03	0.18	0.02	0.18	0.12	0.19	0.06
P_2O_5	0.06	0.03	0.08	0.04	0.27	0.2	0.08	0.02	0.13	0.01
V_2O_5	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
As_2O_5	0.03	0.03	0.01	0.01	0	0	0.01	0.02	0.25	0.25
Sb_2O_5	1.66	1.35	0.63	0.59	0.13	0.11	1.01	0.79	0.14	0.1
SiO_2	67.18	2.83	65.88	1.87	59.64	1.7	67.75	3.28	45.87	1.34
TiO_2	0.07	0	0.08	0.01	0.12	0.01	0.09	0	0.06	0.01
SnO_2	0.18	0.32	0.2	0.17	0.49	0.05	1.17	2.16	3.68	1.13
Al_2O_3	2.63	0.72	2.73	0.03	2.38	0.47	2.42	0.15	2.08	0.14
Cr_2O_3	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.01	0	0
Fe_2O_3	1.09	0.79	1.6	0.79	1.28	0.27	1.8	1.47	0.57	0.02
MgO	0.63	0.09	0.83	0.03	3.32	0.52	0.67	0.09	0.44	0.05
CaO	6.03	0.41	7.36	0.27	7.54	0.35	6.24	0.54	3.56	0.79
MnO	0.4	0.14	0.85	0.25	1.05	0.18	0.67	0.37	0.28	0.03
CoO	0.02	0.03	0.02	0.02	0.02	0	0.03	0.02	0.02	0.02
NiO	0.01	0.01	0.01	0.01	0	0	0.01	0.01	0.03	0
CuO	0.34	0.6	0.44	0.16	1.31	0.93	0.83	0.78	0.04	0.02
ZnO	0.02	0.02	0.01	0.01	0.05	0.05	0	0	0.04	0.04
BaO	0	0	0	0	0	0	0	0	0	0
PbO	3	3.98	1.07	0.52	5.72	1.59	0.56	0.38	34.42	2.42
Na_2O	14.91	1.74	15.91	1.47	13.98	0.73	16.34	0.81	8.95	2.97
K_2O	0.63	0.13	0.79	0.21	1.74	0.54	0.61	0.04	0.4	0.03
Ag_2O	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Cl	0.84	0.15	0.96	0.02	0.7	0.06	0.89	0.12	0.59	0.25

Table 12 - Mean composition for selected elements for each of the 4 groups of Ribe dataset analysed in this dissertation.

	Ribe Group 1 (n=6)		Ribe Group 2 (n=2)		Ribe Group 4 (n= 3)		Ribe Group 5 (n=4)		Ribe Group 6 (n=2)	
Element	**Average**	**Sd**	**Average**	**Sd**	**Average**	**Sd**	**Average**	**Sd**	**Average**	**Sd**
Li	5.45	1.17	4.71	0.27	9.07	2.88	6.48	1.7	13.17	7.66
B	171.89	16.05	212.75	26.05	131.17	19.52	162.51	20.13	99.18	9.52
Ti	652.59	146.5	1272.83	448.17	975.11	236.05	643.81	120.63	659.3	135.63
Cr	14.1	2.94	19.74	6.01	26.64	9.58	14.2	2.94	12.93	1.99
Mn	4563.61	1201.23	2563	843.33	5328.11	2484.47	4568.98	2203.96	2415	15
Fe	8727.44	5348.22	16947.5	6952.5	9357.33	2690.56	12681.5	11437.19	4611.67	951.67
Rb	12.15	4.52	9.38	1.12	12.06	3.93	10.35	1.83	13.43	5.96
Sr	436.39	34.68	745.97	9.93	536.09	122.05	412.69	47.07	291.4	13.5
Y	6.21	0.52	7	1.3	6.34	1.24	7.26	1.61	5.45	0.79
Zr	59.27	8.49	71.52	16.45	72.72	3.78	59.55	10.59	47.83	1.83
Nb	2.07	0.33	3.75	1.02	2.91	0.55	2	0.22	2.31	0.56
Cs	0.3	0.12	0.14	0.04	0.28	0.16	0.21	0.06	1.5	1.18
Ba	264.96	42.64	272.87	12	237.44	105.65	276.89	76.63	190.48	17.62
La	6.59	0.45	7.47	1.4	7.33	0.24	6.78	0.52	6.47	1.37
Ce	11.88	0.8	14.58	2.86	14.04	0.05	12.25	1.37	11.79	2.49
Pr	1.49	0.09	1.77	0.34	1.69	0.06	1.58	0.18	1.45	0.3
Nd	6	0.4	7.05	1.45	6.74	0.5	6.43	0.69	5.83	1.05
Sm	1.25	0.1	1.44	0.28	1.37	0.08	1.34	0.19	1.16	0.23
Eu	0.33	0.02	0.38	0.09	0.34	0.06	0.34	0.05	0.27	0.04
Gd	1.13	0.1	1.39	0.37	1.23	0.19	1.36	0.21	1.01	0.17
Tb	0.17	0.01	0.2	0.04	0.17	0.03	0.19	0.03	0.14	0.02
Dy	1.03	0.11	1.22	0.25	1.11	0.2	1.21	0.28	0.94	0.12
Ho	0.2	0.02	0.24	0.05	0.21	0.04	0.23	0.04	0.19	0.02
Er	0.61	0.06	0.69	0.15	0.65	0.12	0.69	0.14	0.57	0.08
Tm	0.08	0.01	0.09	0.02	0.09	0.02	0.1	0.02	0.08	0.01
Yb	0.55	0.05	0.66	0.13	0.58	0.1	0.61	0.12	0.5	0.1
Lu	0.08	0.01	0.1	0.02	0.09	0.01	0.09	0.02	0.08	0.02
Hf	1.47	0.21	1.72	0.39	1.82	0.05	1.49	0.26	1.26	0.14
Th	1.23	0.16	1.47	0.32	1.44	0.03	1.24	0.22	1.4	0.47
U	0.99	0.08	0.88	0.12	0.87	0.13	0.99	0.04	0.85	0.12

5.1.4 Summary compositional analysis

Compositional data presented in this chapter suggest that glass found at Comacchio, Barking Abbey, and Ribe falls within compositional major and trace compositional limits of known Late Byzantine and Early Medieval recipes. Comacchio glass belongs to both the HIMT weak (group 2B) and strong variant (group 8) and Levantine I composition (group 1A, 2A, and 3), with the integration of small quantities of plant ash glass (group 4). Barking Abbey and Ribe on the other hand see the presence of respectively Levantine (Barking group 1, 2, and 3) or weak HIMT (Ribe group 1, 2, and 5) respectively. Barking Abbey also includes a limited group of potash high alumina-low calcium silica glasses (group 4), which are characteristic of South and Southeast Asia and potentially made in China. Finally, two samples of lead soda glasses (group 6) have been found at Ribe.

If we compare basic EMPA results (Figure 130, Figure 131, and Figure 132), we can overall state that there is a general agreement between the different compositions across the three sites. Comacchio and Ribe against Barking Abbey.

Barking shows variable K_2O, but the compositions are still included in the known natron limits.

There is an increase of both K_2O and MgO values in group 4, the majority of Ribe samples cluster tightly around lower values of both oxides (0.5wt%). Comacchio samples on the other hand overall show spread values across both MgO and K_2O, which can be explained as contamination from furnace and crucible as described in section 5.1.1.3.

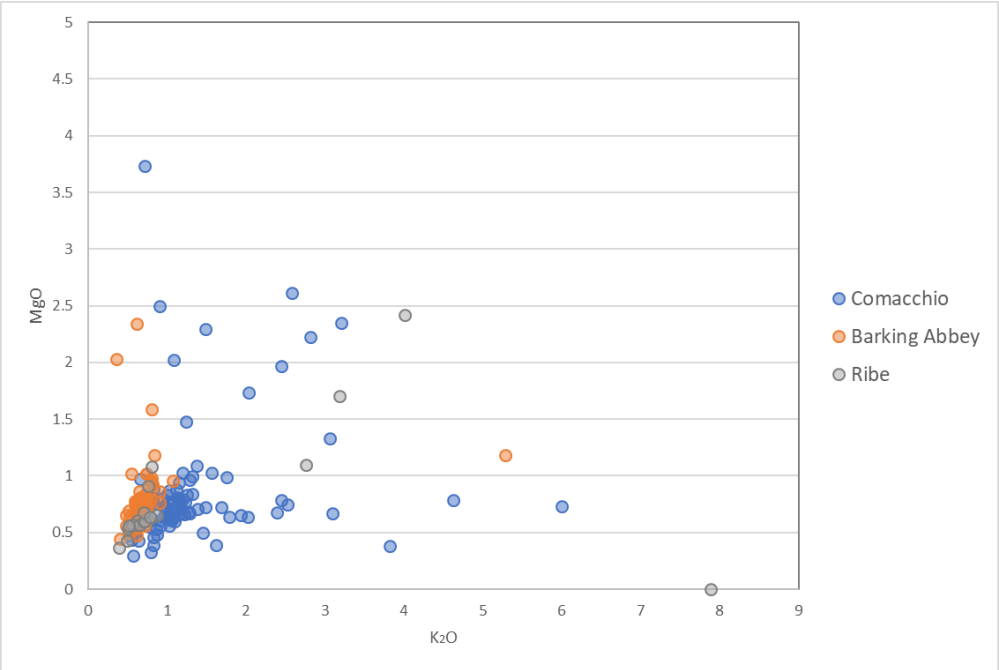


Figure 130 – K_2O vs. MgO contents in Comacchio, Barking Abbey, and Ribe glass.

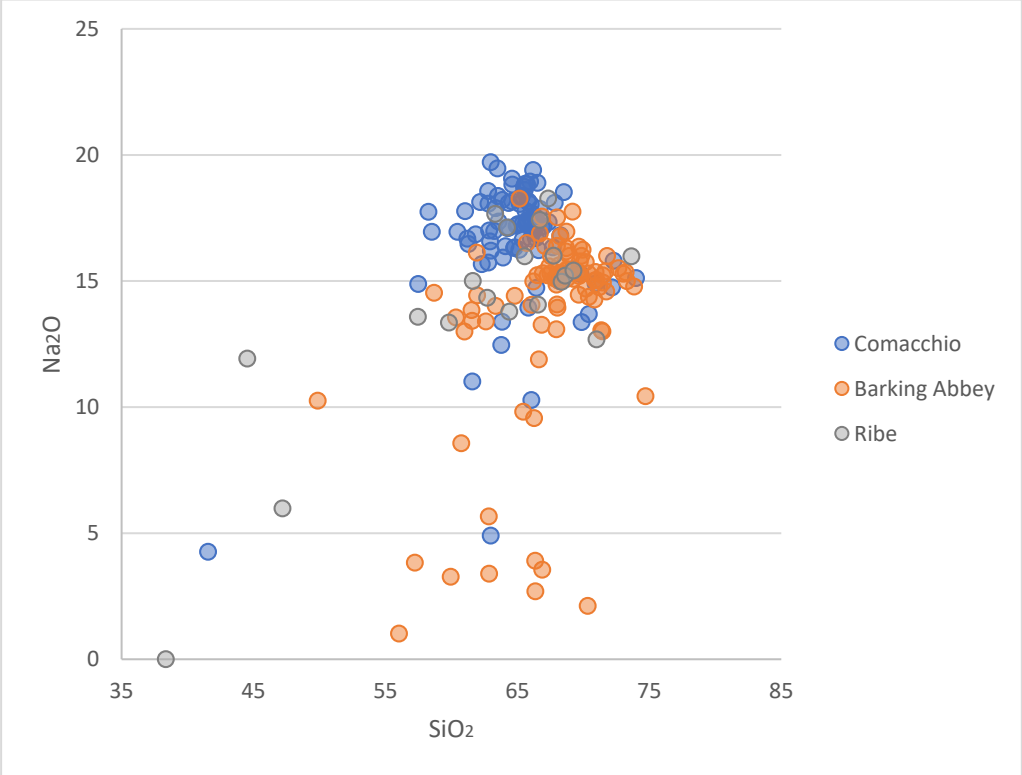


Figure 131 – SiO_2 vs. Na_2O contents in Comacchio, Barking Abbey, and Ribe glass.

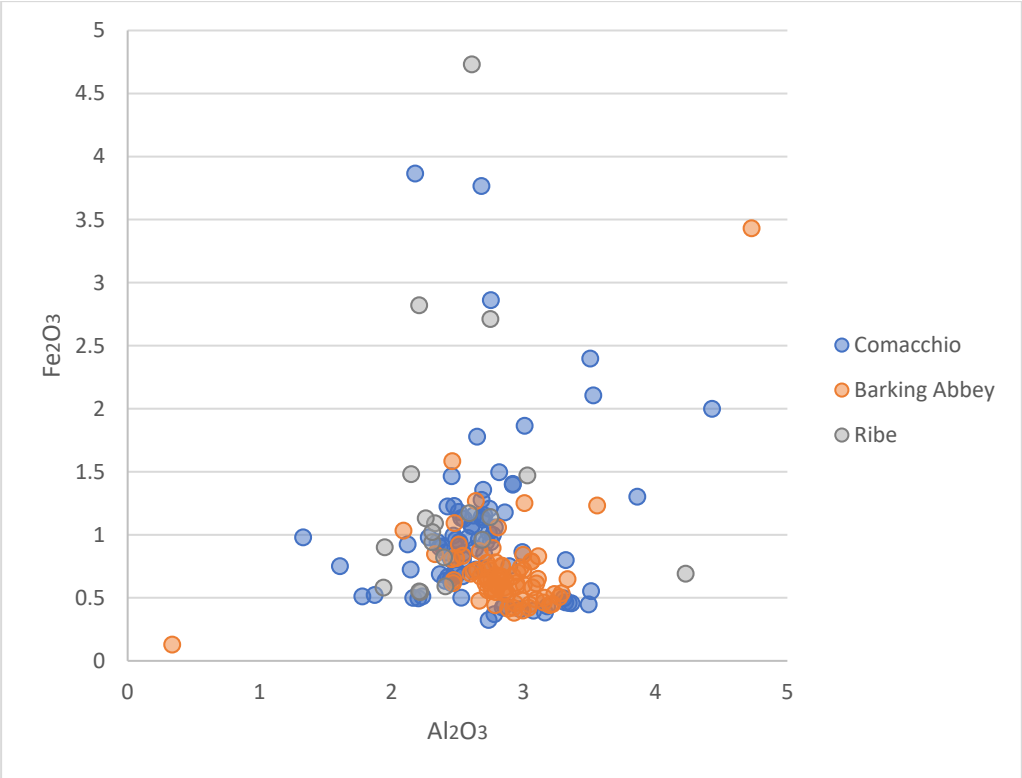


Figure 132 – Al_2O_3 vs. Fe_2O_3 contents in Comacchio, Barking Abbey, and Ribe glass.

Barking Abbey samples shows an overall higher SiO_2 content (Figure 131), save in group 2 and part of group 4. The majority of Comacchio samples have much higher Na_2O and lower SiO_2 levels, which are compatible with the prevalence of the HIMT recipe. Interesting enough, Ribe samples spread between Comacchio and Barking Abbey SiO_2 values, which might account for its heavily recycled nature and presence of opacifiers which replace/stand for other network formers (such as silica).

If alumina and iron are compared throughout the three datasets (Figure 132), Comacchio samples do separate well between HIMT and Levantine values. Part of Barking samples falls within the Comacchio Levantine limits, which might suggest a common origin of raw materials. The remaining Barking Abbey samples falls in-between Comacchio wHIMT and Levantine, which may account for the impurities in group 1

Barking group 2 which falls instead with Comacchio wHIMT, which again might account for the potentially mixed nature (more elevated impurities levels) of the group itself as described in section 5.1.2.15.1.2.2, and 5.1.2.3.

On the other hand, RIbe samples fall within Comacchio wHIMT values, which agrees with the initial interpretation of Ribe as majority of HIMT samples.

All groups mentioned above are more or less widespread in the Western World, which suggest that all three sites were engaged within the centralised glass-making network, but at different levels.

As noted before, Barking Abbey glass agrees well with other contemporary site from British sites, such as the Anglo-Saxon sites of Hamwic, Jarrow and Wearmouth. The Hamwic glass situation is complicated to assess, given not only the nature of limited nature of the assemblage itself (domestic environment), but also by the lack of compositional reference given in the original study by Hunter and Heyworth (1998). Hence in my opinion the original material needs further investigation to be compared effectively with the Barking material. High levels of recycling markers and the potential addition of cullet is mentioned though (Hunter and Heyworth, 1998, 49).

Freestone and Hughes discuss the nature of Jarrow glasses (Freestone and Hughes, 2006, 153), and they agree that its composition is closer to Levantine groups rather than HIMT, according to their CaO and Al_2O_3 levels: only four samples fall within the HIMT range (Freestone et al., 2008, fig. 27.3.3. 152). Moreover, despite increased levels of iron oxide

and titania, Jarrow glass content of both oxides falls between alumina and iron oxide values expected from both Levantine and HIMT glasses. Increasing levels of both iron oxide and titania therefore might due to repetitive recycling and from glass-working instruments and crucibles, introducing contaminants through reuse and remelting (Freestone and Hughes, 2006, fig. 27.3.4, 153; 148). Two samples that show markers for recycling show comparable low levels of Fe_2O_3 with Levantine composition (0.3 -0.4wt%) and indicate a limited history of recycling. These two samples could represent the original glass from the primary Levantine source. Willmott and Welham (2015, 236) mention that glass from Glastonbury might have a Levantine origin too.

This correspondence suggests a preference for Levantine glass throughout Southern England, at least from the Barking material. We know from work by Foster and Jackson on earlier 4th – 5th century AD from Romano-British assemblages (2009) that HIMT and Levantine glass were present at the same time in England and therefore, they were sharing the same market. 5th – 8th century AD glass analysed by Freestone et al. (2008) shows also interesting compositional variability, with the Period II glasses (550 - 700) presence of both natron and plant ash-based recipes, which is not found in later material from Barking. In addition, Foster and Jackson also underlined the preference of HIMT glasses over Levantine in such early British assemblages (2009, 195-6). The main question is why HIMT glass is not present at Barking and why Levantine seems to be preferred in Southern Britain after a certain date?

First, the limited presence of HIMT in Southern Britain could be due to a lack of published studies and assemblages, as the Hamwic example shows. Secondly, the presence of Levantine at Barking Abbey could be relegated to a matter of preference (colour or shape of that object made with that specific glass recipe), or to movement of artisans travelling with their own glass supplies. If we take Bede's account for accurate, artisans were called first from Gaul in 674 and then from Mainz in the 8th century AD, because locals could not produce neither windows or glass vessels

for Jarrow and Wearmouth. The hypothesis of artisans importing their own glass to be used locally is quite plausible and we cannot exclude that something similar could occurred at Barking too. The evidence of the addition of materials characterised by high levels of opacifier components (such as tin and lead) and therefore the production of new "fresh" glass together with the high-quality millefiori and reticella rods wasters needs to be view as the work of highly skilled and specialised artisans.

Most likely, the selective presence of the Levantine recipe is due to selective trade of glass, at where it concerns Barking Abbey. As suggested by Foster and Jackson (2009, 195) for an earlier period "*perhaps we should stop seeing these two glasses as servicing the same markets. Although they are both contemporary [HIMT and Levantine I], and present evidence indicates that their provenance is possibly in the east Mediterranean, they were in fact manufactured at different locations whose products may have been destined for different consumers*".

Could it be that for Southern England, Levantine was the best glass option in the 9th – 10th century, and even potentially from an earlier date. It has been previously suggested an earlier chronology for Barking material by Evison (1991) and remarked for Glastonbury furnaces potentially at the 7th – 9th century AD too (Willmott and Welham, 2015, 233). Could it be that certain trade routes were preferred over others, and that only certain glass compositions were travelling (or at least favoured)? In my opinion, the difference in preference between Barking with its predominance of Levantine I and Ribe and Comacchio, where HIMT glass in its weak form was still circulating and re-worked, needs to be considered in this same perspective. Crypta Balbi glass is a perfect example of HIMT glass still circulating and recycled in the 7th and 8th century (Mirti et al., 2000, 2001), or Foy2 from 10th – 11th century Nogara samples.

Comacchio shows a consistent presence of Levantine too (group 1A, 2A, and 3) paired with HIMT. Was perhaps Comacchio privileged because of its geographical position and trade routes?

Potash high alumina low calcium silica group 4 at Barking it is not an isolated occurrence in the Western world. The presence of high alumina glass fluxed with both soda and potash (like Barking group 4) has been recently the object of a renewed interest in the glass community. For example, red-orange glass potentially made in South and Southeast Asia with n-ma-K composition in high-alumina mixed-alkali composition found in 7th -8th century AD Scandinavia has been discussed in a recent article by Sode and colleagues (2017). Such a presence has been associated mostly with bead trade, but Barking group 4 does not include beads, and therefore we might be looking at scrap material gathered to be re-worked at the Abbey. Ba61's compositionally mixed character seems to support the existing of mixing of the natron and high potash group too, potentially in the same Barking workshop.

Even though the number and character of samples from Ribe included in this dissertation is limited in both number and typology, its blurred compositional signature cannot be ignored, even more so in light of the compositional variability that instead was available at 9th century Kaupang, where six major glass groups were identified (Gaut and Skre, 2011, 269). The same undefined compositional signature endured when trace elements and Empa normalised silica were paired, hence the hypothesis of continuous mixing of glass, potentially from HIMT weak source.

If Ribe was supplying its glass needs by importing only one recipe, as was occurring for Barking, why this was happening? Is this the result of long-distant trade routes between selected and privileged actors? If we look at glass from Dorestad analysed by Sanderson and colleagues (1984), the picture that we get from its major element data is similar. As we observed previously (section 5.1.3.2), major elementals compositional data from Dorestad results are closer in composition to a Levantine I recipe than HIMT. Henderson's work on Dorestad glass (Henderson, 1995, 53-52) suggest also that Dorestad glass is made by

Old Roman glass recycled or potentially by a fresh glass with the addition of tesserae.

Given that those glasses in the 8th century were made in totally different places, respectively in the Palestine region (Freestone et al., 2003) and supposedly Egypt (Nenna, 2014), could this difference imply the existence of separate trade routes (and maybe trading agents), at least when glass was involved?

An invisible *fil rouge* connects Northern Italy with Ribe not only because of the concurrent presence of HIMT, but also throughout their mosaic tesserae compositional similarities, which has been suggested (Feveile, 2012) but never proved until now. Could this occurrence also imply similar trade routes and a special connection between Northern Italy and Scandinavia? Could Northern Italy constitute a hub for gathering glass material (such as for example Byzantine mosaic tesserae) and then carry on them to the North, throughout the Alps, the rivers Rhine network directly to Scandinavia (or at least to Ribe)? An also, does the difference in glass composition between Ribe and Dorestad imply a difference in trade route also?

From the data gathered in this chapter, Comacchio compositional data show a more heterogeneous picture, not only for the variety of recipes present at the site, but also because of the degree of glass-working processes occurring such as evidence for potential mixing HIMT and Levantine composition or intermixing between the same base Levantine glass recipe, as well as plant ash with natron glass, even if limited to few samples. The concurrent presence of Levantine and HIMT glass is not an unlikely occurrence in the 7th – 8th century AD in Northern Italy: Uboldi and Verità report for glass from Lombardy (2003, 130) for group N1 (4th – 8th century AD) and N2 (4th – 10th century AD), respectively Levantine and HIMT recipes. The same can be said about mixing of natron and plant ash (Verità et al., 2002; Uboldi and Verità, 2003; Andreescu-Treadgold et al., 2006; Silvestri and Marcante, 2011). There is also no reason to doubt glass-working at Comacchio, given the presence of

numerous crucibles and glass-working debris associated chronologically with the workshop's furnace (late 7th – early 8th century AD).

Mixing of different recipes of glass implies the presence of skilled artisans working at the workshop and deliberate technological choices, but the motives behind this choice could be numerous. Scarcity of glass coming from the primary zone of production as always being considered the main underlined motive behind recycling and mixing of glass, especially in the Southern Italian Peninsula. Could mixing of HIMT and Levantine arisen instead from a high demand of glass in the area?

Besides the manufacture of various types of glass-wear, like goblets, as suggested by Ferri (Gelichi et al., 2012, note 25, 178), we know that from the 8th century a new cathedral was built in the same area, and the glass production from the workshop might be connected to the construction itself. Unfortunately, we cannot answer to this question at the moment, since the glass workshop in Comacchio is associated with the period immediately before the cathedral construction, even though Gelichi and colleagues do not exclude the possibility that the workshop could have been moved elsewhere (Gelichi et al., 2012).

Comacchio's geographical position and its role as Early Medieval commercial hub makes it a potential contender as a privileged access point for plant ash in Northern Italy. Given the later chronology (10th – 11th century AD) plant ash – group 4 when compared to the other glass present at the site (most of glass from Comacchio is associated with late 7th - 8th century AD), when was group 4 traded to Northern Italy? Was plant ash connected to the workshop?

Com21 together with its positive correlation in P_2O_5 vs. K_2O with other natron-based samples dated to 7th – 8th century AD from group 1 (Com63 and 36), group 2 (Com79), group 3 (Com76), and 7 (Com40), suggests two main hypotheses.

First, mixing with plant ash glass could be earlier than the 10th -11th century AD date associated with group 4: given the nature of such mixed

composition samples (crucibles and wasters), the workshop must have been involved. As a consequence, group 4 might have been produced earlier than thought and circulated in Comacchio until its last deposition.

Second, plant ash group 4 is indeed dated to the 10th -11th century AD, and group 4 cannot be considered an end-member in the fore-mentioned correlation. Therefore, the increased amount in K_2O, and P_2O_5 associated with those samples has to be considered the product of contamination from fuel ash or the same samples could have been diluted with small quantities of another plant ash that has not been included in this dissertation. The same can be said for supposedly mixed Com14 (group 2C). I think the second hypothesis has to be preferred at the moment in light of the different chronologies assigned to the material.

Where plant ash from group 4 was produced initially? Trace elements data provided in this chapter has evidenced how plant ash in Comacchio is different in trace elements from glass from Raqqa, known primary centre for the 8th – 9th century AD. Therefore, plant ash made in Comacchio could have been made in a still-unknown primary workshop different from Raqqa. 10th and 11th century Tyre could be a potential contender (and group 4 chronology would match well with this hypothesis), but no trace elements data are available for comparison at the moment. We need also to consider the eventuality that group 4 might be made earlier than 10th – 11th century, and therefore Tyre has to be excluded as potential source for our glass.

5.2 Isotopic analysis

In this section, the provenance of a selected group of samples from Comacchio and Barking Abbey will be addressed with the help of Sr and Nd isotopic analysis. The number of analysis for each different isotope is listed according to each site are listed in Table 13. Full isotopic results are presented in Appendix 4.

Table 13 – Number of isotopic analysis for each isotope divided by site.

Site	$^{87}Sr/^{86}Sr$ (n = 55)	$^{143}Nd/^{144}Nd$ (n =39)
Barking Abbey	21	17
Comacchio	34	22

The main aim for this section is to address the provenance of lime and sand for each of the groups identified at Comacchio and Barking for the:

- Raw materials' provenance of Barking Levantine glass (group 1, 2, and 3);
- Raw materials' provenance of high potash high alumina low lime group 4 at Barking Abbey;
- Mixing practices between group 1, 2, and 3 at Barking Abbey;
- Raw materials' provenance of Levantine glass from Comacchio (group 1A and 3);
- Raw materials' provenance of both HIMT weak and strong variant from Comacchio (group 2B and 8);
- Mixing practices between base groups (1A, 2A, 2B, 3, and 8) and mixed groups (1B, 1C 2C) at Comacchio;
- Raw materials' provenance of plant ash from Comacchio (group 4);

The combination of Sr and Nd signatures will help addressing the provenance of Levantine, HIMT (weak and strong), plant ash glass found at Comacchio and Barking Abbey, of Levantine and high potash glass recipes by identifying their potential difference in isotopic signatures and comparing it with known published literature (Freestone et al., 2005, 2009; Henderson et al., 2005; Degryse et al., 2006; Degryse and Schneider, 2008; Henderson et al., 2009; Degryse et al., 2009a and 2009b; Degryse et al., 2010; Degryse, 2014; Gallo et al., 2015; Maltoni et al., 2015). The combination of the same isotopes will help to address recycling and mixing of HIMT and Levantine in Comacchio and Levantine recycling practices at Barking Abbey. Unfortunately, no isotopic signature (Sr or Nd) are available for group 2A (Com20).

The nature of plant ash in Comacchio will also be addressed by comparing it with plant ash from primary glass Sr and Nd signature from Raqqa, Syria (Henderson et al., 2009, 2005) and Tyre, Lebanon, and secondary glass-making site of Banias, Israel (Degryse et al., 2010). Sr signatures from plants harvested near Raqqa will be also plotted to be compared to our results. Group 4 area of production will be addressed by comparing its Sr and Pb signatures of potash silica glass (Brill and Fullagar, 2012; Li, 1999). Finally, I will summarise and comment on the results presented in this chapter, while introducing issues that will be discussed in the conclusions (chapter 6).

5.2.1 Sr isotopes

5.2.1.1 Comacchio

In Figure 133, $^{87}Sr/^{86}Sr$ ratios are plotted by group for Comacchio glass.

Group 3 is the closest group to modern sea water value (0.70917), with a range of 0.708921 – 0.709175 $^{87}Sr/^{86}Sr$, which suggests that lime

derived from a sand where the carbonate fraction consist mainly of modern marine shell with minor limestone material (Freestone et al., 2003, 28). The same can be said for group 1A (0.708991), hence confirming the original hypothesis of being of a Levantine recipe made with beach sand.

Group 8 (HIMT) Sr signatures (0.708127 - 0.708408) are included in the range of values published by Freestone and colleagues (2009, tab. 1.2, 42) for HIMT glass for Carthage (0.708079 – 0.708858) and North Sinai (0.708251 – 0.708785). It was therefore getting strontium less from shells and more from limestone-rich material (Freestone, et al., 2003, 28), closer to the one expected for a Tertiary limestone (Oligocene or possibly late Eocene date).

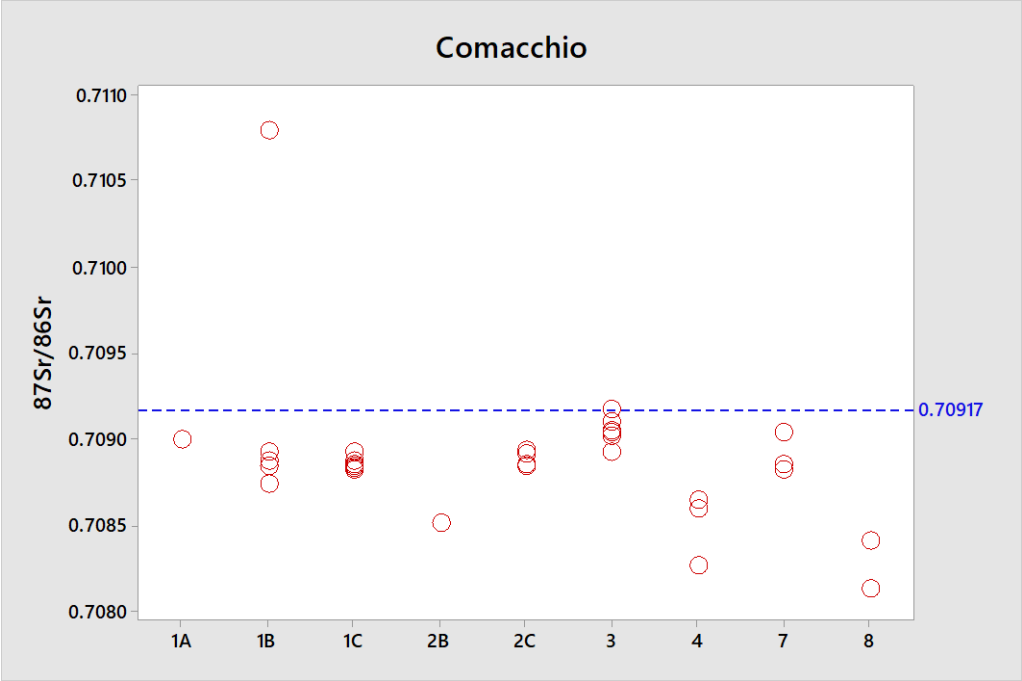


Figure 133 – Strontium isotope results for Comacchio glass divided by groups. Modern sea water signature is underlined in blue.

Group 2B - Com85 (0.708509) is close to these values (0.708127 - 0.708408), reinforcing the hypothesis that it is also of the HIMT composition, but with a signature slightly closer to sea water. Com42

(goblet) from group 1 is an outlier with a high Sr signature of 0.710782, which indicates that its Sr signature has not been influenced by content of sea shells but reflecting instead the influence of other minerals with a more radiogenic strontium signature.

Groups 1B (0.708739 – 0.708920), 1C (0.708826 – 0.708919), and 2C (0.708842 – 0.708935) shows intermediate values between main Levantine groups (1A and 3) and HIMT weak (group 2B), with an overall a signature closer to sea water compared to HIMT groups. Not only might this be an indication of the mixing practices occurring in Comacchio, but it shows how the Sr content in such groups is more influenced by the seashell fraction rather than other minerals, which might indicate a stronger Levantine component in its melt. As remarked earlier though, HIMT too has a beach sand component in its ingredients, and therefore the final Sr signature in Comacchio mixed groups might be the result of combining both Levantine and HIMT recipes.

The range of Group 7 $^{87}Sr/^{86}Sr$ is consistent with macro group 1 and 2 plus group 3 (0.708825 – 0.708847) except for Com80, which has a slightly higher $^{87}Sr/^{86}Sr$ ratio of 0.709042, albeit still consistent with the fore mentioned groups. Feldspars contain significant amount of Sr and, given the Al_2O_3 amount of 7.61wt% derived, most likely by contamination (Com80 is a drip from a crucible), it is possible that a minimum contribution of its Sr signature might have been influenced by the feldspar content from the melting pot.

Plant ash glass Com 21 and 23 (group 4) show similar $^{87}Sr/^{86}Sr$ signatures of respectively 0.708644 and 0.708598. Such values are close to $^{87}Sr/^{86}Sr$ register for Cretaceous, Eocene and Neogene sedimentary deposits characteristic of Syria geology (Henderson et al., 2009, 418).

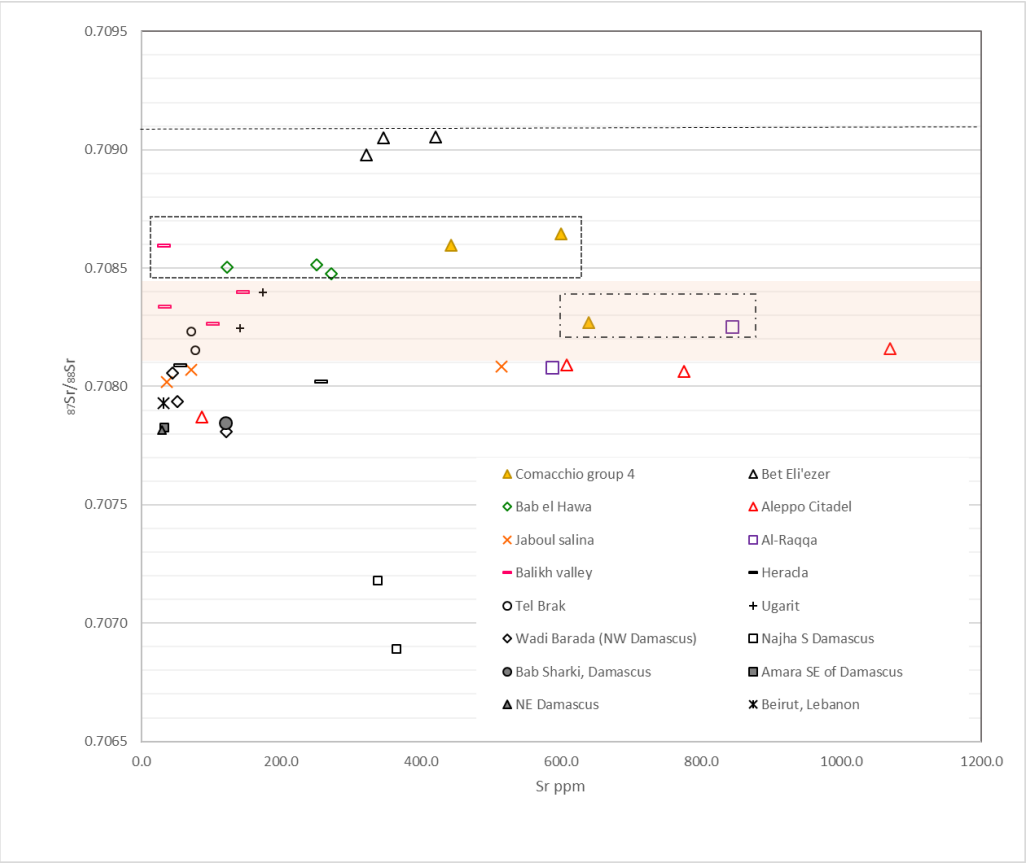


Figure 134 - Sr isotopes and strontium concentration in Comacchio group 4 and Middle Eastern plant ash. Comparison data: after Henderson et al., 2009. Legenda: sites with plants sampled from Syria and Lebanon with Sr signature and concentration closes to plant ash found in Comacchio. Bet Eli'ezer data are plotted as reference. Lined box underlines Com22 and SYR – 13 from Raqqa, and Com 21 and 23 with samples from Bab el Hawa and Balikh valley. The orange band delineates Sr signature from Tyre, data after Degryse et al., 2010.

Henderson and co-workers (Henderson et al., 2009, tab. 1, 417) report Sr signature and concentrations for several species of plant ash harvested in Syria and Lebanon (Figure 134). Com 21 and 23 are close to samples SYR 01, 03 (both from Bab el Hawa, Lebanon), and SYR 17 (Balikh valley, Syria). On the other hand, Com22 instead registers a lower $^{87}Sr/^{86}Sr$ of 0.708270, which might indicate the use of a different plant ash compared to Com21 and 23; in particular, Com 22 is similar to sample SYR 13 from Raqqa, and SYR 18 from the Balikh valley.

The concentrations of strontium in plant ashes are not dependent on the Sr signature, but they will vary instead according to the nature of the bedrock and the soil geochemistry in which the plants grew and from the

plant physiognomy of the plant genus and species (Henderson, 2013, 329). Therefore, the fact that Comacchio plant ash Sr concentration do not match with the one registered from Bab el Hawa and the Balikh valley, could be seen as an expected variation within plants from the same geographical area.

The restricted analytical range for plants harvested in Syria does not allow further distinction, but the correspondence with Sr signatures with plant from Syria and Lebanon demonstrate that plants harvested in these areas might have been used to make plant ash found in Comacchio.

The next step is to pair the Sr signature with its concentration (Figure 135) and assess its compatibility with comparable materials.

Group 3 – Levantine show slightly different Sr contents, which indicates that a different sand has been used in two separate batches: paired with its Sr signature, it plots within the Bet Eli'ezer sample range, and close to the sea water Sr signature as expected by samples made with beach sand. Group 1A again plots close to sea water levels, but with different concentrations (Com16: 401 ppm, Com34: 502 ppm), which might indicate also in this case the use of a different beach sand between the two samples.

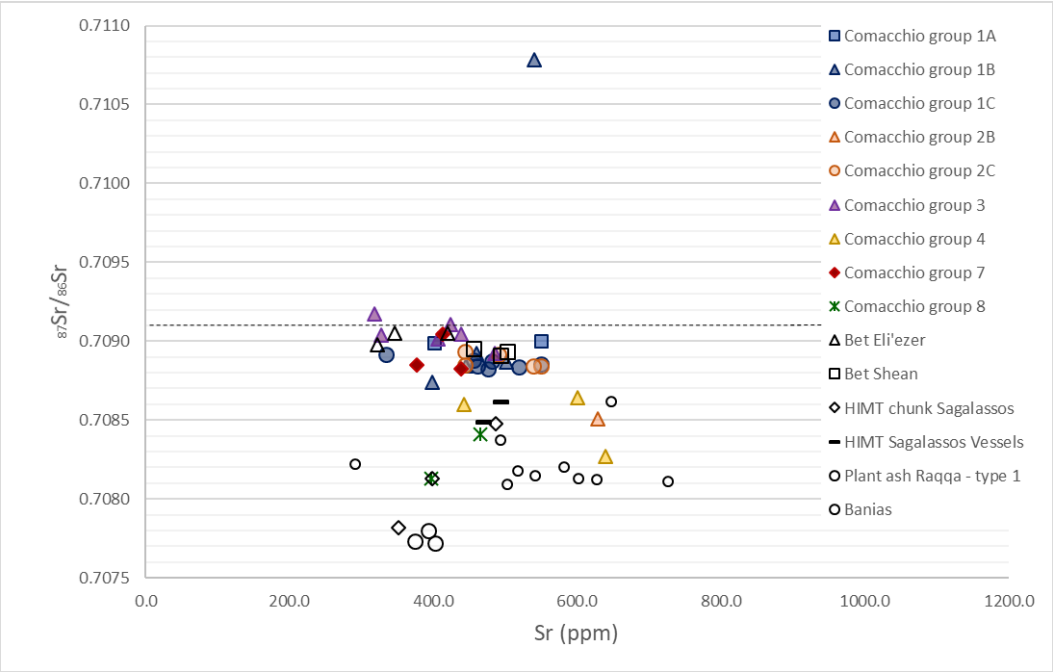


Figure 135 - Sr isotopes and strontium concentration in Comacchio glass. Comparison data: Bet Eli'ezer, Bet Shean, and Banias after Freestone et al., 2003; HIMT Sagalassos after Degryse et al., 2009b; Raqqa after Henderson et al., 2009.

Group 2B (Com85) has a Sr signature comparable with one of the Sagalassos chunks, but its Sr concentration is around 628 ppm, way over the values reported for both Sagalassos and group 8 in Comacchio, which again might result from the use again of a different beach sand/ mineral sand mix compared to the one used in Sagalassos. At the present moment, there are no isotopic analysis of HIMT weak to compare my group 2B with. Group 8 plots instead within the HIMT expected range, with one perfect correspondent for one chunk (SA00JP25) from Sagalassos.

Com22 (0.70827 – 639ppm) falls within Raqqa sample Sr signatures and concentration, hence it might have been made with plants harvested close to Raqqa, confirming the previous comparison with the Sr signature and concentration of plant ashes analysed by Henderson et al. (2009).

Mixed group 1B, 1C and 2C do not plot close to either HIMT strong – 8 neither to HIMT weak – group 2B. On the other hand, as anticipated, both their Sr signature plots instead closer to Levantine (and Bet Shean glass

more specifically), but with a higher concentration (c. 440 - 550ppm). Mixed group values plot half-way between Levantine and HIMT groups, which could support their recycled origin, with a prevalent Levantine component. Moreover, a mixed line is observed in Figure 135, having as end members HIMT strong – group 8 (centre) and Levantine I – group 3 (top left).

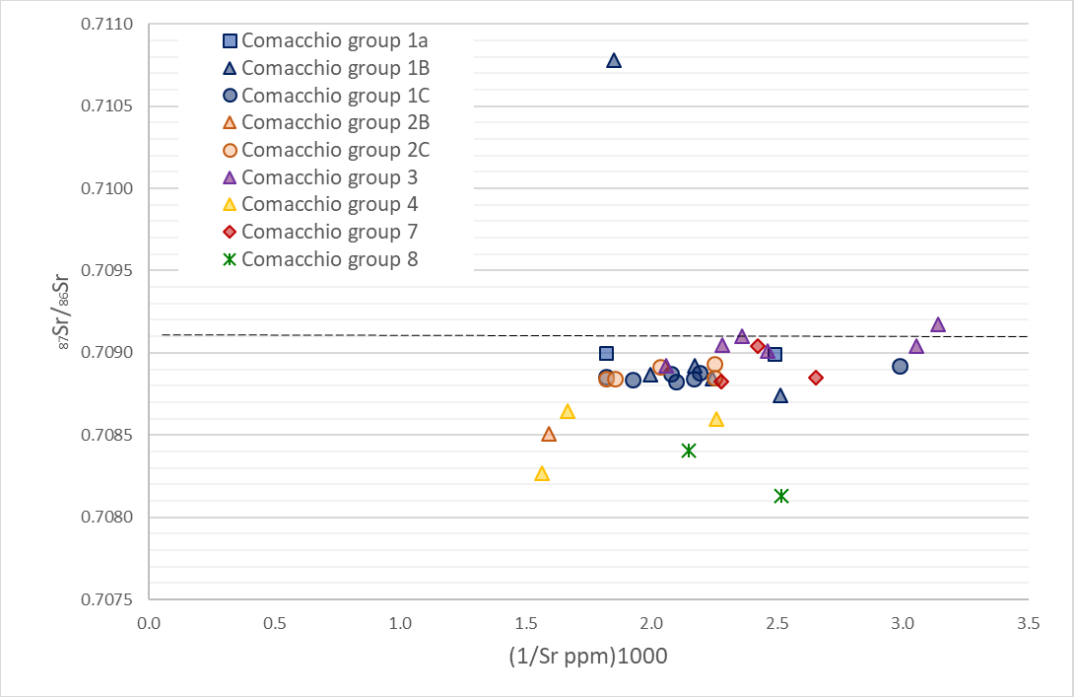


Figure 136 - Sr mixing diagram of Comacchio glass as described after Dickin, 2005, 179.

To highlight further potential mixing lines between our end-members, Dickin (2005, 179) suggests plotting the inverse of the Sr concentration, against the isotopic signature (Figure 137, Figure 138, and Figure 139): this trick will transform the hyperbola resulting from a normal two-component system (like the normal Sr signature vs. concentration) into a straight line, making mixing lines more evident. The same method has been applied by Degryse et al. (2006) to underline recycling practices in Sagalassos.

The result in Figure 136 indeed highlight a potential mixing line between group 4 (Com74) and Levantine group 3 (com 59 and 60). I created several potential mixing lines with non-recycled groups Levantine (1A and 3 groups) and HIMT (2B and 8 groups) as end - members and see if mixed groups 1B, 1C, and 2C would fall along the created mixed lines[93]. I have excluded plant ash (group 4) given its more recent chronology.

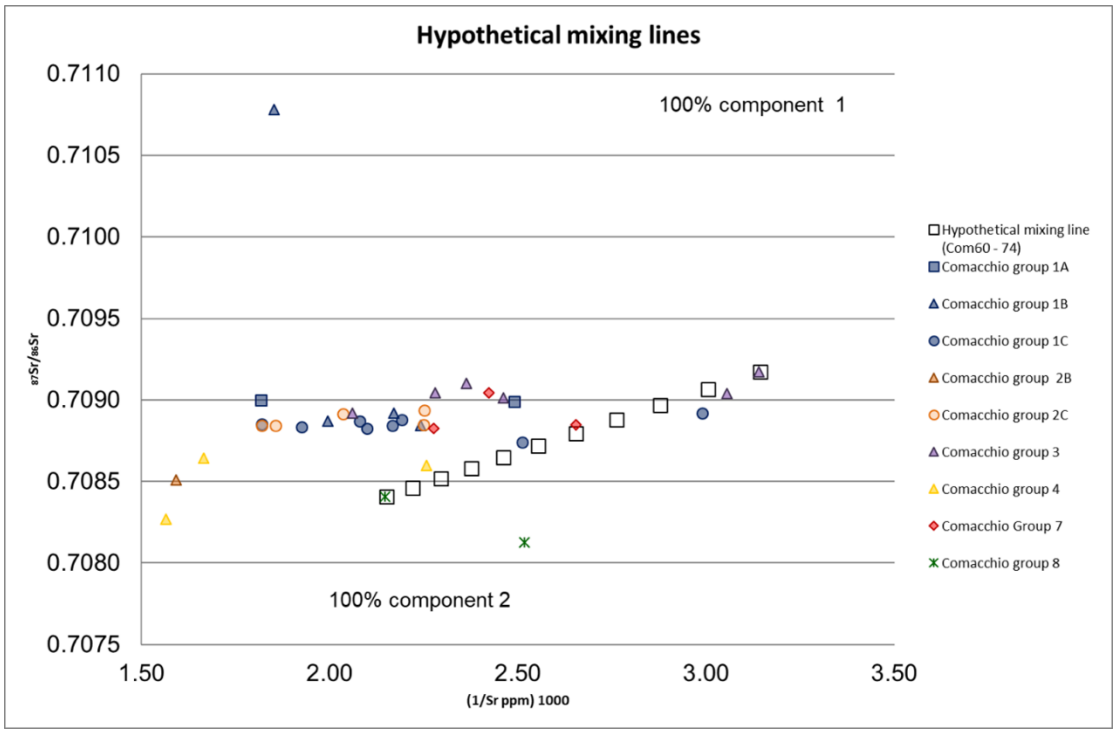


Figure 137 - Hypothetical mixing line between Com 60 (group 3) and Com74 (group 8).

In Figure 137, the afore mentioned mixing line between Com 59 – 60 and Com74 is highlighted, and sample Com 40 (waster), Com 82 (crucible base) falls within the created line. This proves that Levantine group 3 and HIMT strong – group 8 have been mixed.

[93] The hypothetical mixing lines have been created by using equations described in Faure et al., 2009, 16.11, 350. Professor Jane Evans kindly pointed me in the right direction and provided help with this issue.

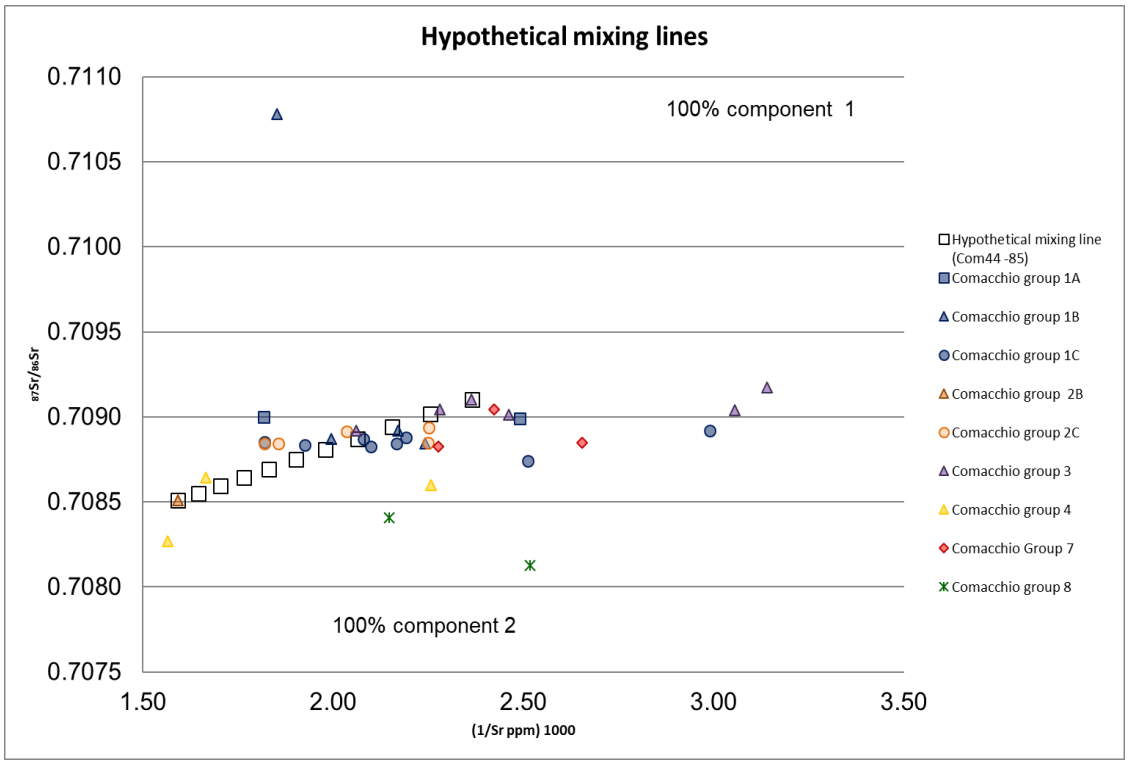


Figure 138 - Hypothetical mixing line between Com 44 (group 3) and Com85 (group 2B).

Moreover, the presence of a crucible on such mixing line would suggest that such mixing was occurring at the Comacchio workshop itself. Figure 138 describe what could happen, on the other hand, Levantine group 3 (Com44) and HIMT weak (Com85) are taken instead as end-members: mixed groups 1B, 1C, and 2C fall within the created mixed line. The same can be said when Com16 (group 1A) and Com65 (2C) are chosen (Figure 139). On the other hand, the latter graph also highlights another interesting question: given that only one analysis from group 2B is available, could it be that one of the real end-members from group 2B might be missing?

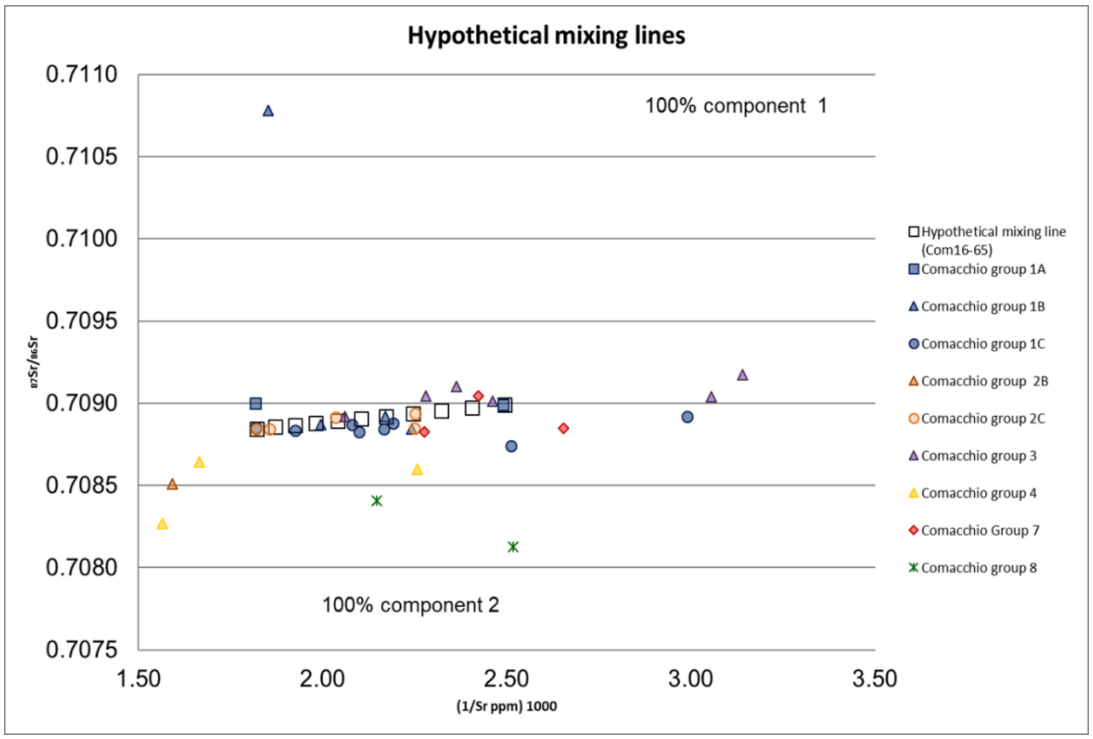


Figure 139 - Hypothetical mixing line between Com16 (group 1A) and Com65 (group 2C).

Secondly, if one sample from the mixed groups is taken as a definite end-member (such as Com65) instead of Com85, mixed groups still follow the mixing line: this occurrence might prove instead that group 1B, 1C, and 2C have been recycled within themselves, which would explain their overall blurred composition.

I would like to start addressing the provenance of plant ash from Comacchio by looking at the difference in Sr concentrations and signatures and comparing it with published data. Com22 from group 4 has similar $^{87}Sr/^{86}Sr$ signature and concentration to Raqqa and similar $^{87}Sr/^{86}Sr$ signature to Tyre samples (Figure 140), while Com 21 and 23 show a higher Sr radiogenic signature, but still close to one Raqqa sample; their different Sr concentration compared to Com22 is due to the different amount of Sr taken up by the plants ashed to make the glass.

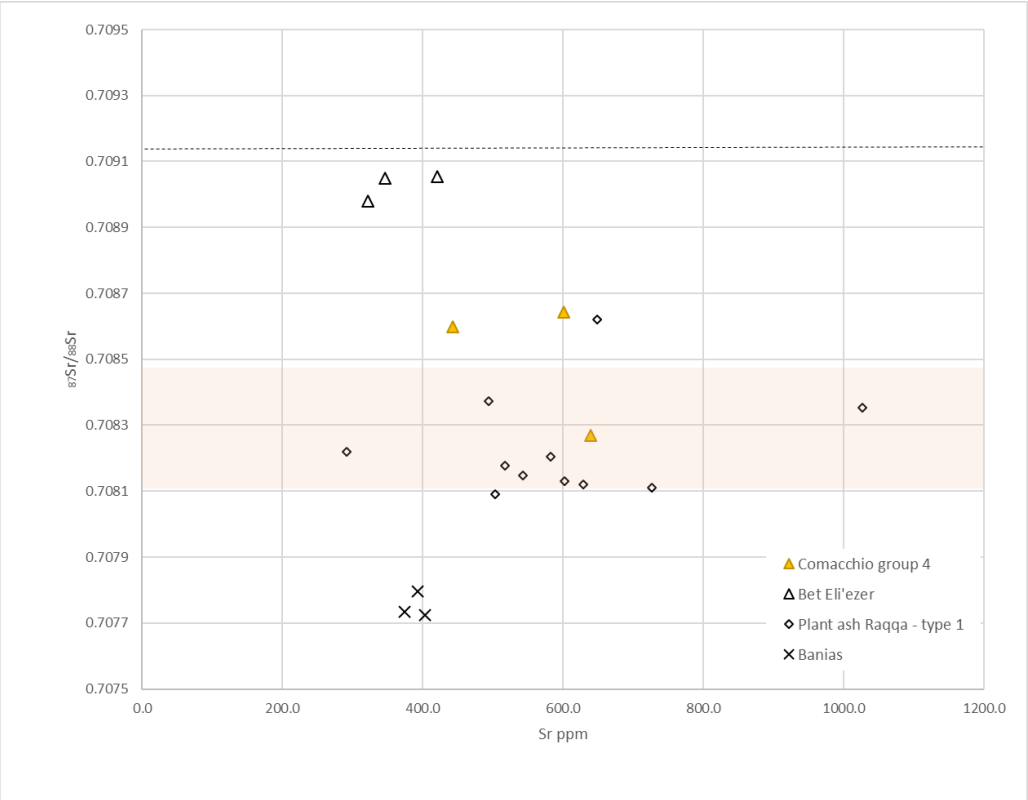


Figure 140 - Sr isotopes and strontium concentration in Comacchio group 4. Comparison data: Bet Eli'ezer and Banias after Freestone et al., 2003; Raqqa after Henderson et al., 2009. The orange band delineates Sr signature from Tyre, data after Degryse et al., 2010.

Since their $^{87}Sr/^{86}Sr$ is similar, I hypothesis that a plant grown on the same geological bedrock has been used but given their difference in concentrations they are the results of different melts.

Banias glass on the other hand, plots with lower $^{87}Sr/^{86}Sr$, showing the influence of a different plant than the one used in Raqqa and Tyre.

Figure 140 examines the variation in Sr signature and concentration of plants sampled from Syria and Lebanon analysed by Henderson and colleagues (Henderson et al., 2009, tab 1, 417) If we compare this data with our results, we can make hypotheses on the area where the plants used to make Comacchio group 4 came from.

Com22 plots show a similar Sr signature (0.708270) to sample SYR – 13 from Raqqa (0.708254), which might be connected with the use of a plant with the same origin. Com 21 and 23 have instead a more radiogenic

signature (0.708644 – 0.708598), which agrees with one sample from Bab el Hawa (SYR – 17) and plant harvested from Balikh valley. On the other hand, both Com21 and 23 show a higher Sr concentration. Interestingly enough, neither sample from group 4 plots close to any plant harvested in Damascus or Beirut, which trace elements suggested previously as potential area or production for this samples (Figure 82, Figure 83, and Figure 84 in this chapter).

5.2.1.2 Barking Abbey

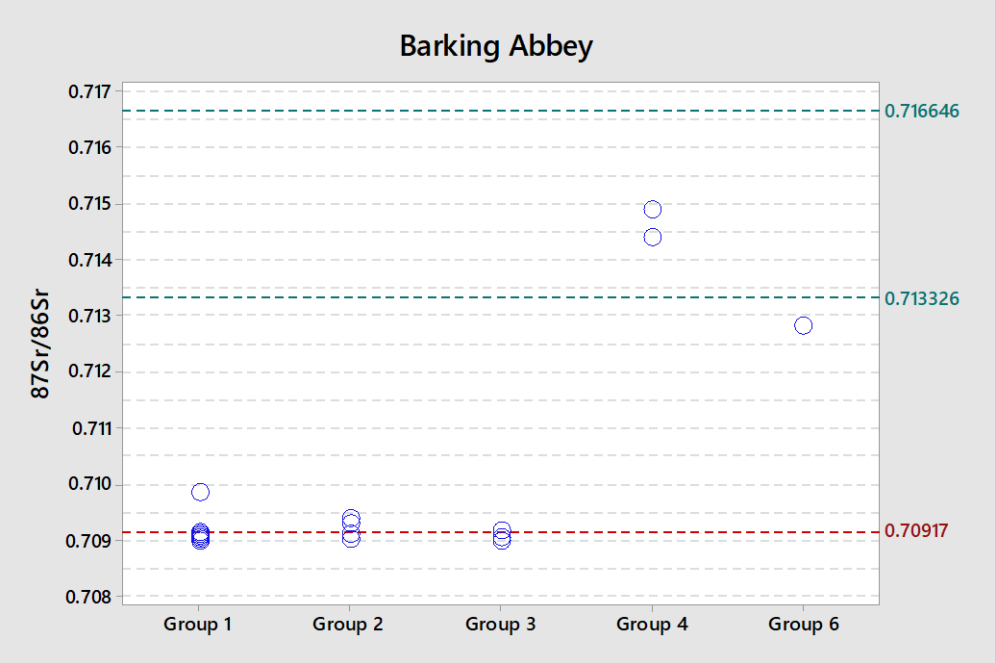


Figure 141 - Strontium isotope results for Barking Abbey glass divided by groups. Modern sea water signature is underlined in red. The Sr range for Central Asian glasses analysed by Brill and Fullagar (2012, 631) are marked in green.

Group 1, 2, and 3 from Barking Abbey all display a Sr signature close to sea water values that suggests a sea shell lime origin and the use of a sand from the Levantine coast, as for Comacchio group 3, though Barking samples have overall a higher Sr signature (Figure 141). Group 1 (0.709020 – 0.709130) and group 3 (0.708982 – 0.709191) fall within

a tighter range, while group 2 (0.709023 – 0.709407) shows a greater spread of values, which might suggest that samples are the result of different sands with different content of shells or minerals that could have influenced its final $^{87}Sr/^{86}Sr$ ratio. Still, group 2 shows a tight $^{87}Sr/^{86}Sr$ ratios, so there is no doubt about their provenance from the Levantine coast. Ba21 has a more radiogenic signature (0.709872) when compared to the other samples from group 1, which indicates the influence of another mineral in its final lime source.

Overall, Potash silica group 4 is the group with the more radiogenic $^{87}Sr/^{86}Sr$ signature (Ba 68: 0.714408; Ba 79: 0.714890), which matches closely at least two samples of potash silica glass (6127 and 6129) from Hazar-tam (China, 0,714369, and 0.714869 respectively) published recently by Brill and Fullagar (2012, 631). In Figure 141, the Sr range for Central Asian glasses analysed by Brill and Fullagar (2012, 631) are marked in green.

Both major element samples compositions however do not match group 4 because of their much higher CaO (7.21 - 5.54wt%) and Na_2O (17.9–15.7wt%) values (Brill, 1999b, 345) compared to our group 4, so their lime and flux source have a different origin. Group 6 outlier Ba52 is lower when compared to group 4, but still much higher than the rest of Barking samples. Ba52 is an outlier also when its Empa results are considered, with low Na_2O (1.02wt%), K_2O (1.12wt%), and SiO_2 (56.04wt%), and high $Al2O_3$ (6.52wt%), CaO (c.24wt%), and MgO (5.28wt%). At the moment, the closest comparison that I have is for another white Chinese glass (Brill, 1999a, n°48, 150, 1999b, n°48, 350), for which unfortunately no isotopic analysis are available.

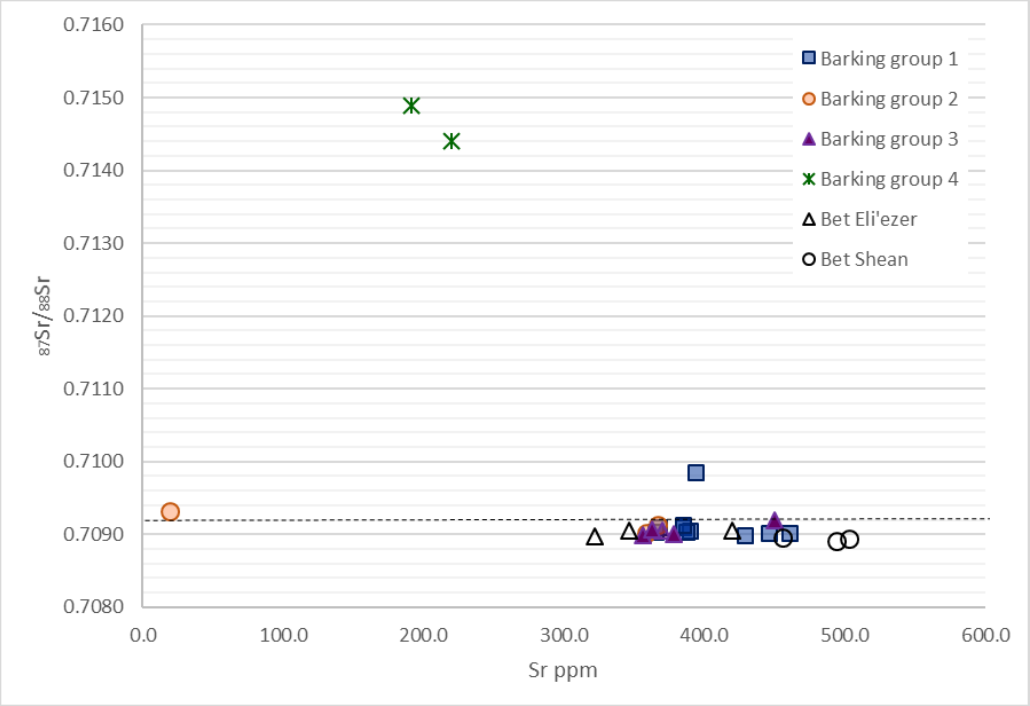


Figure 142 - Sr isotopes and strontium concentration in Barking Abbey glass. Comparison data: Bet Eli'ezer, Bet Shean, and Banias after Freestone et al., 2003.

Barking Abbey (Figure 142 and Figure 143) instead shows much tighter Sr signature with variable Sr concentration (c. 356 – 461 ppm) compared to Comacchio samples, falling within both Bet Eli'ezer and Bet Shean range. Surprisingly, Ba 24 has relatively low Sr concentration (c. 18ppm). At the moment we do not have an explanation for such low Sr concentration, hence I have to consider Ba24 Sr concentration as failed measurement.

If only group 1, 2, and 3 are considered (Figure 143), they split in two groups according to their Sr concentration, with most of the glass plotting close to Bet Eli'ezer material. A small sub-group of three samples (Ba54, 19, and 74, two vessels and one window) falls instead closer to Bet Shean. The base glass for group 1, 2, and 3 therefore would have been still Levantine I, but the different Sr concentration suggest the use of a different beach sands for the small sub-groups of samples from group 1.

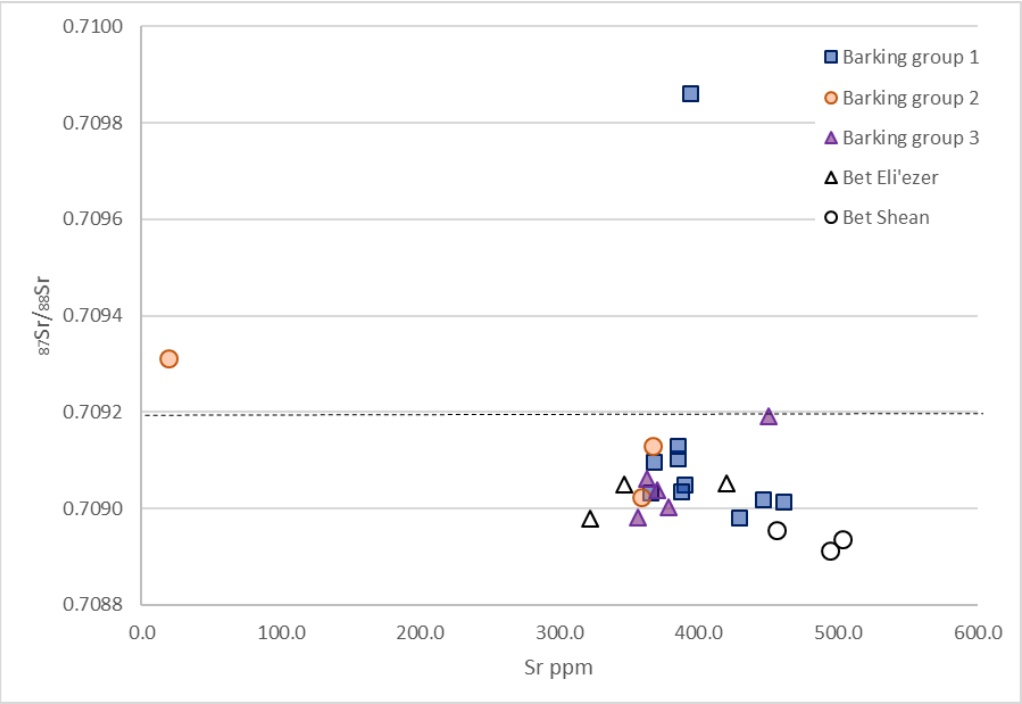


Figure 143 - Sr isotopes and strontium concentration in Barking Abbey glass minus group 4. Comparison data: Bet Eli'ezer, Bet Shean, and Banias after Freestone et al., 2003.

Four samples (Ba35, 78, and 53 from group 1 and Ba17 from group 2) have Sr signatures closer to seawater. The same can be said for Ba23 (group 3), but it has relatively higher values in both parameters (respectively 450 ppm and 0.709191). In this case, all five samples have CaO values that are within the average limits of group 1, 2, and 3. The difference in Sr signature has to be taken as a difference in a sand source compositionally similar to the majority of Levantine group, but with a different lime content. The fact that part of group 1 shows different Sr signature and concentrations reinforce the idea of the results of mixing of different quality of glass (and therefore mixed) while group 3 has a tighter Sr signature (save Ba23) and represents the base glass.

Group 4 as expected plots completely separately for the signature and concentration, combining a low Sr concentration with a high radiogenic signature when compared to group 4. Another (more radiogenic) mineral must have been the source for lime in potash group 4 other than sea

shells, but at the current state of research, I cannot find any comparable material to assess group 4 provenance.

5.2.2 Nd isotopes

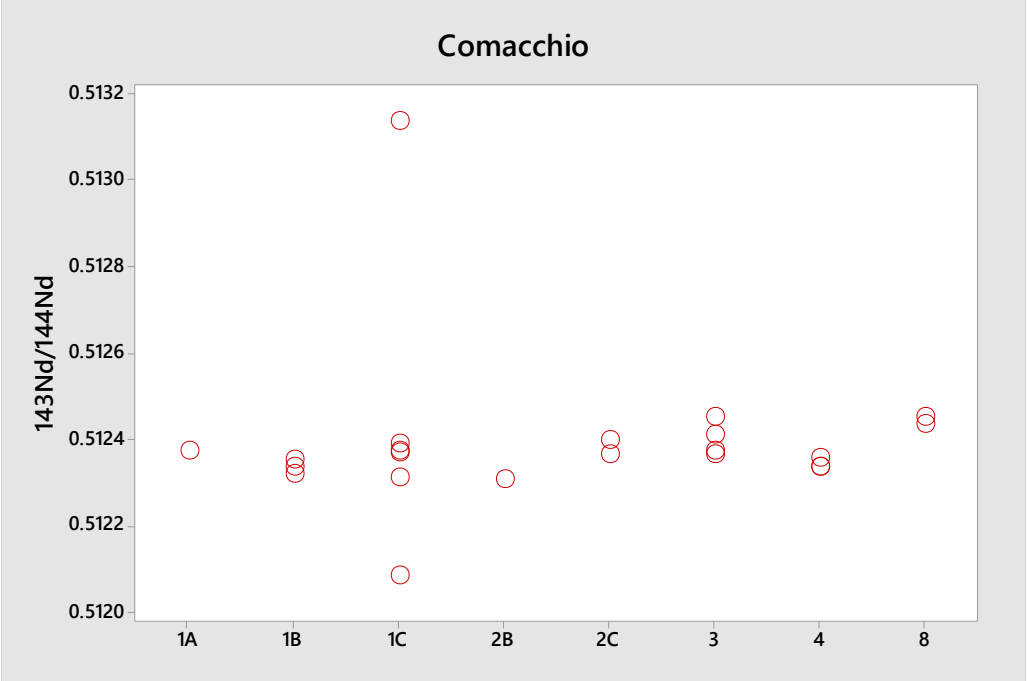


Figure 144 – Neodymium isotope results for Comacchio glass dataset divided by groups.

Concerning the Nd isotopic signatures, in Figure 144 neodymium isotope results for Comacchio glass dataset are shown according to their compositional groups.

Levantine groups 1A (0.512372) and 3 (0.512366 – 0.512450) plot within the same range.

At the moment, no neodymium isotopic signature has been published for primary glass workshop in the Levantine, even if three chunks from Bet Eli'ezer and one from Apollonia have been discussed (εNd values) (Degryse, 2014; Gallo et al., 2015). Degryse and colleagues report that Nd isotopic composition from Banias are quite similar, which have been

indeed published (Degryse et al., 2010, 85): their range of values (0.512326 - 0.512382) is close to two samples from Comacchio (Com 15 and 25), respectively 0.512366 and 0.512372.

Com59 and 60, show a higher Nd signature of 0.512411 and 0.512460 respectively, plot closer to group 8 (0.512434 and 0.512450) that agree with some samples from 1st -3rd century (0.512425 - 0.512460) and 5th – 7th century (0.512420) Sagalassos (Degryse et al., 2009b, tab. 2.1, 62). Such values match late 3rd – 6th century AQ/2 – Levantine I group from Aquileia (Gallo et al., 2015, 88) and CL2- Levantine I material from 5th century Classe (0.512438) presented by Maltoni et al. (2015, tab. 6, 16). One outlier (Com45) from group 1C shows a distinctive lower Nd signature (0.512085), which agrees with samples from 2nd century AD sample Tie 37 from Tienen, Belgium (Degryse et al., 2009b, table 2.1, 62). This sample is included in the group of glasses presented by Degryse and co-workers (Degryse and Schneider, 1997, 2008; Degryse et al., 2009b, 66) as characteristic of Western glass production because of their “exotic” isotopic composition closer to the range of beach and deep-sea sediments from the Western Mediterranean.

Finally, group 4 – plant ash shows a range of values (0.512335 - 0.512357) that has not been registered in unmixed plant ash from Raqqa (Henderson et al., 2009, tab 2, 418). Comacchio three plant ash glass samples (Com21, 22, and 23) instead agrees with materials from Tyre, which range from 0.512350 to 0.512473 (Degryse et al., 2010, tab. 2, 85).

In Figure 145, Neodymium isotope results for Barking abbey glass divided by groups are illustrated. Group 1 (0.512325 – 0.512354), 2 (0.512344 -0.512354) and 3 (0.512334 - 0.512372) falls within the same Nd isotopic range paired with low Nd content (mostly between 5 and 6), but group 1 plots overall with lower values despite the two outliers (respectively Ba48 - 0.51226 and Ba35 - 0.512450). Degryse and colleagues report that Nd isotopic composition from Banias are quite similar, which have been indeed published (Degryse et al., 2010, 85):

their range of values (0.512326 - 0.512382) is close to the $^{143}Nd/^{144}Nd$ signature of all three groups in Barking Abbey.

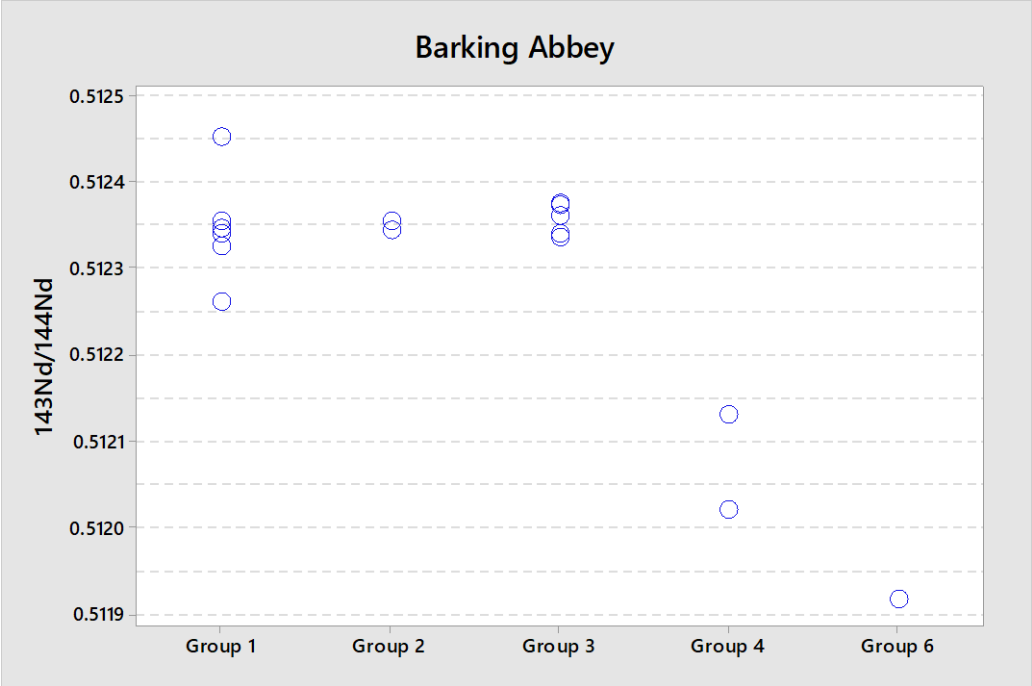


Figure 145 - Neodymium isotope results for Barking abbey glass divided by groups.

Levantine group 1, 2, and 3 do not match AQ/2 – Levantine I (Gallo et al., 2015, 88), but matches instead Levantine I – CL2 material (0.512438) presented by Maltoni et al. (2015, tab. 6, 16). Group 4 and group 6 display a much lower Nd signature (respectively 0.51213, 0.512021, and 0.511918) paired with relatively higher Nd concentration (15.14 – 20.51) when compared to both Levantine and HIMT glass. Currently there are no parallel Nd isotopic compositions from South-eastern Asia to compare group 4 and 6 with, but we can say with confidence that both groups have not been made with the same raw materials as the other groups present at Barking Abbey.

Given the small range of $^{143}Nd/^{144}Nd$ ratios, 0.510–0.514 (Best 2003, 47), the isotopic composition of a system is frequently shown normalised to the chondritic meteorite standard in the form of ε_{Nd} values:

$$\varepsilon\mathrm{Nd} = \left(\frac{(^{143}\mathrm{Nd}/^{144}\mathrm{Nd})_{\mathrm{sample}}}{(^{143}\mathrm{Nd}/^{144}\mathrm{Nd})_{\mathrm{CHUR}}} - 1\right) \times 10^4$$

where CHUR stands for Chondritic Uniform Reservoir, which represents the bulk earth Nd isotopic composition deduced from measurements in chondrites (DePaolo and Wasserburg, 1976; Jacobsen and Wasserburg, 1980). The present-day chondritic value of $^{143}Nd/^{144}Nd$ is 0.512638.

The compositions of sands in the south-eastern Mediterranean are dominated by the sedimentary load of the River Nile, since the Nile sedimentary material was carried around the South-eastern Mediterranean coast by the seasonal advancing of the Nile Delta and by tidal currents and longshore drift eastwards along the Egyptian and Israeli coasts (Stanley et al., 1998; Freestone et al., 2009).

The final Nd isotopic composition of deep-sea sediment is also influenced by sediment influx from the Sahara Desert (aeolian origin) and from the European continent (fluvial origin) (Brems et al., 2013b, 451). εNd signatures have started recently to be mapped across the Mediterranean (Goldstein et al., 1984; Frost et al., 1986; Weldeab et al., 2002): the isotopic pattern of the eastern Mediterranean surface sediments shows east–west εNd = -1 at the mouth of the River Nile and the coasts of Egypt and Israel gradient, from as high as εNd to εNd = -12 south of Sicily.

From the published literature, the Bet Eli'ezer and Apollonia material εNd signature published by Devulder and Degryse (Devulder and Degryse, 2014, tab. 5.2, 93) varies respectively between -4.7/-5.0 and -4.1/-4.6.,while Freestone et al. reports εNd values between -5.0 and -6.0 for the same sites (2009, 36).

HIMT εNd range between -5 and -6, which is similar to Levantine range of values, but given that HIMT glass have lower $^{87}Sr^{87}Sr$ ratios, Freestone et al. (2009, 44) suggest the Egyptian coast between Alexandria and Gaza (between the Nile Delta northwards to the Levant) as potential provenance for HIMT glasses from London, where the Nile dominates the sediments (Weldeab et al., 2002).

By combining Sr signature and εNd it will be possible to assess when different sand raw materials used for glass production. This combination has been used in glass studies successfully by Degryse and Schneider (2008) to first identify an Eastern and Western production for late Roman and early Byzantine period. The Eastern Mediterranean primary glass has a Nile dominated Mediterranean Nd signature (higher than -6.0 εNd), while glass with a primary production location in the western Mediterranean or north-western Europe should have a different Nd signature (lower than -7.0 εNd).

A plot Sr isotope versus εNd values for both Comacchio (Figure 146) and Barking Abbey is shown in Figure 148 compared with results from Levantine primary production centres and other known data from the literature to assess the provenance of both lime and sand raw materials.

Com15 and 25 from group 3 and Com 16 from group 1A plot within the εNd Levantine range, with respectively -5.31, -5.19, and -5.19. The other samples from group 3, Com 59 and 60, have lower Nd values of -4.43 and -3.67. Analysis of quartz sands that were considered suitable for glass-making (Brill, 1988; Degryse et al., 2006) from the River Belus (Israel) registered higher εNd range of -4.8 to -1.0 (Degryse and Schneider 2008, tab. 2, 1997).

The difference in both Sr signatures and εNd indicates that a different sand has been used to make Com 59 and 60. The use of a different raw material opens up the chance that a different workshop from Apollonia made both samples. Overall though, such values are still compatible with

Nile sediment εNd values and overall with glass produced in the Levant (Freestone et al., 2000).

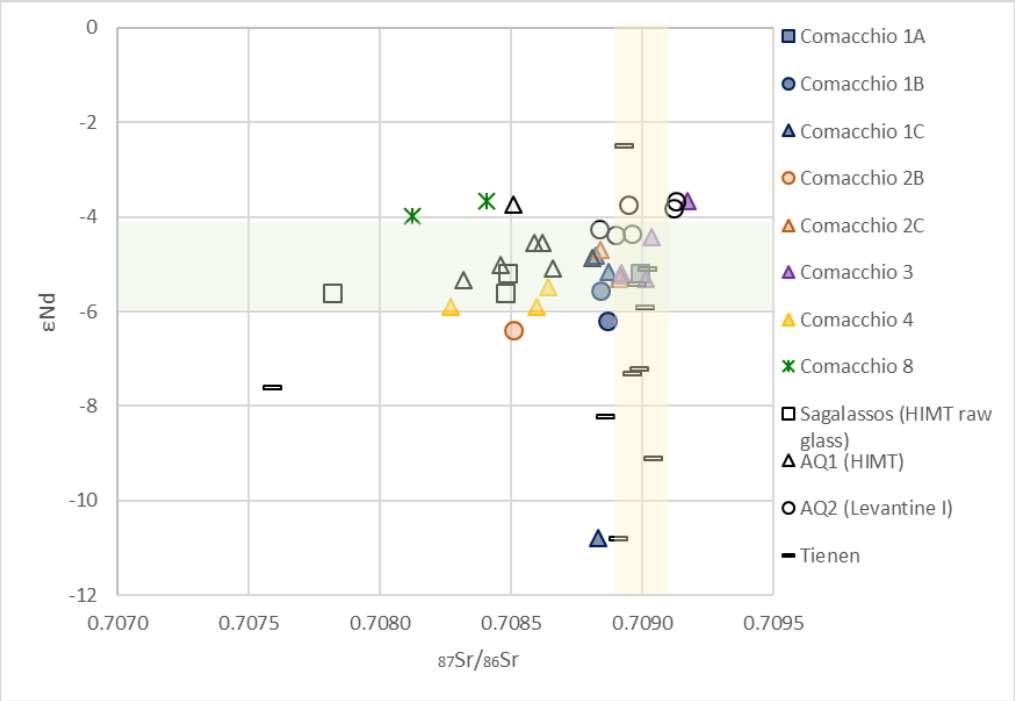


Figure 146 - Sr isotopes vs. εNd values in Levantine and HIMT glass from Comacchio. Green and yellow band describe the range Sr isotopes (0.7088 – 92) and εNd range of Apollonia and Bet Eli'ezer primary workshop material, after respectively Freestone et al., 2003, Brems and Degryse, 2014, 104, and Devulder and Degryse, 2014, tab. 5.1, 93. Data comparison: 4th -5th century AD glass from Sagalassos, after Degryse et al., 2009b, tab. 2.1, 62; late 3rd – mid 6th century AD AQ1 and AQ2 material from Aquileia, after Gallo et al., 2015, tab 2, 58; 2nd century AD glass from Tienen (Belgium), after Degryse and Schneider, 2008, tab. 1, 1996.

Com60 in particular plots close to both Sr signatures and εNd values for two late 3rd – early 5th century samples (AQ106-15 and AQ106-12) from Aquileia. Overall Aquileia samples show a tight εNd value with Com59 and 60. Group 1B, 1C, and 2C plots within the expected εNd values for Levantine glass (εNd = -6.20 to -4.70), albeit with a lower Sr signature, so they do not match precisely the primary workshop range.

One sample from group 1C, Com45, shows a low εNd of -10.79: such εNd matches one 2nd century sample (Tie 37) from Tienen, Belgium. While -10.8 εNd is not consistent with any sediment in the Eastern Mediterranean, it matches instead the isotopic range of beach and deep

sand from the Western Mediterranean from the Italian Peninsula, the French and Spanish coast and North-Western Europe (Degryse and Schneider, 2008). Given the nature of the sample itself (waster from glass-working, droplet), I cannot exclude some contamination from the melting pot which might have altered the final εNd.

Com85 – Foy 2 plots closer to the AQ1 HIMT from Aquileia and Sagalassos chunks in terms of Sr signature, but it registers a more negative εNd values of -6.40; group 8 (εNd = -3.98, - 3.67) on the other hand plots within the range of HIMT group AQ1 from Aquileia (εNd = -3.37), dated to half the 5th – 6th century AD.

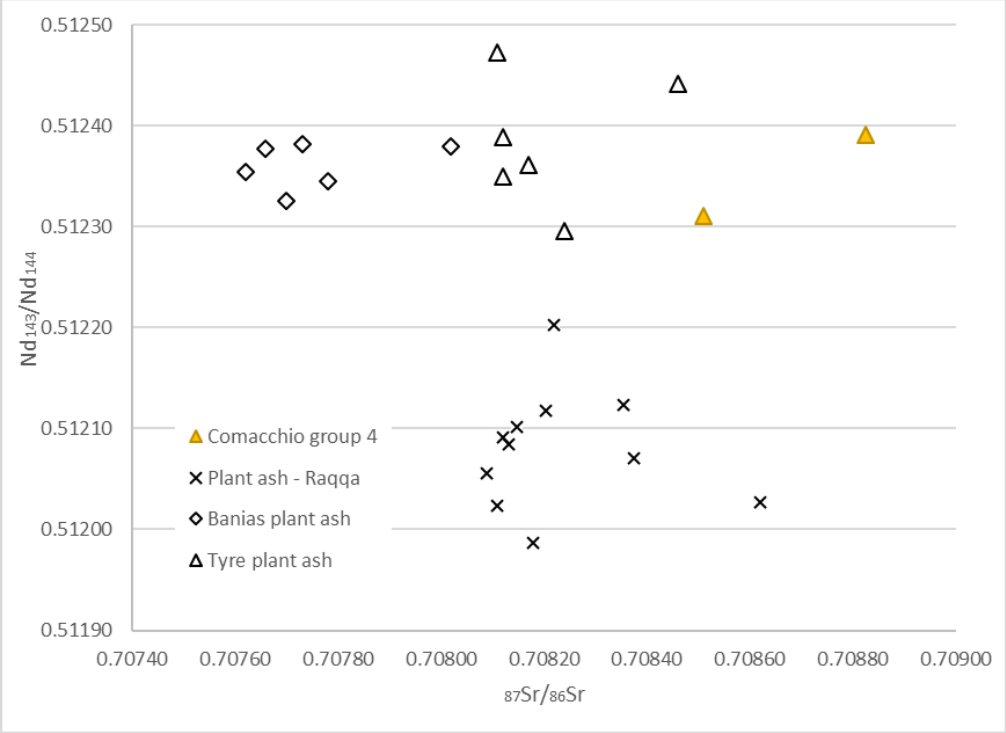


Figure 147 - Sr isotopes vs. Nd isotopes in plant ash group 4 from Comacchio. Comparison data: plant ash (group 1) from 9th century Raqqa, after Henderson et al., 2009, tab. 2, 416; 10th - 13th century Banias and 10th -11th century Tyre after (Degryse et al., 2010, tab. 2, 85).

The HIMT weak variant represented by Com85 – group 2B (end of 7th early 8th century AD) falls within still lower Sr signature (0.708509) comparable with other published material, but the lower -6.40 εNd values

of Com85 – group 2B paired with a less radiogenic Sr signature (0.708509) indicates the use of a different sand (and therefore potentially a different workshop) from group 8. A value of -6.4 εNd is consistent with the sands from the Western Mediterranean area but, as Degryse and Schneider remarked (Degryse et al., 1998, 2006), intermediate εNd values between -6.4 and -6.8 could be the result of recycling of glass or mixing of primary sources from the eastern and western Mediterranean area. Group 8 (Com74 – 75) falls within the known Levantine/HIMT range (-5.0 to -6.0). Both groups have a lower Sr signatures which indicate a predominance of the mineral component (limestone) in the original sand source, which is characteristic of HIMT glass.

εNd has not been used until now to comment on the nature of sand used to make plant ash glass from Raqqa, hence I decided to assess the nature of Comacchio group 4 by plotting both Sr and Nd signatures instead (Figure 147). Interestingly enough, all plant ash glass sample from Comacchio have a quite tight Nd range (0.512335 - 57), which suggests the use of one sand for all three samples.

Moreover, Com21, 22, and 23 do not plot within the area of pertinence to Raqqa, but instead they do fall within both Sr and Nd of samples from Tyre. As mentioned, two out of three samples from group 4 plotted closer to plant ashes form Bab El Hawa, Lebanon. This correspondence together with the Nd signature matching Tyre samples (0.512330 - 40 range) might suggests that samples from Comacchio could have been made in Tyre rather than Raqqa, or at least they were use the same raw materials. Another intriguing hypothesis is that they could have used ashes from plants harvested in Raqqa together with local sand closer to the primary workshop (potentially Tyre in this case), since the Sr signature does match Raqqa samples as seen in Figure 147.

Trade of plant ashes has been demonstrated for 10/11th – 13th century plant ash from Banias (Degryse et al., 2010, 87), and earlier Freestone (2006, fig. 14, 22) noticed the same correspondence between Sr isotopic signature of plant ash glass made in Tyre with Raqqa glass. There is a

difference in oxygen isotopic ratios ($\delta^{18}O$) is due to the different silica source used to made both glass (Tyre from sand; Raqqa from quartz pebbles), but Sr signatures do overlap as it is shown in Figure 147.

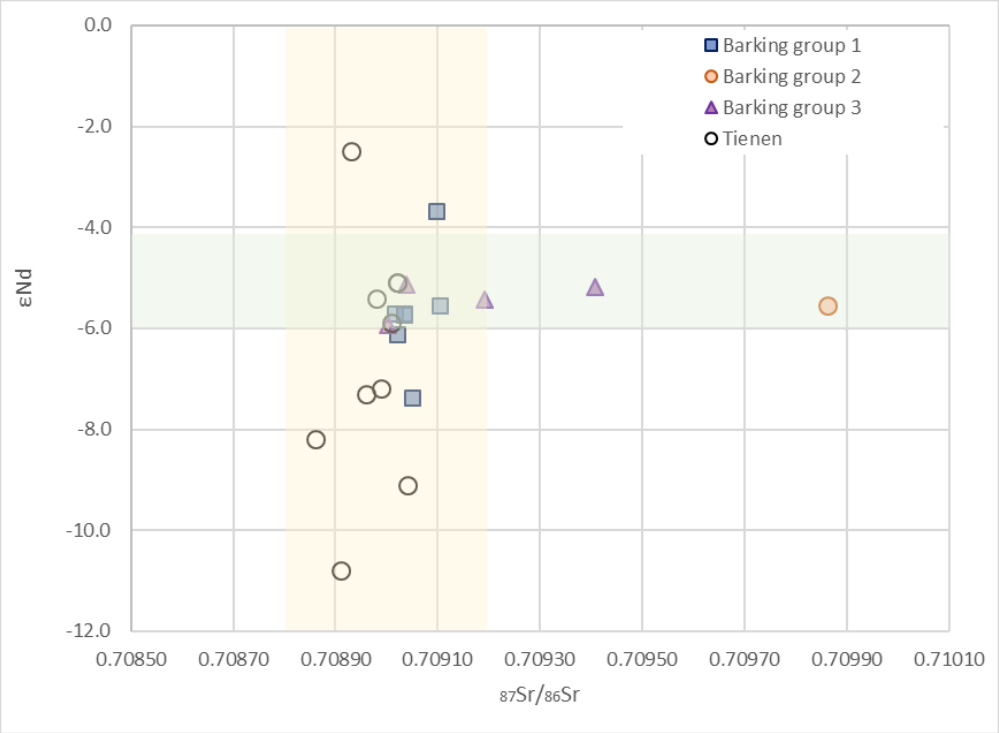


Figure 148 - Sr isotopes vs. εNd values in Levantine glass from Barking Abbey. Green and yellow band describe the range Sr isotopes (0.7088 – 92) and εNd range of Apollonia and Bet Eli'ezer primary workshop material, after respectively Freestone et al., 2003, Brems and Degryse, 2014, 104, and Devulder and Degryse, 2014, tab. 5.1, 93. Data comparison: 2nd century AD glass from Tienen (Belgium), after Degryse and Schneider, 2008, tab. 1, 1996.

Sr signatures and εNd for Barking Abbey are shown in Figure 148. Group 1 (-5.54 to -6.11), 2 (-5.54), and 3 (-5.13 to -5.93) all plot tightly within Levantine εNd limits. Only two samples plots outside the expected values, which suggested that a sand from the Levantine coast has been used to produce these samples.

Ba35 (Vessel) registers a higher value of -3.67 εNd which, as said before for Com59 and 60, is still compatible with Nile sediment εNd values and overall with glass produced in the Levant (Freestone et al., 2000). Ba48 (waster, droplet) show a lower εNd value of -7.37, which matches the

εNd values for the so-called Early Roman Western production (Degryse and Schneider, 2008), hence this sample might have been produced with a sand from the Western Mediterranean. As in the case of Com45, being Ba48 a waster from glass-working, I cannot exclude that also in this case some contamination from the melting pot which might have altered the final εNd.

Finally, high potash-silica glass group 4 (Com68 -79) and 6 (Com52) show a range of very low εNd values of respectively -9.91, -12.04, and -14.04. These values do find correspondence within the Western Mediterranean sand from Italy, Spain, and France analysed by Brems et al. (2013b, tab 1). On the other hand, merely three sands were considered suitable for glass-making (Brems et al., 2013b, tab 1), and only Sand IT34 from Tuscany has a rather low εNd value of -9.42 (Brems et al., 2013b, 461), which does agrees with only one sample from group 4. In addition, given the group 4 is not a natron base group, it seems highly unlikely that it was made in the workshop in the Western Roman provinces. Currently, there is no other comparable εNd data from Southern-Asian glass material.

5.2.3 Summary isotopic analysis.

Isotopic analytical work included in this section confirmed the hypotheses made for both Barking Abbey and Comacchio materials' origin.

Barking Abbey Sr and Nd results are the first isotopic analytical study for Anglo-Saxon glass from England[94]. Group 1, 2, and 3 Sr signatures are close to Holocene sea water values and relatively higher Sr concentration (c. 350 -400 ppm) plus εNd values fall within the range of Nile sediments (-5 < εNd < -6), and therefore that they must have been made with raw materials sourced from the Levantine coast. Given the variation in Sr concentration between samples (Figure 143), the Levantine groups in Barking, at least two sands with different shells content used to make such glasses: if we assume that sand used within the manufacture process was taken from sources close to the workshop itself, the variation in raw materials suggests the existence of two different primary workshops close to the Levantine coast using their local sands, or that one workshop was using sands sourced from two different locations and that we are looking at two different batches made with their own distinctive raw materials. The nature of the sand though remains within the Levantine parameters.

Recently, the transition for natron to plant ash production in Palestine between 7th and 12th century AD has been discussed by Phelps and colleagues (Phelps et al., 2016). By pairing compositional data from well dated and diagnostic fragments of domestic vessel types, they argued that Levantine I production on Levantine coast near Apollonia - Levantine I (Group 1, 2, and 3 from Barking Abbey) ceased by the 8th century AD and was replaced by that at Bet Eli'ezer - Levantine II (Phelps et al.,

[94] Willmott and Welham (2015, 235) mention that some glass from Glastonbury furnaces has been selected for isotopic analysis, but no further information is given in the publication.

2016). Phelps and co-workers agree that most of natron glass stopped being produced by the 9th century AD in any significant quantity.

Natron glass was also present at Raqqa between the late 8th and early 9 century AD (Henderson et al., 2004; Henderson et al., 2005, 670). As suggested by Phelps and colleagues (Phelps et al., 2016, 66), the concurrent presence of both Levantine natron from Raqqa and Bet Eli'ezer suggests a parallel production of a Levantine I and II glass recipe, so the variation in sand sources in Barking Abbey material fit this picture.

This new perspective on Levantine production poses an interesting dilemma for the Barking materials, which we need to remember were dated to the 9th/10th century AD based on C^{14} analysis associated with the furnace structure. If we are taking such chronology as valid, the Levantine material from Barking could be residual old natron production of Levantine I - Apollonia glass or from potentially another workshop, and Barking Abbey Levantine groups must have been circulating for quite some time, potentially representing an "old" stock of Levantine glass. If another workshop was producing natron glass between the 9th and 10th century, group 1, 2, and 3 represent fresh new glass imported, but the origin of such glass and the location of such workshop are not clear at the moment. Given that we have no evidence that Levantine I type production survived till the 9th century AD, this last hypothesis seems the least plausible.

Group 4 represent a unique presence at Barking Abbey and currently has no comparison in Anglo-Saxon England, with its raw materials different greatly from the other Levantine glasses: highly radiogenic strontium (c. 0.7140 - 0.7150) paired to a low Sr concentration of c. 200 ppm and negative εNd between -9.91 and -14.40. The comparison with strontium analytical data recently published by Brill and Fullagar (2012) unfortunately does not allow us to draw conclusions on their provenance for now.

Comacchio glass Sr and Nd analytical results also mirror the area of production suggested by EMPA and trace elements analysis.

Group 8 fall within the HIMT range suggested in the literature (Degryse et al., 2006; 2009b; Freestone et al., 2005, 2009) with low Sr signature influenced by terrestrial strontium source (limestone) and high εNd values of -3.67 and -3.98. Moreover, 8th century Com75 (cup) matches one chunk glass from Sagalassos (Degryse et al., 2006). The latter sample has been dated between the 450–650/75 AD (Degryse et al., 2005, 290).

The precise location of HIMT production has not been yet established, but HIMT was competing for the same markets as Levantine between the middle 4th and the middle/end 7th century AD throughout the Mediterranean and Europe (Nenna 2014, 186). In a later period, the production of HIMT moved from northern Syria workshops to Egypt to an unknown location (or more than one as suggested by Nenna) to this day.

Therefore, our HIMT group 8 (8th century AD) could be reused old "Roman" glass or new glass from Egyptian workshops. The perfect matching between Com75 and Sagalassos early Byzantine (450–650/75 AD) sample SA00JP25 would suggest that group 8 might have been produced in the same area, if not the same workshop. In addition to such comparison, if we think consider that HIMT is supposedly the mix between two sand components (beach sand plus sand material with strong terrestrial component) the coincidence of producing such a precise combination is quite remarkable.

Therefore, the hypothesis of the use of Old Roman glass seems more plausible.

The HIMT weak variant represented by Com85 – group 2B (end of 7th early 8th century AD) falls within still lower Sr signature (0.708509) comparable with other published material, but with a lower -6.40 εNd values, which indicates the use of a different sand, and therefore potentially a different workshop from group 8, but also falls within the

known Levantine/HIMT range (-5.0 to -6.0). A value of -6.4 εNd is consistent with the sands from the Western Mediterranean area but, as Degryse and Schneider remarked (Degryse et al., 1998, 2006), intermediate εNd values between -6.4 and -6.8 could be the result of recycling of glass or mixing of primary sources from the eastern and western Mediterranean area. Recycling markers contents do not point towards suggesting extensive recycling in the case of Com 85 (Cu, Co, Sn, Pb <100 ppm; Sb c.121 ppm), but we cannot exclude that limited mixing might have occurred and it was not detected in our analysis.

Therefore, the nature of Com85 – group 2A cannot be assessed with confidence. Further analysis on other samples from group 2A should clarify in the future this matter. Another sample, Com45, shows a low εNd of -10.79, but the nature of the sample itself (waster, droplet) does not allow us to assign it with confidence to Western Mediterranean glass production.

Group 1A, 2A, and 3 fall within closer Apollonia Levantine I range for both Sr and Nd signatures but, as notice for Levantine Barking glass, a variation in Sr concentration and εNd values in some of the sample from group 3 and 1A suggests that at least two (if not more) different sand sources were used to produce Com 59, 60 from group 3 and Com16 from group 1A.

Group 1A, 2A and 3 are dated to between the late 6th and the 8th century AD, which matches partially Comacchio furnace active period (late 7th – early 8th). The presence of another workshop area immediately earlier or later cannot in the same area, especially in connection of the artisanal and construction work of the new church (Gelichi et al., 2012). Moreover, Com16 and 34 samples (analysed for Sr and Nd analysis) falls within the fore mentioned time frame. Therefore, at least two variations of Levantine I formula were potentially worked or at least traded to/at Comacchio workshop.

From a broader perspective, 1A, 2A, and 3 Levantine I groups represent fresh glass coming directly from a primary workshop (given that none of such groups shows markers of extensive recycling) and HIMT should represent late Roman – Early Byzantine glass produced in the same Levantine area but potentially centuries earlier.

Mixing practises spotted by trace elements analysis were confirmed by isotopic analysis: mixed lines between Sr signature and Sr ppm (Figure 135ff.) and proved that both HIMT strong group 8 and HIMT weak were potential end-members together with Levantine raw glass groups of, resultant in group 1B, 1C, and 2C. The latter groups presents intermediated isotopic signature but closer to Levantine values, which suggests a prevalent beach sand component in its silica source.

Hence, for the first time, isotopic analysis proved that mixing practices in Northern Italy were occurring between HIMT glass and “new” fresh Levantine I glass traded from the primary workshop centres. Until now, recycling and mixing between natron glass were framed as reflex of a stagnant economy, but the data included in this dissertation proves that unrecycled Levantine I glass was still traded to Northern Italy.

Mixing between natron and plant ash was also occurring in Comacchio, as the Com21 plant ash-based sample major and isotopic composition showed, but the later chronology associated to the same plant ash material (10th -11th century AD) clashes with such a hypothesis. I also suggested previously that Com14 is a natron-based sample mixed with plant ash of similar composition to group 4. Com14 is instead dated to the 2nd half of the 7th century, which suggests an earlier presence of plant ash at Comacchio, as it is been previously registered for the Venetian Lagoon (Verità and Toninato, 1990; Verità et al., 2002)

The idea that a compositionally similar plant ash was circulating earlier in Comacchio is therefore possible, but at the current state of the research it is not demonstrable.

Group 4 chronology has a perfect match with both Sr and Nd with 10th - 11th century material from Tyre (Freestone et al., 2003; Degryse et al., 2010) and suggests that the latter was the potential primary workshop for the Comacchio plant ash group. This correspondence also reinforces the hypothesis that group 4 would not match the period during which the Comacchio workshop would have been active.

Another possibility is that group 4 was made earlier that the 10th century and then it circulated for a long time until its deposition: this possibility would better fit with the analytical work suggesting that plant ash glasses were worked indeed together with the other compositions in Comacchio. Both Aldsworth et al. 2002) and Freestone (2002) do not exclude that the furnace at Tyre was operating before the 10th century AD, hence, I can tentatively suggest that a trade of plash ash glass from Tyre or another earlier workshop using geologically compatible raw materials is should not be dismissed entirely, but at the moment it unfortunately remains only an intriguing hypothesis.

6 Conclusions

The results in this study have demonstrated undoubtedly the connection of three secondary glass-making areas in Southern England, Northern Italy, and Southern Scandinavia to primary glass-making workshops located in the Levant between the 6th and 11th century AD. The provenance of Early Medieval glass in Western Europe has always been previously suggested because of the compositional similarities in major, minor, and trace elements (Callmer and Henderson, 1991; Hunter and Heyworth, 1998; Henderson, 2000; Verità et al., 2002; Uboldi and Verità, 2003; Brill, 2006; Freestone and Hughes, 2006; Gaut 2011; Silvestri and Marcante, 2011), but not proved by until now.

By combining the use of three different analytical techniques (EMPA, LA-ICP-MS, and isotopic analysis), it was possible to discuss and compare the acquired data with the known literature and explore its potential within three different layers of interpretation.

The determination of major and minor elements allowed the recognition of each recipe for the selected group of samples from the three sites. Moreover, it was possible to suggest precise glass-making processes (recycling and mixing) occurring at each secondary workshop based on recycling and contamination markers. These results were then compared with assemblages from their respective regions.

Trace elements and REE profiles helped to characterise further each of the recipes underlined by compositional analysis. By pairing element ratios of selected elements as shown previously by Ceglia and co-workers (2017), it was possible to further discuss mixing practices between potential end-members for each of the non-recycled compositions. For the first time trace elements ratios were able to prove mixing between Levantine I, HIMT (both strong and weak variants), and potentially also plant ash at Comacchio workshop. Concentrations of

recycling markers over 100ppm add further evidence for heavy recycling practice at Comacchio and Barking Abbey.

Finally, in this study the provenance of glass from Southern England and Northern Italy is discussed for the first time.

The provenance of such raw materials was proved by comparing with previously published and discussed isotopic studies (Freestone et al., 2003; Degryse et al., 2006; Degryse and Schneider, 2008; Henderson et al., 2009; Degryse, 2014; Gallo et al., 2015; Maltoni et al. 2015). The combination of Sr and Nd allowed the exploration of the nature of the raw materials for each recipe in Comacchio and Barking Abbey, and for the first time to link unequivocally glass made in the Levant with these areas. Isotopic analysis and the use of hypothetical mixing lines also confirmed previous suggestions of mixing practices in Comacchio glass based on end-members identified by trace element ratios.

These results clearly show how secondary workshops are essential to understand the nature of the glass-working processes. Not only secondary glass-making centres become the intermediate link between primary glass-making centres and their final distribution areas, but also they allow us to investigate secondary glass-working processes at the same place where they were undertaken As a consequence, the chance to reconstruct the “starter” materials used in mixing and recycling processes is increased (as for example, the mixing of Levantine and HIMT glass at Comacchio and the production of opaque blue glass at Barking Abbey).

Moreover, Comacchio, Barking, and Ribe symbolise three potential scenarios occurring at secondary workshops.

At Barking Abbey, it appears that a restricted number of recipes were worked (Levantine I and potash-silica high alumina glass) and that group 1 and 3 based on PCA are not associated to a specific group of artefacts produced and/or traded. Group 2 makes it an exception since it almost

exclusively includes white rods, but the base glass is also in this case Levantine I.

The exclusive preference for Levantine I glass, which seems to be common for other contemporary sites in England (Freestone and Hughes, 2006; Willmott and Welham, 2015), leads to the conclusion that only Levantine I glass was reaching England by the 8th century AD. Multiple mixing of Levantine I in the different groups reinforces the idea that Levantine I was the only glass available at that time to sustain Barking Abbey glass production. The nature of the glass-working wasters itself found at Barking makes it clear that some sort of fine specialised production was indeed occurring in the form of millefiori and reticella rods.

Turning to Barking group 4 (potash silica glass), the idea of long-distant trade ultimately with Southern Asia via middle-men regions appears incredibly intriguing, but I would suggest that more work needs to be done on this subject before proposing this hypothesis. As I remarked previously in section 5.1.2, the presence of high potash glass is not new for this period in the Western world (Pion and Gratuze, 2016; Sode et al., 2017), and trade with South-East Asia has already been hypothesised for 8th – 9th century material from Scandinavia by Sode and colleagues from India, through the Caspian Sea and via the Russian river systems or along the Silk route through Iran (Sode et al., 2017, 332). The closest compositional reference for Barking group 4 is the m-K-Al (high alumina, low lime) group from Southern Asia potentially made in China (Lankton et al., 2006; Liu et al., 2013; Dussubieux, 2016) dated to 2nd century AD at the latest. Group 4 might represent a small group of residual glass made potentially way before the furnace in Barking was operating and consequently it is not an expression of contemporary long-distance trade but instead re-use of available glass at the site.

Comacchio provides a much more diverse and complex glass working context, with the presence at the same secondary workshop of numerous recipes. There is no doubt that Levantine I and HIMT (both strong and

weak variant) were worked at the same time to produce glass in Comacchio.

Moreover, even though the provenance of plant ash in Comacchio cannot still be pointed with certainty to Tyre (see section 5.1.1), mixing lines show that some plant ash formula was worked at the same time as the other natron-based compositions: the “new” reintroduced plant ash formula must have represented a luxury import compared to the “old” natron-based glasses, which would also explain its limited presence. The product of the Comacchio workshop is the result of multiple raw glass sources, contrary to Barking which instead appears to be supplied only by the Levantine I recipe, albeit potentially made with different raw materials (see section 5.2.1.2 and 5.2.25.2.1.2).

The situation of Ribe appears instead to be dominated by the presence of only HIMT – Foy 2 type extensively reworked, as both EMPA and LA-ICP-MS revealed the intense recycled character of its composition. Like Barking, only one formula dominates the assemblage, and there is no apparent match between recipe and archaeological phase and/or artefact. The compositional differences evidenced in PCA might correspond therefore to different batches of the same HIMT-based glass.

Furthermore, the materials that supposedly could have been used as raw glass (lumps of glass or tesserae) have the same composition as the other artefacts (such as rods or beads). This suggests that the mosaic tesserae and lumps of glass to be worked in Ribe could have been traded in a heavily recycled state, since no furnaces or equivalent glass-working structures are connected to 8th century Ribe. Another possibility is that such artefacts were worked at another secondary workshop and only re-melted in Ribe (for example to create beads).

Trace elements analysis revealed that PCA defined groups in Ribe separate according to Zr/SiO_2 versus. Ce/La ratios (section 5.1.3.3) between transparent and opaque coloured glass, a division that might be connected with the bead-making industry. Such correspondence

between colours and recipes indicates that Ribe artisans operated a careful selection of raw material (cullet) to pair glass recipe with colour, which indicates control over both manufacture and organisation of production and storage.

One main question remains: when was the glass found at these three sites made and for how long was it circulating?

The circulation of a specific recipe cannot be confined to the supposed activity span of the main primary workshop: Levantine I, for example, was made both at Jalame, dated to the 4th century (Brill, 1988) and Apollonia, dated to the 6th - 7th century AD (Tal et al., 2004). Therefore, the Levantine workshops were operating during both the Roman and the Late Antique period (Nenna et al., 1997; Freestone et al., 2000; Degryse, 2014).

I also remarked many times in this dissertation how glass can be recycled and therefore circulate for a long period in the form of cullet. This means that a recipe, albeit altered by secondary processes such as recycling and mixing, might have been primarily produced a long time before a specific object was made (and later included in an archaeological deposit). This latter consideration becomes significant when we consider the three sites mentioned in this dissertation, since the material included has not been examined from the typological point of view.

Recently, Phelps and co-workers (2016) discussed an interesting paradox concerning primary glass production in Palestine during the period of transition between natron-based glass and plant ash glass. Their compositional data from well-dated glass datasets from 7th-12th century Palestine support the hypothesis that during the 8th century AD the production of natron glass moved from Apollonia to Bet Eli'ezer (transition from Levantine I to Levantine II recipe). The latter would have been active until the 8th century AD when natron glass production inevitably declined in favour of plant ash glass. They also remarked how in the 8th century, when natron should have been declining, other sites

such as 8th century Raya, Sinai peninsula (Kato et al., 2009) and 8th -9th century Raqqa (Henderson et al., 2004) were in fact working with natron-based glass similar (but not identical) in composition to Levantine I. The case of Raqqa is particularly relevant to this dissertation, since Comacchio deals with plant ash glass that might have been made with plant ashes potentially harvested in the Raqqa area (section 5.2.1.15.2.2). During the Early Byzantine period, other variations of Levantine I glass were indeed circulating across the Mediterranean (Freestone et al., 2002; Foy et al., 2003; Ceglia et al., 2015), as Phelps and colleagues remark (Phelps et al., 2016, 65-6).

I am not suggesting that natron-based glass included in this dissertation was made in Raqqa, but the paradox expressed by Phelps et al. underlines that the chronological limits of Levantine I composition might not be tied necessarily to Apollonia glass workshops and therefore to its time range (6th – 7th century). It might have been produced earlier in the Roman period (and therefore represents a reserve of "old" glass) or immediately after, in some unknown as yet undiscovered primary workshop (hence fresh glass). A similar objection can be made for HIMT, for which there is currently no alternative hypothesis other than primary production in Egypt after the production sites moved from North-Sinai. HIMT kept circulating, as seen in this dissertation, during the 7th – 8th centuries, especially in Italy (Mirti et al., 2000, 2001; Foy et al., 2003; Uboldi and Verità, 2003; Silvestri and Marcante, 2011).

Is it then possible to discuss suggestions about when glass was made at Comacchio, Barking Abbey, and Ribe?

The presence at Comacchio of Levantine I glass similar to Apollonia, could let us think that at least some "fresh" glass (group 3) was still coming in at least during the first period of its activity (late 7th century).

Similar group 3 Sr isotope signatures matches Bet Eli'ezer samples does not indicate necessarily that the same glass has been produced at this workshop, since Comacchio group 3 is not compositionally similar to

Levantine II 5.1.1.2), supposedly produced at Bet Eli'ezer from the 8th century AD (Freestone et al., 2000; Phelps et al., 2016). This isotopic similarity might instead indicate that raw materials from the same geographical area might have been used. Therefore, it is vital to get new Levantine comparable isotopic data in the future to assess this issue.

The presence of "old" unrecycled Levantine I (group 1A and 2A), more similar in composition to 3rd – 5th century Aquileia AQ2 group (Gallo et al., 2014), indicates that potentially these two groups might have been circulating for at least two centuries as small reserve of 3rd to 5th century glass collected as cullet in Comacchio. Such occurrence indicates how the same Levantine I higher Na_2O variant was circulating in Veneto for at least two centuries or even more. In another case, we might be looking at the product of a different workshop not yet discovered producing glass with a higher Na_2O content.

This debate becomes more interesting when HIMT is also discussed. We know that HIMT was circulating in Veneto at least until the 11th century AD (Uboldi and Verità, 2003; Silvestri and Marcante, 2011) and in Central Italy until the 8th century AD (Mirti et al., 2000, 2001).

Moreover, 6th – 8th century unrecycled HIMT[95] from Comacchio (group 8) resembles in composition and isotopic provenance 5th - 7th century chunk glass from Sagalassos Therefore, Comacchio (and therefore potentially Veneto and Northern Italy) were receiving unrecycled HIMT from the Byzantine world. Comacchio HIMT is also similar to 3th – 6th century AQ1 glass from Aquileia (Gallo et al., 2015), showing continuity of supply of HIMT glass to Veneto. Unfortunately, it is not possible to establish with certainty if Comacchio HIMT was freshly made (6th -7th century) or of Roman production.

Even though its chronology is still dubious, plant ash in Comacchio definitely represents freshly produced glass coming directly from the

[95] Only one sample, Com06, from group 2B, dated to the 10th -11th century AD.

Levant. Byzantine ships were trading oil, wine, and spices through the Adriatic Sea route (Gelichi, 2009; McCormick, 2001, 524), together with 8th century globular amphorae (Negrelli, 2012). The Liutprand Capitular pact allowed Comacchio boats to circulate across the Po Valley to Pavia and Milan. Could fresh glass from the Levant have being traded to Comacchio and then redistributed across the whole of Northern Italy via the Po Valley?

Moving on to the context of glass production in South-East England, the Barking Abbey glass chronology represents a problem at the moment. If we accept the date suggested of the late 9th AD to the late 10th AD for the excavated remains (MacGowan, 1996), Levantine I glass at Barking could represent a reserve of old glass, both recycled and non, potentially made in at least two workshops in the Levant. The real question would be why Barking Abbey had to use glass potentially made at least two centuries earlier? If this was the case, the addition of opaque material to the basic Levantine formula to make group 1 would agree well with this scenario. Was glass scarce? Or did they simply decide to use what they had locally available?

If we accept the 8th century date for Barking glass as suggested previously by Evison (1991) and Bayley (2000a) based on the vessel typologies, according to Phelps and co-workers Levantine I was already scarce compared to Levantine II – Bet Eliezer production (Phelps et al., 2016, 63), and therefore we need to be aware when considering group 1 and 3 at Barking as a reflection of direct contact with the Levant.

Levantine I is also prevalent at other contemporary 8th century Anglo-Saxon sites in England, such as Jarrow (Freestone and Hughes, 2006) and Glastonbury, if we agree with its suggested earlier chronology (Willmott and Welham, 2015). Therefore, was fresh glass not getting to Southern England? Could Levantine I formula have been traded before the period of activity of the Barking furnace through designated trade routes to Southern England through the Rhineland route or Northern

France as suggested by typological similarities (Hunter and Heyworth, 1998; Evison, 2000a; Feveile, 2006b)?

Also, Ribe and Barking do differ in base natron composition: does this change (Levantine I versus HIMT weak) mirrors different glass exchange routes or movement of glass-workers? We cannot dismiss the possibility of itinerant artisans from Northern France, as written sources suggested for Jarrow (Cramp, 2006), or from other areas taking glass with them or using what was locally available. The latter hypothesis fits well with the recycling practices occurring at Barking and re-use of opaque glass material as the work of skilled professionals.

The circumstances with Ribe glass appear complex. The presence at Ribe of HIMT in the 8th century associated with the high degree of recycling of the same glass, would suggest that Ribe glass should somehow represent a bulk of HIMT glass being re-worked (and therefore circulating) for a long time. Marketplaces such as Ribe must have represented the perfect place where cullet could have been gathered to be used in bead-making industries (Feveile 2006b, 254). Given that no isotopic data are available for Ribe glass, no further assumption can be made.

On the other hand, tesserae from Comacchio and Ribe do agree compositionally. While it cannot be said with certainty with current data that Northern Italy was supplying glass to Scandinavia (as it is implied in other publications), what can be said is that they might have had a common (potentially Byzantine) origin. Moreover, this dissertation showed how both sites share HIMT weak composition in the 8th century AD. In addition, 9th century material from Kaupang is compositionally similar to Ribe, (section 5.1.3.2), contrary to 8th – 9th century Levantine I - Dorestad material (Sanderson et al., 1984).

Does this dissimilarity mirror a difference in sourcing glass too, potentially through different trade routes? Moreover, could Northern Italy be the middle-man source region for the HIMT glass ultimately traded to Ribe?

It can be suggested from the analytical evidence that at least two distributional networks were in operation from the 7th century for the supply of glass to Northern Europe and Western Scandinavia.

Firstly, a route supplying predominantly Levantine I glass seems to have operated from North-Eastern Italy probably via the Po Valley across the Alps and the Danube and the Rhine to North-West Europe, via the ports of the Rhine delta region (Domburg and Dorestad), and then to Anglo-Saxon England (Campbell 2007; Loveluck 2013, Ch 9; Loveluck 2017).

Secondly, a different route supplying predominantly HIMT glass provisioned Western Scandinavia. Given the near absence of Levantine I glass in Western Scandinavia, the trade route providing the HIMT probably lays to the East of the Trans-Alpine Rhine route, and the transport and exchange pathway for this glass is at present undefined. It is possible that some of the glass may have been imported into the Jutland peninsula, during the mid to late Roman period (3rd and 4th centuries AD) in the same era as the Roman weaponry from Jutland bog deposits, such as Illerup Ådal (Ilkjær 2000). The early Byzantine glass may have arrived via the links with the Byzantine world through eastern and Eastern-Central Europe, reflected in the Scandinavian and Byzantine stylistic influences on metalwork in the latter parts of Europe (Høilund-Nielsen 2009).

The scope of this dissertation does not entail exploring the dynamics of trade and exchange of glass from the social-economic standpoint. Nonetheless, it is undeniable that the presence of glass material in Western Europe between the 7th and 10th century AD suggests routes of exchange between the Channel and North-Sea regions.

The idea introduced by Hodges (1982) of 7th–9th century emporia founded on both sides of the English Channel and southern North Sea coasts as ‘gateway communities’ controlling the redistribution of imported luxuries, surpluses, and manufactured goods for kings or regional rulers has been discussed and revisited in recent years. More specifically, the role of

coastal communities and regions, in addition to the major ports and smaller landing places has been recognised in promoting access to commodities (including glass) through coastal households, and communities living and travelling along major river corridors: the dispersion of commodities, such as glass artefacts, mirrors the extent of the existing marine and riverine networks between Eastern England, Northern France, Flanders, Frisia, the Northern coast of Germany and Western Scandinavia, along the Channel, North-Sea coast and the Kattegatt coasts, and major river systems leading inland (Loveluck and Tys 2006; Loveluck 2013; Loveluck 2017).

At Flixborough (UK), fragments of sixty-five glass vessels from northern France and Rhineland were found (Loveluck 2013, 186). The same can be said for imported glass vessels from the Rhineland and coastal regions of Oost Friesland, Lower Saxony, and coastal Flanders. The 8th - and 9th century glass palm cups and funnel beakers from the north of Norway at Borg (Lofoten Islands) might also reflect the Frisian maritime networks (Holand 2003a and 2003b; Loveluck 2013, 196).

All glass vessel-types from Ribe have a west European-Anglo Saxon distribution area, which centres around the central and eastern English Channel, at the estuaries of the major European rivers, the southern North Sea and the western part of the Baltic (Feveile 2006b, 253; Loveluck 2017).

The distribution of glass and other imported goods in these three regions would therefore mirror the dynamism of economic agents involved in cross-Channel and North Sea exchange networks, which is an expression of the same economic push behind the foundation of emporia such as Dorestad, Quentovic and the major Anglo-Saxon ports (Lebecq 1997, 75; McCormick 2007, 44–6).

It is more difficult to hypothesise in what form glass moved around Western Europe.

On numerous occasions, glass specialists have assumed that glass fragments of the finest quality vessels found at several settlements, such as Fishergate, York (Hunter and Jackson 1993, 1333-42), Lundenwic-London (Stiff 2003, 241-4), and Hamwic (Hunter and Heyworth, 1998), were used as cullet, mostly in bead-making practices (Stiff, 2001). This might have been indeed true in some respect, but their presence at such sites might have a different meaning than recycling purposes alone: the wide range of their deposition contexts makes it extremely likely that a significant proportion of merchant and artisan households were using the glass vessels as drinking containers prior to any recycling, and that they should not be seen as evidence of procurement of cullet from aristocratic households (Loveluck 2013, 206).

Although recycled copper might have constituted a significant component of the metal circulating in Britain during the 1st millennium AD, Pollard and colleagues (2015, 711-2) hypothesised the presence of fresh metal (copper) supply in Britain during the middle Saxon period, and more specifically of copper (CC12) alloyed with c. 11% zinc.

New data from integrated analysis of the Colle Gnifetti ice core, studied alongside other environmental, archaeological, numismatic and textual records from Western Europe has identified a pollution record likely stemming from new silver mining and bullion production, between c. 640 ±10 and 660 ±10 AD, with the mines at le Melle in western France as the most likely identifiable source (Loveluck et al., 2018, in press).

In this view, it is safe to assume that fresh glass as well as other non-recycled material supplies (such as freshly made silver coins and copper) were indeed being mined, smelted and moved around Western Europe. The combination of three different analytical techniques in this dissertation proved that fresh glass in the form of Levantine compositions was indeed reaching Western Europe (Italy and Eastern Britain at least).

Future work will need three important components.

First, there is a need to increase existent compositional datasets (trace elements in particular) for Early Medieval material from a wide range of sites in the three regions studied. Southern England and Scandinavia would particularly benefit from this, since very few analytical studies have been attempted until now, and the lack of existing comparisons impacted on the results of this thesis. Moreover, we need to move further from the mere recipe identification and future analytical data need to be evaluated much more comprehensively within period-cultural context.

Secondly, future work should focus into producing analyses of unrecycled glass from the same areas to assess the impact of mixing and recycling practices, in particular for Scandinavia and Southern England. Analysis of colourless and faintly coloured glass and associated recycling practices from Ribe would be particularly beneficial, since it could not be done in this dissertation seeing the nature of the material itself (opaque and strongly coloured).

The presence of potash silica high alumina glass in Western Europe and its potential implication for glass trade along the land and maritime Silk routes should be examined further: isotopic characterisation of Asian glass (ideally from China) will allow us to find meaningful comparisons with the Barking material and it will help to verify the primary production of potash silica glass in China as suggested by Dussubieux and colleagues (2016). Isotopic analysis for potential raw materials for Asian glass would also be a positive step forward.

Finally, the study included in this dissertation represents only a first attempt into progressing the debate concerning the provenance of Western glass in the Early Medieval period. Future isotopic studies should focus on including new data from several additional secondary production areas that have not been included in this work, such as Scandinavia, Central Europe, France, Spain, and Ireland.

7 Bibliography

Aerts, A., Velde, B., Janssens, K., Dijkman, W., 2003. Change in silica sources in Roman and post-Roman glass. Spectrochimica Acta Part B: Atomic Spectroscopy 58(4), 659–667.

Aldsworth, F., Haggarty, G., Jennings, S., Whitehouse, D., 2002. Medieval glassmaking at Tyre, Lebanon. Journal of Glass Studies 44, 49–66.

Allan, J.W., 1973. Abū'l-Qāsim's treatise on ceramics. Iran 11, 111–120.

Andersen, I.H., Sode, T., 2010. The Glass Bead Material. In: Bencard, M., Madsen, H.B. (Eds.), Ribe Excavations, 1970-76, Volume 6. Aarhus Universitetsforlag, 17–128.

Andreescu-Treadgold, I., Henderson, J., Roe, M., 2006. Glass from the Mosaics on the West Wall of Torcello's Basilica. Arte medievale, 87–140.

Askeland, D.R., Fulay, P.P., Wright, W.J., 2010. The science and engineering of materials, 6th ed. Stamford, CT: Cengage Learning.

Banner, J.L., 2004. Radiogenic isotopes: Systematics and applications to earth surface processes and chemical stratigraphy. Earth-Science Reviews 65, 141–194.

Barkoudah, Y., Henderson, J., 2006. Plant ashes from Syria and the manufacture of ancient glass: ethnographic and scientific aspects. Journal of Glass Studies 48, 297–321.

Bass, G.F., 1984. The nature of the Serçe Limani glass. Journal of Glass Studies 26, 64–69.

Bass, G.F., 1986. A Bronze Age Shipwreck at Ulu Burun (Kaş): 1984 Campaign. American Journal of Archaeology 90, 269–296.

Bass, G.F., Van Doorninck, F.H., 1978. An eleventh century shipwreck at Serçe Liman, Turkey. International Journal of Nautical Archaeology 7, 119–132.

Bass, G.F., Brill, R.H., Lledó, B., Matthews, S.D., 2009. Serçe Limani: Glass of an eleventh-century shipwreck, Vol. 2, Rachel Foundation Nautical Archaeology Series, College Station, Texas: Texas A&M University Press.

Baxter, M.J., Cool, H.E.M., Jackson, C.M., 2005. Further studies in the compositional variability of colourless Romano-British vessel glass. Archaeometry 47, 47–68.

Bayley, J., 2000a. Glass-working in early medieval England. In: Price, J. (Ed.), *Glass in Britain and Ireland AD 350-1100*, Occasional Paper. British Museum 127, 137–142.

Bayley, J., 2000b. Saxon Glass-working at Glastonbury Abbey. In: Price, J. (Ed.), *Glass in Britain and Ireland AD 350-1100*, Occasional Paper. British Museum 127, 161–188.

Bencard, M., 1981. Ribe Excavations 1970-76, Volume 1. Esbjerg: Sydjysk Universitetsforlag, Esbjerg.

Bencard, M., 1984. Ribe Excavations 1970-76, Volume 2. Esbjerg: Sydjysk Universitetsforlag.

Bencard, M., 1988. The stratigraphy and dating of 8th century Ribe. Journal of Danish Archaeology 7, 225–228.

Bencard, M., Jørgensen, L.B., 1990. The foundation of Ribe. Antiquity 64, 576–583.

Bencard, M., Jørgensen, L.B., Madsen, H.B., 1990. Ribe Excavations 1970-76, Volume 4. Esbjerg: Sydjysk Universitetsforlag.

Bencard, M., Jørgensen, L.B., Madsen, H.B., 1991. Excavations 1970-76, Volume 3. Sydjysk Universitetsforlag, Esbjerg.

Bencard, M., Rasmussen, A.K., Madsen, H.B., 2004. Excavations 1970-76, Volume 5. Aarhus: Aarhus Universitetsforlag.

Bendixen, K., 1981. Sceattas and Other Coin Finds. In: Bencard, M. (Ed.), Ribe Excavations 1970-76, Volume 1. Sydjysk Universitetsforlag, Esbjerg, 63–101.

Bertini, C., Henderson, J., Gelichi, S., Basso, E., Riccardi, M.P., Ferri, M., 2017. Technological transition in Early Medieval Northern Italy: preliminary data for Comacchio glass. In: Wolf, S., De Pury-Gysel, A. (Eds.), *Proceedings of the Annales du 20e Congrès AIHV*, 7-11 September 2015, Rahden: Verlag Marie Leidorf, 354-9.

Boschetti, C., Leonelli, C., Macchiarola, M., Veronesi, P., Corradi, A., Sada, C., 2008. Early evidences of vitreous materials in Roman mosaics from Italy: An archaeological and archaeometric integrated study. Journal of Cultural Heritage 9, 21–6.

Boschetti, C., Henderson, J., Evans, J., Leonelli, C., 2016. Mosaic tesserae from Italy and the production of Mediterranean coloured glass (4rd century BCE - 4th century CE). Part I: Chemical composition and technology. Journal of Archaeological Science: Reports 7, 303–311.

Boschetti, C., Henderson, J., Evans, J., 2017. Mosaic tesserae from Italy and the production of Mediterranean coloured glass (4th century BCE – 4th century CE). Part II: Isotopic provenance. Journal of Archaeological Science: Reports 11, 647–657.

Bostock, J., Riley, H.T., 1857. The Natural History of Pliny, Vol. VI. London: Henry G. Bohn.

Brems, D., Degryse, P., 2014. Trace Element Analysis in Provenancing Roman Glass-Making. Archaeometry 56, 116–136.

Brems, D., Degryse, P., Hasendoncks, F., Gimeno, D., Silvestri, A., Vassilieva, E., Luypaers, S., Honings, J., 2012. Western Mediterranean sand deposits as a raw material for Roman glass production. Journal of Archaeological Science 39, 2897–2907.

Brems, D., Ganio, M., Latruwe, K., Balcaen, L., Carremans, M., Gimeno, D., Silvestri, A., Vanhaecke, F., Muchez, P., Degryse, P., 2013a. Isotopes on the beach, Part 1: Strontium isotope ratios as a

provenance indicator for lime raw materials used in roman glass-making. Archaeometry 55, 214–234.

Brems, D., Ganio, M., Latruwe, K., Balcaen, L., Carremans, M., Gimeno, D., Silvestri, A., Vanhaecke, F., Muchez, P., Degryse, P., 2013b. Isotopes on the beach, Part 2: Neodymium isotopic analysis for the provenancing of roman glass-making. Archaeometry 55, 449–464.

Brill, R.H., 1962. A Note on the Scientist's Definition of Glass. Journal of Glass Studies 4, 127–138.

Brill, R.H., 1963. Ancient glass. Scientific American 209, 120–131.

Brill, R.H., 1967. A great glass slab from ancient Galilee. Archaeology 20, 88–95.

Brill, R.H., 1970. Lead and oxygen isotopes in ancient objects. Philosophical Transactions of the Royal Society of London. Series A, Mathematical and Physical Sciences 269, 143–164.

Brill, R.H., 1988. Scientific investigations of the Jalame glass and related finds. In: Weinberg, G.D. (Ed.), Excavations at Jalame: Site of a Glass Factory in Late Roman Palestine. Columbia: University of Missouri, 257–294.

Brill, R.H., 1995. Scientific research in early Asian glass. In: *Proceedings of the 17th International Congress on Glass*, Beijing 1995, Volume I, Beijing: International Academic Publisher, 270–279.

Brill, R.H., 1999a. Chemical analyses of early glasses. Volume 1: catalogue of samples. Corning, NY: The Corning Museum of Glass.

Brill, R.H., 1999b. Chemical analyses of early glasses. Volume 2: tables. Corning, NY: The Corning Museum of Glass.

Brill, R.H., 2006. Chemical analyses of some glasses from Jarrow and Wearmouth. In: Cramp., R. (Ed.), *Wearmouth and Jarrow, Monastics sites*. Swindon: English Heritage, 123–147.

Brill, R.H., Wampler, J.M., 1965. Isotope ratios in archaeological objects of lead. In: Application of Science in Examination of Works of Art. Proceedings of the Seminar, September 7 - 16 1965, Boston: Research Laboratory, Museum of Fine Arts, 155–166.

Brill, R.H., Wosinski, J.F., 1965. A huge slab of glass in the ancient necropolis of Beth She'arim. Proceedings of the 7th International Congress on Glass, Brussels.

Brill, R.H., Wosinski, J.F., 1988. Glass manufacture. In: Weinberg, G.D. (Ed.), *Excavations at Jalame: Site of a Glass Factory in Late Roman Palestine*. Columbia: University of Missouri Press, 283-88.

Brill, R.H., Fullagar, P.D., 2012. Strontium isotope studies of Historical glasses and related materials. In: Brill, R.H., Stapleton, C.P. (Eds.), *Chemical Analyses of Early Glasses: Volume 3: The Years 2000–2011, Reports, and Essays.* Corning, NY: The Corning Museum of Glass, 621–679.

Brill, R.H., Barnes, I.L., Adams, B., 1974. Lead isotopes in some ancient Egyptian objects. In: Bishay, A. (Ed.), *Recent Advances in Science and Technology of Materials*. New York and London: Plenum Press, 9–27.

Brown, T., Christie, N., 1989. Was there a Byzantine model of settlement in Italy?. Temps modernes 101, 377–399.

Bussell, D.A., Brown, J.N., 2012. Barking's Lives, the Abbey and its Abbesses. In: Jennifer N. Brown, J.N., Bussel, D.A (Eds), *Barking Abbey and Medieval Literary Culture: Authorship and Authority in a Female Community.* Woodbridge, Suffolk: York Medieval Press, 1–30.

Cable, M., 2001. The World's Most Famous Book on Glassmaking, The Art of Glass by Antonio Neri, translated into English by Christopher Merrett. Sheffield: Society of Glass Technology.

Calaon, D., 2007. Lo scavo di Villaggio San Francesco 1996. Le strutture portuali di Comacchio?. In: F.Berti;, Bollini;, M., Gelichi;, S., Ortalli, J. (Eds.), U*omini, Territorio E Culto dall'Antichità all'Altomedioevo. Genti Nel Delta. Da Spina a Comacchio.* Ferrara: Corbo editore, 125–304.

Callmer, J., 1977. Trade beads and bead trade in Scandinavia ca. 800--1000 AD Acta Archaeologica Lundensia 11, Bonn : R. Habelt : Lund : Gleerup.

Callmer, J., 2002. North-European trading centres and the early medieval craftsman. Craftsmen at \AAhus, North-Eastern Scania, Sweden ca. AD 750--850. Central Places in the Migration and Merovingian Periods 6, 125–157.

Callmer, J., Henderson, J., 1991. Glassworking at Ahus, S. Sweden (eighth century AD). Laborativ Arkeologi 5, 143–154.

Campbell, E., 1997. The Early Medieval imports. In: Hill, P., Campbell, E. (Eds.), *Whithorn and St Ninian : The Excavation of a Monastic Town, 1984-91.* Whithorn Trust/Sutton Pub, 643.

Campbell, E., 2007. Continental and Mediterranean imports to Atlantic Britain and Ireland, AD 400-800. York: Council for British Archaeology.

Carboni, S., 1998. Gregorio's Tale; or, Of enamelled glass production in Venice. In: Ward, E (Ed.), *Gilded and enamelled glass from the Middle East.* London: The British Museum press, 101–106.

Ceglia, A., Cosyns, P., Nys, K., Terryn, H., Thienpont, H., Meulebroeck, W., 2015. Late antique glass distribution and consumption in Cyprus: a chemical study. Journal of Archaeological Science 61, 213–222.

Ceglia, A., Cosyns, P., Schibille, N., Meulebroeck, W., 2017. Unravelling provenance and recycling of late antique glass from Cyprus with trace elements. Archaeological and Anthropological Sciences 1–13.

Cessi, R., 1963. Venezia ducale. Venezia: A spese della Deputazione.

Cholakova, A., Rehren, T., Freestone, I.C., 2016. Compositional identification of 6th c. AD glass from the Lower Danube. Journal of Archaeological Science: Reports 7, 625–632.

Christensen, K., 1990. Wood-anatomical and Dendrochronological Studies. In: Bencard, M, Jørgensen, L. B.; Madsen, H. B., Skovgaard-Petersen, I., K. (Eds.), *Ribe Excavations 1970-76, Volume 4.* Esbjerg: Sydjysk Universitetsforlag, 169–181.

Clapham, A.W., 1911. The Benedictine Abbey of Barking: a Sketch of Its Architectural History and an Account of Recent Excavations on Its Site. Colchester: Morant Club Publications.

Cool, H.E.M., 1995. Glass vessels of the fourth and early fifth century in Roman Britain. In: Foy, D. (Ed.), *Le verre de l'Antiquite tardive et du Haut Moyen-Age. Typologie-Chronologie-Diffusion.* Guiry-en-Vexin: Museée Archéologique du Val d'Oise, 11-23.

Corti, C.S., 2007. Santa Maria in Padovetere: la chiesa, la necropoli e l'insediamento circostante. In: Gelichi, S. (Ed.), *Comacchio E Il Suo Territorio Tra La Tarda Antichità e L'alto Medioevo.* Ferrara: Corbo editore, 531–552.

Cramp, R., 2005. Wearmouth and Jarrow Monastic Sites, Volume I. Swindon: English Heritage

Cramp, R., 2006. Wearmouth and Jarrow Monastic Sites; Volume II. Swindon: English Heritage.

Croix, S., 2014. Permanency in Early Medieval Emporia: Reassessing Ribe. European Journal of Archaeology 18(3), 497-523.

Davison, S., Newton, R.G., 2006. Conservation and restoration of glass. London: Routledge.

Degryse, P., 2014. Glass making in the Greco-Roman world: results of the ARCHGLASS project. Leuven: Leuven University Press.

Degryse, P., Schneider, J., 2008. Pliny the Elder and Sr--Nd isotopes: tracing the provenance of raw materials for Roman glass production. Journal of Archaeological Science 35, 1993–2000.

Degryse, P., Schneider, J., Poblome, J., Waelkens, M., Haack, U., Muchez, P., 2005. A geochemical study of Roman to early Byzantine Glass from Sagalassos, South-west Turkey. Journal of Archaeological Science 32, 287–299.

Degryse, P., Schneider, J., Haack, U., Lauwers, V., Poblome, J., Waelkens, M., Muchez, P., 2006. Evidence for glass 'recycling'using Pb and Sr isotopic ratios and Sr-mixing lines: the case of early Byzantine Sagalassos. Journal of Archaeological Science 33, 494–501.

Degryse, P., Henderson, J., Hodgins, G., 2009a. Isotopes in vitreous materials, a state-of-the-art and perspectives. In: Degryse, P., Henderson, J., Hodgins, G. (Eds.), Studies in Archaeological Sciences - Isotopes in Vitreous Materials. Leuven: Leuven University Press, 15-30.

Degryse, P., Schneider, J., Lauwers, V., Henderson, J., Van Daele, B., Martens, M., Huisman, H., De Muynck, D., Muchez, P., 2009b. Neodymium and strontium isotopes in the provenance determination of primary natron glass production. In: Degryse, P., Henderson, J., Hodgins, G. (Eds.), Studies in Archaeological Sciences - Isotopes in Vitreous Materials. Leuven: Leuven University Press, 53–72.

Degryse, P., Freestone, I.C., Schneider, J., Jennings, S., 2010. Technology and provenance of Levantine plant ash glass using Sr-Nd isotope analysis. In: Drauschke, J., Keller, D. (Eds), *Glass in Byzantium - Production, usage, analyses.* Regensburg: Schnell & Steiner, 83–90.

Deliyannis, D.M., 2006. Agnelli Ravennatis Liber pontificalis ecclesiae Ravennatis. Turnhout: Brepols.

Dell'Amico, P., 2001. La nave romana di Grado. Analisi preliminare delle strutture del relitto. Navis 2, 36–65.

DePaolo, D., Letters, G.W., 1976. Nd isotopic variations and petrogenetic models. Geophysical Research Letters 3, 249–252.

Devulder, V., Degryse, P., 2014. The sources of natron. In: Degryse, P. (Ed.), *Glass Making in the Greco-Roman Wold: The Results of the ARCHGLASS Project*. Leuven: Leuven University Press, 87–95.

Dickin, A.P., 2005. Radiogenic isotope geology, 2nd ed. Cambridge: Cambridge University Press.

Dotsika, E., Poutoukis, D., Tzavidopoulos, I., Maniatis, Y., Ignatiadou, D., Raco, B., 2009. A natron source at Pikrolimni Lake in

Greece? Geochemical evidence. Journal of Geochemical Exploration 103, 133–143.

Duckworth, C.N., 2011. The created stone: chemical and archaeological perspectives on the colour and material properties of early Egyptian glass, 1500-1200 BC. PhD thesis. University of Nottingham.

Dussubieux, L., 2016. Potash glass: A view from South and Southeast Asia. In: Gan, F., Qinghui, L., Henderson, J. (Eds.), *Recent Advances in Scientific Research on Ancient Glass and Glaze*. Hackensack: World Scientific Publishing Company Incorporated, 95-111.

Evison, V., 1991. Vessel fragments. In: Webster, L., Backhouse, J. (Eds.), T*he Making of England. Anglo-Saxon Art and Culture, AD, 600-900*. University of Toronto Press, Toronto, 90–93.

Evison, V., 2000a. Glass vessels in England, AD 400-1100. In: Price, J. (Ed.), *Glass in Britain and Ireland AD 350-1100, Occasional Paper*. British Museum 127, 47-104.

Evison, V., 2000b. The glass fragments from Glastonbury. In: Price, J. (Ed.), *Glass in Britain and Ireland AD 350-1100, Occasional Paper*. British Museum 127, 189-99.

Evison, V., 2009. Glass vessels. In: Evans, D.H., Loveluck, C. (Eds.), *Life and economy at early medieval Flixborough c. AD. The artefact evidence*. Oxford: Oxbow books, 103-113.

Evison, V., Marzinzik, S., Freestone, I., Hughes, M.J., Stapleton, C.P., 2008. Catalogue of Anglo-Saxon Glass in the British Museum. London: British Museum.

Faure, G., Mensing, T.M., 2009. Isotopes: principles and applications, 3rd ed., New Delhi: Wiley India.

Fenzi, F., Lerma, S., Mendera, M., Messiga, B., Riccardi, M.P., Vigato, P.A., 2013. Medieval Glass-Making and-Working in Tuscany and Liguria (Italy). Towards a Standard Methodology for the Classification of Glass-Making and Glass-Working Indicators. In: Janssens, K. (Ed.), *Modern Methods for Analysing Archaeological and Historical Glass, Volume I*. Oxford: John Wiley & Sons Ltd, 473–513.

Ferri, M., 2006. Reperti vitrei altomedievali dagli scavi di Torcello e San Francesco del Deserto–Venezia. Journal of glass studies 48, 173-89.

Feveile, C., 2006a. Ribe on the north side of the river, 8th - 12th century - overview and interpretation. In: Feveile, C. (Ed.), *Det Ældste Ribe. Udgravninger På Nordsiden Af Ribe Å 1984-2000*. Ribe Studier, I.I. Højbjerg: Jysk Arkæologisk Selskab, 13-91.

Feveile, C., 2006b. The glass-vessel sherds from Ribe marketplace, ASR 9 Posthuset. In: Feveile, C. (Ed.), *Det Ældste Ribe. Udgravninger På Nordsiden Af Ribe Å 1984-2000*. Ribe Studier, I.I. Højbjerg: Jysk Arkæologisk Selskab, 195-256.

Feveile, C., 2012. Ribe. Emporium and Town in the 8th-9th Century. In: Gelichi, S., Hodges, R. (Eds.), *From One Sea to Another: Trading Places in the European and Mediterranean Early Middle Ages, International Conference,* Comacchio, 27th-29th March 2009. Turnhout: Brepols, 111–22.

Feveile, C., Jensen, S., 2000. Ribe in the 8th and 9th century. A Contribution to the Archaeological Chronology of North Western Europa. Acta Archaeologica 71, 9–24.

Foster, H.E., Jackson, C.M., 2009. The composition of 'naturally coloured' late Roman vessel glass from Britain and the implications for models of glass production and supply. Journal of Archaeological Science 37, 3068–3080.

Foy, D., Sennequier, G., 1989. A travers le verre du Moyen Age à la Renaissance. Seine Maritime: Musées et Monuments départementaux de la Seine-Maritime.

Foy, D., Nenna, M. D., 2001. Tout feu, tout sable: Mille ans de verre antique dans le Midi de la France. Edisud.

Foy, D., Vichy, M., Picon, M., 2000. Lingots de verre en Méditerranée occidentale (IIIe siècle av. J.-C. - VIIe siècle après J.-C.: approvisionnment et mise en oevre, donées archèologiques et donées de laboratoire). In: *Annales Du 14eme Congres de l'Association Internationale Pour l'Histoire Du Verre*. AIHV, Lochem: AIHV, 51–57.

Foy, D., Picon, M., Vichy, M., Thirion-Merle, V., 2003. Caractérisation des verres de la fin de l'Antiquité en Méditerranée occidentale: l'émergence de nouveaux courants commerciaux. In: Foy, D., Nenna, M. D. (Eds.), *Échanges et Commerce Du Verre Dans Le Monde Antique, Actes Du Colloque de l'Association Française Pour l'Archéologie Du Verre*, Aix-En-Provence et Marseille. Montagnac: Moniqdue Mergoil, 41-85.

Frandsen, L.B., Jensen, S., 1987. Pre-Viking and Early Viking Age Ribe: Excavations at Nicolajgade 8, 1985--86. Journal of Danish Archaeology 6, 175–189.

Frandsen, L.B., Jensen, S., 1988. The Dating of Ribe's earliest Culture Layers. Journal of Danish Archaeology 7, 228–231.

Freestone, I.C., 1987. Composition and microstructure of early opaque red glass. Early Vitreous Materials, 173–191.

Freestone, I.C., 1994. Chemical analysis of 'raw' glass fragments. In: Hurst, H. (Ed.), *Excavations at Carthage*, volume 2, 1 The circular Harbour, North Side. Oxford: Oxford University Press for the British Academy, 290.

Freestone, I.C., 2002. Composition and affinities of glass from the furnaces on the island site, Tyre. Journal of Glass Studies 44, 67–77.

Freestone, I.C., 2005. The provenance of ancient glass through compositional analysis. In: Vendiver, P. (Ed.), *Materials Issues in Art and Archaeology VII: Materials Research Society Symposium*, November 30

- December 3, 2004, Warrendale, Pa: Materials Research Society, 195–208.

Freestone, I.C., 2006. Glass production in Late Antiquity and the Early Islamic period: a geochemical perspective. Geological Society, London, Special Publications 257, 201–216.

Freestone, I.C., 2009. Pliny on Roman glassmaking. In: Martinón-Torres, M., and Rehren, T. (Eds.), *Archaeology, history and science: integrating approaches to ancient materials*. Walnut Creek, CA: Left Coast Press, 77–100.

Freestone, I.C., 2015. The Recycling and Reuse of Roman Glass: Analytical Approaches. Journal of Glass Studies 57, 29-40.

Freestone, I.C., Gorin-Rosen, Y., 1999. The Great Glass Slab at Bet She'arim, Israel: An Early Islamic Glassmaking Experiment? Journal of Glass Studies 41, 105–116.

Freestone, I.C, Hughes, M.J., 2006. The origins of the Jarrow glass. In: Cramp., R. (Ed.), *Wearmouth and Jarrow, Monastics sites*, Volume II. Swindon: English Heritage, 147–155.

Freestone, I.C., Gorin-Rosen, Y., Hughes, M.J., 2000. Primary glass from Israel and the production of glass in late antiquity and the early Islamic period. In: Nenna, M.D. (Ed.), Travaux de la Maison de l'Orient méditerranéen, 65–84.

Freestone, I.C., Ponting, M., Hughes, M.J., 2002. The origins of Byzantine glass from Maroni Petrera, Cyprus. Archaeometry 44, 257–272.

Freestone, I.C., Leslie, K.A., Thirlwall, M., Gorin-Rosen, Y., 2003. Strontium Isotopes in the Investigation of Early Glass Production: Byzantine and Early Islamic Glass from the Near East. Archaeometry 45, 19–32.

Freestone, I.C., Wolf, S., Thirlwall, M., 2005. The production of HIMT glass: elemental and isotopic evidence. In: Cool, H.E.M., Nenna, M.-D. (Eds.), *Annales Du 16e Congres de l'Association Internationale Pour l'Histoire Du Verre*, 2003. London, Nottingham: AIHV, 153–157.

Freestone, I.C, Hughes, M.J., Stapleton, C.P., 2008. The composition and production of Anglo-Saxon glass. In: Evison, V. I, Marzinzik, S. (Eds.), Catalogue of Anglo-Saxon glass in the British Museum, Research publication (British Museum), 167. London: British Museum. 29–46.

Freestone, I.C, Wolf, S., Thirlwall, M., 2009. Isotopic composition of glass from the Levant and south-eastern Mediterranean Region. In: Degryse, P., Henderson, J. (Eds.), Hodgings, G., *Isotopes in vitreous materials*. Leuven: Leuven University Press, 31–52.

F**rost, C.D., Onions, R.K., Goldstein, S.L., 1986.** Mass balance for Nd in the Mediterranean-Sea. Chemical Geology 55, 45–50.

Gallo, F., Marcante, A., Silvestri, A., Molin, G., 2014. The glass of the 'Casa delle Bestie Ferite': a first systematic archaeometric study on Late

Roman vessels from Aquileia. Journal of Archaeological Science 41, 7–20.

Gallo, F., Silvestri, A., Degryse, P., Ganio, M., Longinelli, A., Molin, G., 2015. Roman and late-Roman glass from north-eastern Italy: The isotopic perspective to provenance its raw materials. Journal of Archaeological Science 62, 55–65.

Galthen, M., 1792. Beskrivelse over Kiøbstæden Ribe fra sin Begyndelse indtil nærværende Tid. Odense.

Ganio, M., Boyen, S., Fenn, T., Scott, R., Vanhoutte, S., Gimeno, D., Degryse, P., 2012. Roman glass across the Empire: an elemental and isotopic characterization. Journal of Analytical Atomic Spectrometry 27, 743–753.

Gaut, B., 2007. Vessel Glass from Kaupang: A Contextual and Social Analysis. Norwegian Archaeological Review 40, 26–41.

Gaut, B., 2011. Vessel glass and evidence of glass-working. In: Skre, D. (Ed.), *Things from the Town: Artefacts and Inhabitants in Viking-Age Kaupang*. Aarhus: Aarhus University press & the Kaupang Excavation Project, 169–279.

Gelichi, S., 2007a. Flourishing places in north-eastern Italy: towns and emporia between late antiquity and the Carolingian age. In: Henning. J. (Ed.), *Post-Roman towns, trade and settlement in Europe and Byzantium 1.* Walter De Gruyter, 77–104.

Gelichi, S., 2007b. Tra Comacchio e Venezia. Economia, societa' e insediamenti nell'arco nord adriatico durante l'Alto Medioevo. In: Gelichi, S. (Ed.), *Comacchio e il suo Territorio tra la Tarda antichita' e l'Alto Medioevo*, Ferrara: Corbo Editore, 365-386.

Gelichi, S., 2009. L'isola del vescovo. Firenze: All'Insegna del Giglio.

Gelichi, S., Calaon, D., 2007. Comacchio: la storia di un emporio sul delta del Po. F.Berti;, Bollini;, M., Gelichi;, S., Ortalli, J. (Eds.), *Uomini, Territorio E Culto dall'Antichità all'Altomedioevo. Genti Nel Delta. Da Spina a Comacchio*. Ferrara: Corbo editore, 387–416.

Gelichi, S., Calaon, D., Grandi, E., Negrelli, C., 2006. '...Castrum Igne combussit...': Comacchio tra tarda antichità ed alto medioevo. Archeologia Medievale 33, 19–48.

Gelichi, S., Calaon, D., Grandi, E., Negrelli, C., 2012. The history of a forgotten town: Comacchio and its archaeology. In: Gelichi, S., Hodges, R. (Eds.), *From One Sea to Another: Trading Places in the European and Mediterranean Early Middle Ages*, International Conference, Comacchio, 27th-29th March 2009. Turnhout: Brepols, 169–206.

Geol.umd.edu. 2018. Molecular weights of some oxides and factors to convert them to elements by weight. Available at: https://www.geol.umd.edu/~piccoli/probe/molweight.html [22-08-18].

Goldstein, S.L., Onions, R.K., Hamilton, P.J., O'Nions, R.K., Hamilton, P.J., 1984. A Sm-Nd isotopic study of atmospheric dusts and particulates from major river systems. Earth and Planetary Science Letters 70, 221–236.

Gorin-Rosen, Y., 1995. Hadera, Bet Eli'ezer. Excavations and Surveys in Israel 13, 42–43.

Gorin-Rosen, Y., 2000. The ancient glass industry in Israel: summary of the finds and new discoveries. In: Nenna, M.D. (Ed.), *Travaux de la Maison de l'Orient méditerranéen*, 49–63.

Grandi, E., 2015. Un delta in movimento. Il caso di Comacchio tra tarda antichità e medioevo. Reti Medievali Rivista 16, 231 -61.

Grandi, E., Calaon, D., Gelichi, S., Lora, S., Negrelli, C., 2008. Uno scavo scomposto. Un accesso alla storia di Comacchio attraverso le indagini presso la Cattedrale. In: Gelichi, S. (Ed.), *Missioni Archeologiche e Progetti di Ricerca e Scavo dell'Università Ca'Foscari–Venezia*, VI Giornata Di Studio. Venezia, 167–178.

Gratuze, B., Blet-Lemarquand, M., Barrandon, J.N., 2001. Mass spectrometry with laser sampling: a new tool to characterize archaeological materials. Journal of Radioanalytical and Nuclear Chemistry 247, 645–656.

Hamilton, H.C., Falconer, W., 1889. The Geography of Strabo, vol. III. London: George Bell & Sons.

Heller, R., Esnault, R., Lance, C., 1998. Physiologie végétale, Volume 1, Nutrition, 6th ed. Paris: Dunob Publishing.

Henderson, J., 1988. Electron probe microanalysis of mixed-alkali glasses. Archaeometry 30, 77–91.

Henderson, J., 1989. The scientific analysis in archaeology and its interpretation. In: Henderson, J. (Ed.), *The scientific analysis in archaeology and its interpretation*. Oxford University Committee on Archaeology Monograph no. 19, UCLA Institute of Archaeology research Tools 5. Oxford: Oxbow books, 30 -62.

Henderson, J., 1991. Technological characteristics of Roman enamels. Jewellery studies 5, 65–76.

Henderson, J., 1995a. Le verre de Dorestad. Continuité technologique ou innovation. Le verre de l'Antiquité tardive et du haut Moyen Age: typologie, chronologie, diffusion. In: Foy, D. (Ed.), *Le verre de l'antiquité et du Haut Moyen Age*, Association française pour l'archéologie du verre, huitième rencontre, Guiry-en-Vexin 18--19 novembre 1993, 51–55.

Henderson, J., 1995b. An investigation of Early Islamic glass production at Raqqa, Syria. In: Vandiver, P. et al. (Eds.), *Proceedings of the Materials Research Society Conference*, Issues in Art and Archaeology IV. Columbus, Ohio: The Materials Research Society, 433-4.

Henderson, J., 1999. Archaeological and scientific evidence for the production of early Islamic glass in al-Raqqa, Syria. Levant 31, 225–240.

Henderson, J., 2000. The science and archaeology of materials: an investigation of inorganic materials. London: Routledge.

Henderson, J., 2013. Ancient glass: an interdisciplinary exploration. Cambridge: Cambridge University Press.

Henderson, J., McLoughlin, S.D., McPhail, D.S., 2004. Radical changes in Islamic glass technology: Evidence for conservatism and experimentation with new glass recipes from early and middle Islamic Raqqa, Syria. Archaeometry 46, 439–468.

Henderson, J., Challis, K., O'Hara, S., McLoughlin, S., Gardner, A., Priestnall, G., 2005a. Experiment and innovation: early Islamic industry at al-Raqqa, Syria. antiquity 79, 130–145.

Henderson, J., Evans, J.A., Sloane, H.J., Leng, M.J., Doherty, C., 2005b. The use of oxygen, strontium and lead isotopes to provenance ancient glasses in the Middle East. Journal of Archaeological Science 32, 665–673.

Henderson, J., Evans, J., Barkoudah, Y., 2009. The roots of provenance: glass, plants and isotopes in the Islamic Middle East. Antiquity 83, 414–429.

Henderson, J., Chenery, S., Faber, E., Kröger, J., 2016. The use of electron probe microanalysis and laser ablation-inductively coupled plasma-mass spectrometry for the investigation of 8th-14th century plant ash glasses from the Middle East. Microchemical Journal 128, 134–152.

Hodges, R., 1991. A fetishism for commodities: ninth-century glass-making at San Vincenzo al Volturno. In: Mendera, M. (Ed.), *Archeologia e storia della produzione del vetro preindustriale*, Atti del Convegno Internazionale, Colle di Val d'Elsa-Gambassi, 1990. Florence: All'Insegna del Giglio, 67–90.

Hodges, R., 2012. Adriatic Sea trade in an European perspective. In: Gelichi, S., Hodges, R. (Eds.), *From One Sea to Another: Trading Places in the European and Mediterranean Early Middle Ages*, International Conference, Comacchio, 27th-29th March 2009. Turnhout: Brepols, 95–119.

Hodges, R., Leppard, S., Mitchell, J., 2011. San Vincenzo Maggiore and its Workshops. London: British School at Rome.

Høilund Nielsen, K., 2009. The real thing or just wannabes? Scandinavian-style brooches in the fifth and sixth centuries (pp. 51-111). In: Quast, D. (Ed.), Foreigners in early Medieval Europe: thirteen international studies on early Medieval mobility. Mainz: Verlag des Römisch-Germanischen Zentralmuseums, Monographien des Römisch-Germanischen Zentralmuseums, 51-111.

Holand, I. 2003a. Pottery. In: Munch, G. S., Johansen, O. S., Roesdahl, E (Eds.), Borg in Lofoten. Trondheim: Tapir Academic Press, 199-209.

Holand, I. 2003b. Glass Vessels. In: Munch, G. S., Johansen, O. S., Roesdahl, E (Eds.), Borg in Lofoten. Trondheim: Tapir Academic Press, 211–27.

Hunter, J., Holdsworth, P., 1980. Excavations at Melbourne Street, Southampton, 1971-76, CBA research report, 33. London: the

Southampton Archaeological Research Committee by the Council for British Archaeology

Hunter, J.R., Heyworth, M., 1998. The Hamwic Glass.York: Council for British Archaeology.

Ilkjær, J., Friberg, R., 2002. Illerup Ådal: archaeology as a magic mirror. Højbjerg: Moesgaard Museum.

Ingemark, D., 1995. Glasblåsning: ett tidigt hantverk i Skandinavien. Fornvännen 90, 241–248.

Isings, C., 1980. Glass finds from Dorestad, Hoogstraat I. In: Van Es, W., Verwers, W.J. (Eds.), *Excavations at Dorestad 1. The Harbour: Hoogstraat 1*. Amersfoort: Rijksdienst voor het Oudheidkundig Bodemonderzoek, 225–37.

Isings, C., 2009. The glass. In: Van Es, W.., Verwers, W.J. (Eds.), E*xcavations at Dorestad 3, Hoogstraat 0, II - IV*. Amersfoort: ksdienst voor Archeologie, Cultuurlandschap en Monumenten, 259–79.

Isings, C., 2010. Some Glass Finds from Dorestad. A Survey. In: Willemsen, A. (Ed.), *Dorestad in an International Framework: New Research on Centres of Trade and Coinage in Carolingian Times*. Turnhout: Brepols Publishers,114–8.

Jackson, C. M., 1997. From Roman to early medieval glasses: many happy returns or a new birth. In: *Annales du 13e Congres de l'Association Internationale pour l'Histoire du Verre*, Pays Bas, 28 Août — 1 Septembre 1995. Lochem: AIHV, 289–302.

Jackson, C.M., 2005. Making colourless glass in the roman period. Archaeometry 47, 763–780.

Jackson, C. M., Nicholson, P. T., 2010. The provenance of some glass ingots from the Uluburun shipwreck. Journal of Archaeological Science 37(2), 295-301.

Jackson, C.M., Paynter, S., 2016. A Great Big Melting Pot: Exploring Patterns of Glass Supply, Consumption and Recycling in Roman Coppergate, York. Archaeometry 58, 68–95.

Jackson, C.M., Booth, C.A., Smedley, J.W., 2005. Glass by design? Recipes and compositional data. Archaeometry 47, 781–795.

Jackson, C.M., Joyner, L., Booth, C.A., Day, P.M., Wager, E.C.W., Kilikoglou, V., 2003. Roman glass-making at Coppergate, York? Analytical evidence for the nature of production. Archaeometry 45, 435–456.

Jacobsen, S.B., Wasserburg, G.J., 1980. Sm-Nd isotopic evolution of chondrites. Earth and Planetary Science Letters 50, 139–155.

Jacoby, D., 1993. Raw materials for the glass industries of Venice and the Terraferma, about 1370--about 1460. Journal of Glass Studies 35, 65–90.

Jochum, K. P., et al. 2011. Determination of reference values for NIST SRM 610–617 glasses following ISO guidelines. Geostandards and Geoanalytical Research 35(4), 397–429.

Kato, N., Nakai, I., Shindo, Y., 2009. Change in chemical composition of early Islamic glass excavated in Raya, Sinai Peninsula, Egypt: on-site analyses using a portable x-ray fluorescence spectrometer. Journal of archaeological science 36, 1698–1707.

Keller, D., 2004. Social and economic aspects of glass recycling. In: Bruhn, J. (Ed.), TRAC 2004: *Proceedings of the Fourteenth Annual Theoretical Roman Archaeology Conference*, University of Durham, 26-27 March 2004. Oxford: Oxbow Books, 65–78.

Kinch, J., 1869. Ribe Bys Historie og Beskrivelse indtil reformationen. Ribe.

Krueger, I., Wedepohl, H., 2003. Composition and shapes of glass of the early medieval period (8th to 10th century AD) in Central Europe. In: Foy, D., Nenna, M. D., (Eds.), *Echanges et commerce du verre dans le monde antique: Actes du colloque de l'Association française pour l'archéologie du verre,* Aix-en-Provence et Marseille 7-9 Juin 2001. Montagnac: Editions Monique Mergoil, 93-100.

Lankton, J., Dussubieux, L., Gratuze, B., 2006. Glass from Khao Sam Kaeo: Transferred technology for an early Southeast Asian exchange network. Bulletin de l'Ecole française d'Extrême-Orient 93, 317–351.

Lebecq, S., 1997. Routes of change: production and distribution in the west (5th–8th century). *The transformation of the Roman World AD*, pp.400-900.

Leciejewicz, L. 2000. Torcello, Nuove ricerche archeologiche, RdA Supplementi 23, Giorgio Bretschneider.

Leciejewicz, L., Tabaczyńska, E., Tabaczyński, S., 1977. Torcello. Scavi 1961-1962. Roma, Istituto Nazionale di Archeologia e Storia dell'Arte.

Leslie, K.A., Freestone, I.C., Lowry, D., Thirlwall, M., 2006. The provenance and technology of near eastern glass: oxygen isotopes by laser fluorination as a complement to strontium. Archaeometry 48, 253–270.

Li, F., 1999. Elemental and isotopic analysis of ancient chinese glass. PhD Thesis, University of Hong Kong.

Lilyquist, C., Brill, R. H., Wypyski, M. T. 1993. Studies in early Egyptian glass. New York: Metropolitan Museum of Art.

Liu, S., Li, Q.H., Fu, Q., Gan, F.X., Xiong, Z.M., 2013. Application of a portable XRF spectrometer for classification of potash glass beads unearthed from tombs of han dynasty in guangxi, china. X-Ray Spectrometry 42, 470–479.

Loveluck, C., 2013. Northwest Europe in the Early Middle Ages, c.AD 600–1150: a comparative archaeology. Cambridge: Cambridge University Press.

Loveluck, C., 2017. The dynamics of portable wealth, social status and competition in the ports, coastal zones and river corridors of northwest Europe, c. AD 650-1100. In: Lorè, V., Bührer-Thierry, G., Le Jan, R. (Eds.), Acquérir, prélever, contrôler: Les ressources en compétition (400-1100).Turnhout: Brepols, 299-322.

Loveluck, C., Tys, D. 2006. Coastal societies, exchange and identity along the Channel and southern North Sea shores of Europe, AD 600-1000. Journal of Maritime Archaeology 1(2), 140–169.

Loveluck, C., McCormick, M., Spaulding, N.E., Clifford, H., Handley, M., Hoffmann, H., Korotkikh, E., Kurbatov, A., More, A., Sneed, S., Mayewski, P., 2018. Ice evidence for transformation of the European Monetary System, AD 640-670: preliminary insights from an Alpine ice core, forthcoming.

MacGowan, K., 1996. Barking Abbey. Current Archaeology 149, 172–178.

Maltoni, S., Chinni, T., Vandini, M., Cirelli, E., Silvestri, A., Molin, G., 2015. Archaeological and archaeometric study of the glass finds from the ancient harbour of Classe (Ravenna-Italy): new evidence. Heritage Science 3, 13.

Mass, J.L., Wypyski, M.T., Stone, R.E., 2002. Malkata and Lisht glassmaking technologies: towards a specific link between second millennium BC. Archaeometry 44, 67–82.

McCormick, M., 2001. Origins of the European economy: communications and commerce AD 300-900. Cambridge: Cambridge University Press.

McCormick, M., 2007. Where do trading towns come from? Early medieval Venice and the northern emporia. In: Hennings, J. (Ed.), *Post-Roman towns, trade and settlement in Europe and Byzantium*, Volume 5. Berlin: De Gruyter, 41–68.

Meek, A., 2011. The chemical and isotopic analysis of English forest glass. PhD thesis, University of Nottingham.

Meek, A., Henderson, J., Evans, J., 2012. Isotope analysis of English forest glass from the Weald and Staffordshire. Journal of Analytical Atomic Spectrometry 27, 786–795.

Mirti, P., Lepora, A., Sagui, L., 2000. Scientific analysis of seventh-century glass fragments from the Crypta Balbi in Rome. Archaeometry 42, 359–374.

Mirti, P., Davit, P., Gulmini, M., Saguì, L., 2001. Glass Fragments from the Crypta Balbi in Rome: the Composition of Eighth-century Fragments. Archaeometry 43, 491–502.

Montanari, M., 1986. Il Capitolare di Liutprando: note di storia dell'economia e dell'alimentazione. In: La civiltà comacchiese e pomposiana dalle origini preistoriche al tardo medioevo : atti del Convegno Nazionale di Studi Storici, Comacchio 17-19 maggio 1984. Bologna: La Nuova Alfa edizioni, 461–475.

Moretti, C., Hreglich, S., 2013. Raw Materials, Recipes and Procedures Used for Glass Making. In: Janssens, K. (Ed.), *Modern Methods for Analysing Archaeological and Historical Glass*, Volume I, Oxford: John Wiley & Sons Ltd, 23–47.

Näsman, U., 1986. Vendel Period Glass from Eketorp-II, Öland, Sweden. Acta archaeologica 55, 55–116.

Näsman, U., 2000. Exchange and politics: the eighth-early ninth century in Denmark. In: Hansen, I. L., Wickham, C. (Eds.), The Long Eighth Century. Leiden: Brill, 35-68.

Negrelli, C., 2012. Towards a definition of early medieval pottery: amphorae and other vessels in the northern Adriatic between the 7th and the 8th centuries. In: Gelichi, S., Hodges, R. (Eds.), *From One Sea to Another: Trading Places in the European and Mediterranean Early Middle Ages*, International Conference, Comacchio, 27th-29th March 2009. Turnhout: Brepols, 394–415.

Nenna, M. D., 2014. Egyptian glass abroad: HIMT glass and its markets. In: Keller, D., Price, J., Jackson, C. (Eds.), Neighbours and Successors of Rome: Traditions of Glass Production and use in Europe and the Middle East in the Later 1st Millennium AD. Oxford: Oxbow Books, 177-193.

Nenna, M. D., Vichy, M., Picon, M. 1997. L'atelier de verrier de Lyon, du 1er siècle apr. J.-C, et l'origine des verres «romains». Revue d'archéométrie, 21(1), 81-87.

Nicholson, P.T., Jackson, C.M., Trott, K.M., 1997. The Ulu Burun glass ingots, cylindrical vessels and Egyptian glass. The Journal of Egyptian Archaeology, 143–153.

Patitucci Uggeri, S., 1976. Testimonianze archeologiche del ‘castrum Comiaclum’. Relazione preliminare degli scavi 1975. Archeologia Medievale III, 283–91.

Patitucci Uggeri, S., 1983. Aspetti dell'insediamento nell'area lagunare a nord di Ravenna tra tardoantico ed altomedioevo. Corso di Cultura sull'Arte Ravennate e Bizantina.–Ravenna 391–433.

Patitucci Uggeri, S., 1986. Il 'castrum Cumiacli': evidenze archeologiche e problemi storico-topografici. In: *La Civiltà Comacchiese E Pomposiana Dalle Origini Preistoriche Al tardomedievo*, Atti Del Convegno Nazionale Di Studi Storici. Bologna: Nuova Alfa, 263–302.

Paynter, S., 2008. Experiments in the reconstruction of Roman wood-fired glassworking furnaces: waste products and their formation processes. Journal of Glass Studies 50, 271–290.

Paynter, S., Dungworth, D., 2011. Archaeological evidence for glassworking. Guidelines for best practice. Swindon: English Heritage publication.

Paynter, S., Jennings, S., Price, J., 2014. Glassworking at Whitby Abbey and Kirkdale Minster in North Yorkshire. In: Keller, D., Price, J., Jackson, C. (Eds.), Neighbours and Successors of Rome: Traditions of Glass Production and use in Europe and the Middle East in the Later 1st Millennium AD. Oxford: Oxbow Books, 32-42.

Paynter, S., Kearns, T., Cool, H., Chenery, S., 2015. Roman coloured glass in the Western provinces: the glass cakes and tesserae from West Clacton in England. Journal of Archaeological Science 62, 66–81.

Pazdur, M.F., 2000. Risultati della calibrazione delle età radiocarbonio convenzionali di frammenti di legno provenienti dal sito archeologico di

Torcello. In: Leciejewicz, L. (Ed.), *Nuove ricerche archeologiche*, RdA Supplementi 23, Giorgio Bretschneider, 83–86.

Phelps, M., Freestone, I., Gorin-Rosen, Y., 2016. Natron glass production and supply in the late antique and early medieval Near East: The effect of the Byzantine-Islamic transition. Journal of Archaeological 75, 57-71.

Pilø, L., Skre, D., 2011. Introduction to the Site. In: Skre, D. (Ed.), *Things from the Town. Artefacts and Inhabitants in Viking-Age Kaupang*. Aarhus: Aarhus Universitetsforlag. 17–26.

Pion, C., Gratuze, B., 2016. Indo-Pacific glass beads from the Indian subcontinent in Early Merovingian graves (5th–6th century AD). Archaeological Research in Asia 6, 51–64.

Pollard, A.M., 2007. Analytical chemistry in archaeology. Cambridge: Cambridge University Press.

Pollard, A.M., Heron, C., 1996. Archaeological Chemistry. Cambridge: Royal Society of Chemistry.

Pollard, A.M., Heron, C., 2008. Archaeological chemistry, 2nd edition. Cambridge: Royal Society of Chemistry.

Preiß, F., 2010. Tesserae and Glass Drops. Indications for Glass Working in Early Medieval Dorestad. In: Willemsen, A., Congress, D., van Oudheden, R. (Eds.), *Dorestad in an international framework: new research on centres of trade and coinage in Carolingian times*, Proceedings of the first Dorestad Congress held at the National Museum

of Antiquities Leiden, the Netherlands, June 24-27, 2009. Turnhout: Brepols, 122-34.

Pulak, C., 1988. The Bronze Age Shipwreck at Ulu Burun, Turkey: 1985 Campaign. American Journal of Archaeology 1–37.

Pulak, C., 2005. Discovering a royal ship from the age of King Tut: Uluburun, Turkey. In: Bass, G. F. (Ed.), *Beneath the Seven Seas: adventures with the Institute of Nautical Archaeology*. New York: Thames & Hudson Inc, 34-47.

Rosenow, D., Rehren, T., 2014. Herding cats--Roman to Late Antique glass groups from Bubastis, northern Egypt. Journal of Archaeological Science 49, 170–184.

Rye, S., Bayley, J., 1996. Glassworking crucibles from excavations at Buckden, Hunts, 1961-64. Ancient Monuments Laboratory Reports 21, 1-6.

Saguì, L., 2002. Roma, i centri privilegiati e la lunga durata della tardoantichità. Dati archeologici dal deposito di VII secolo nell'esedra della Crypta Balbi. Archeologia Medievale 29, 7-42.

Sanderson, D.C.W., Hunter, J.R., 1981. Major element glass type specification for roman, post-roman and mediaeval glasses. Revue d'Archéométrie 1, 255–264.

Sanderson, D.C.W., Hunter, J.R., Warren, S.E., 1984. Energy dispersive X-ray fluorescence analysis of 1st millennium AD glass from Britain. Journal of Archaeological Science 11, 53–69.

Sayre, E. V, 1963. The intentional use of antimony and manganese in ancient glasses. In: Matson, F. R., Rindone, G. E. (Eds.), *Advances in Glass Technology. Part 2: History Papers and Discussions of the Technical Papers of the VI International Congress on Glass*. New York: Plenum Press, 263–282.

Sayre, E. V, Smith, R.W., 1961. Compositional categories of ancient glass. Science 133, 1824–1826.

Schibille, N., Freestone, I.C., 2013. Composition, production and procurement of glass at San Vincenzo al Volturno: an early medieval monastic complex in Southern Italy. PloS one, 1-13.

Schibille, N., Degryse, P., Corremans, M., Specht, C.G., 2012. Chemical characterisation of glass mosaic tesserae from sixth-century Sagalassos (South-West Turkey): chronology and production techniques. Journal of Archaeological Science 39, 1480–1492.

Schibille, N., Sterrett-Krause, A., Freestone, I.C., 2016. Glass groups, glass supply and recycling in late Roman Carthage. Archaeological and Anthropological Sciences,1–19.

Shepherd, J., 1986. The Roman Features at Gateway Flouse and Watling House, Watling St., City of London. In: *Transactions of the London and Middlesex Archaeological Society 37*. London: Museum of London, 125–44.

Shortland, A.J., 2004. Evaporites of the Wadi Natrun: seasonal and annual variation and its implication for ancient exploitation. Archaeometry 46, 497–516.

Shortland, A.J., Eremin, K., 2006. The analysis of second millennium glass from Egypt and Mesopotamia, part 1: new WDS analyses. Archaeometry 48, 581–603.

Shortland, A.J, Schachner, L., Freestone, I., Tite, M., 2006. Natron as a flux in the early vitreous materials industry: sources, beginnings and reasons for decline. Journal of Archaeological Science 33, 521–530.

Shortland, A.J, Rogers, N., Eremin, K., 2007. Trace element discriminants between Egyptian and Mesopotamian late Bronze Age glasses. Journal of Archaeological Science 34, 781–789.

Shortland, A.J, Degryse, P., Walton, M., Geer, M., Lauwers, V., Salou, L. 2011. The evaporitic deposits of Lake Fazda (Wadi Natrun, Egypt) and their use in Roman glass production. Archaeometry, 53(5), 916-929.

Silvestri, A., 2008. The coloured glass of Iulia Felix. Journal of Archaeological Science 35, 1489–1501.

Silvestri, A., Molin, G., Salviulo, G., 2008. The colourless glass of Iulia Felix. Journal of Archaeological Science.

Silvestri, A., Marcante, A., 2011. The glass of Nogara (Verona): a window on production technology of mid-Medieval times in Northern Italy. Journal of archaeological Science 38, 2509–2522.

Silvestri, A., Molin, G., Salviulo, G., Schievenin, R., 2006. Sand for Roman glass production: an experimental and philological study on source of supply. Archaeometry 48, 415–432.

Skovgaard-Petersen, I., 1981. The written sources. In: Bencard, M. (Ed.), Ribe Excavations, 1970-76. Aarhus: Aarhus University Press, 21–62.

Skre, D., 2007. Towns and markets, kings and central places in south-western Scandinavia c. AD 800--950. In: Skre, D. (Ed.), *Kaupang in Skiringssal*, Kaupang Excavation Project Publication Series, volume 1. Århus: Aarhus University Press, 445-469.

Skre, D., 2008. Post-Substantivist Towns and Trade, AD 600--1000. In: Skre, D. (Ed.), *Means of exchange: dealing with silver in the Viking Age*, Kaupang Excavation Project Publication Series, volume 2. Århus: Aarhus University Press, 327–341.

Sode T. 2004. Glass bead making technology. In: Bencard M., Rasmussen, A.K., Madsen H.B. (Eds.), Ribe excavations 1970–76, volume 5, Aarhus: Aarhus University Press, 83–102.

Sode, T., Gratuze, B., Lankton, J.W., 2017. Red and orange high-alumina glass beads in th 7th - 8th century Scandinavia: evidence for long distance trade and local fabrication. n: Wolf, S., De Pury-Gysel, A. (Eds.), P*roceedings of the Annales du 20e Congrès AIHV*, 7-11 September 2015, Rahden: Verlag Marie Leidorf, 326–33.

Speakman, R., Neff, 2005. The application of laser ablation ICP–MS to the study of archaeological materials—an introduction. In: Speakman, R.J., Neff, H. (Eds.), *Laser ablation–ICP–MS in archaeological research*. Albuquerque: UNM Press, 1-16.

Stanley, D. J., Nir, Y., Galili, E. 1998. Clay mineral distributions to interpret Nile cell provenance and dispersal: III. Offshore margin between Nile delta and northern Israel. Journal of coastal Research, 196-217.

Sternini, M., 1995. Il vetro in Italia tra V e IX secolo. Le verre de l'Antiquité tardive et du haut Moyen Age: typologie, chronologie, diffusion. Association française pour l'archéologie du verre (huitième rencontre, Guiry-en-Vexin 18--19 novembre 1993), 243–289.

Stiaffini, D., 1999. Il vetro nel Medioevo: tecniche, strutture, manufatti. Roma: Fratelli Palombi.

Stiff, M. 2001. Typology and Trade: A Study of the Vessel Glass from Wics and Emporia in Northwest Europe. In: Hill, D., Cowie, R. (Eds.), *Wics: The Early Medieval Trading Centres of Northern Europe*. Sheffield: Sheffield archaeological monographs, 14, 43-49.

Stiff, M. 2003. The glass finds. In: Malcom, G., Bowsher, D., Cowie, R. (Eds.), *Middle Saxon London: Excavations at the Royal Opera House, 1989-1999*. London: Museum of London Archaeology Svc, 246-250.

Tal, O., Jackson-Tal, R.E., Freestone, I.C., 2004. New evidence of the production of raw glass at Late Byzantine Apollonia-Arsuf, Israel. Journal of Glass Studies 46. 51–66.

Taylor, M., Hill, D., 2008. Experiments in the Reconstruction of Roman Wood-Fired Glassworking Furnaces. Journal of Glass Studies 50, 249–270.

Terpager, P. 1736. Ripæ Cimbricæ seu urbis Ripensis in Cimbria sita descriptio ex antiquis monumentis, bullis, diplomatibus et variis iconibus æri incisis et suis locis insertis illustrata. Flensburg.

Thorup, P.N., 1839. Efterretninger angaaende Byen Ribe. Ribe.

Tortorici, E., 1994. Il carico. In: Babbini, L. (Ed.), Operazione Iulia Felix: Lo Scavo Subacqueo Della Nave Romana Rinvenuta Al Largo Di Grado. Edizioni della laguna.

Turek, S.L., 1984. The knee. In: Turek, S.L. (Ed.), Orthopaedics-Principles and Their Application. London: Lippincott Williams & Wilkins, 1397–1401.

Turner, W.E.S., 1956. Studies in ancient glasses and glassmaking processes. V. Raw materials and melting processes. Journal of the Society of Glass Technology 40, 277–300.

Uboldi, M., 1999. I vetri. In: Brogiolo, G.P. (Ed.), *S. Giulia Di Brescia: Gli Scavi Dal 1980 Al 1992. Reperti Preromani, Romani E Alto Medievali*. Firenze: All'Insegna del Giglio., 271–307.

Uboldi, M., Verità, M., 2003. Scientific analyses of glasses from Late Antique and Early Medieval archeological sites in Northern Italy. Journal of Glass Studies 45, 115 -37.

Vallotto, M., Verità, M., 2002. Glasses from Pompeii and Herculaneum and the sands of the rivers Belus and Volturno. Studi della Soprintendenza archeologica di Pompei 6 (6), 63–73.

Van Es, W.A., Verwers, W., 1980. Excavations at Dorestad 1 - The Harbour: Hoogstraat I, Nederlandse Oudheden 9. Amersfoort: Rijksdienst voor Archeologie.

Van Es, W.A., Verwers, W., 2009. Excavations at Dorestad 3, Ned Oudhed. ed, Hoogstraat 0, II–IV. Nederlandse Oudheden 9. Amersfoort: Rijksdienst voor Archeologie.

Verita, M., Toninato, T., 1990. A comparative analytical investigation on the origins of the Venetian glassmaking. Rivista della Stazione sperimentale del vetro 20, 169–176.

Verità, M., Renier, A., Zecchin, S., 2002. Chemical analyses of ancient glass findings excavated in the Venetian lagoon. Journal of Cultural Heritage 3, 261–271.

Verità, M., Zecchin, S., 2009. Thousand years of Venetian glass: the evolution of chemical composition from the origins to the 18th century. In: Janssens, K., Degryse, P., Cosyns, P., Caen, J., Van't dack. L. (Eds.), *Annales Du 17eme Congres de l'Association Internationale Pour l'Histoire Du Verre*. Antwep, Belgium: AIHV, 602-13.

Verità, M., Basso, R., Wypyski, M.T., Koestler, R.J., 1994. X-ray microanalysis of ancient glassy materials: a comparative study of wavelength dispersive and energy dispersive techniques. Archaeometry 36, 241–251.

Vose, R.H., 1980. Glass. London: Collins.

Wedepohl, K.H., 1997. Chemical composition of medieval glass from excavations in West Germany. Glass science and technology 70, 246–255.

Wedepohl, K.H., 2003. Glas in Antike und Mittelalter, Geschicte eines Werkstoffs. Stuggart: Schweitzerbartsche Verlagbuchhandlung.

Wedepohl, K.H., Baumann, A., 2000. The use of marine molluskan shells for Roman glass and local raw glass production in the Eifel area (Western Germany). Naturwissenschaften 87, 129–132.

Wedepohl, K.H., Simon, K., Kronz, A., 2011. The chemical composition including the Rare Earth Elements of the three major glass types of Europe and the Orient used in late antiquity and the Middle Ages. Chemie der Erde-Geochemistry 71, 289–296.

Weldeab, S., Emeis, K.C., Hemleben, C., Siebel, W., 2002. Provenance of lithogenic surface sediments and pathways of riverine suspended matter in the Eastern Mediterranean Sea: Evidence from 143Nd/144Nd and 87Sr/86Sr ratios. Chemical Geology 186, 139–149.

Whitehouse, D., 1999. Glass in the Epigrams of Martial. Journal of Glass Studies 41, 73–81.

Whitehouse, D., 2003. Things that travelled': the surprising case of raw glass. Early Medieval Europe 12, 301–305.

Whitehouse, D., 2006. Glass: a pocket dictionary of terms commonly used to describe glass and glassmaking, rev. edition. Corning, New York: Corning Museum of Glass.

Wickham, C., 2000. Overview: production, distribution and demand II. In: Hansen, I. L., Wickham, C. (Eds.), *The Long Eighth Century*. Leiden: Brill, 345–377.

Willard, H., Jr, L.M., Dean, J., Jr, F.S., 1988. Instrumental methods of analysis. Belmont, California: Wadsworth Pub. Co.

Willemsen, A., 2009. Dorestad: een wereldstad in de middeleeuwen. Walburg Pers.

Willmott, H., Welham, K., 2007. Late Seventh-Century Glassmaking at Glastonbury Abbey. Journal of Glass Studies 55, 71–83.

Willmott, H., Welham, K., 2015. Saxon Glass Furnaces. In: Gilchrist, R., Greene, C. (Eds.), *Glastonbury Abbey: Archaeological Investigations 1904-79*. London: Society of Antiquaries of London, 218–238.

Wilson, I., Pollard, A.M., 2001. The Provenance Hypothesis. In: Brothwell, D.R., Pollard, A.M. (Eds.), *Handbook of Archaeological Sciences*. Chichester: John Wiley & Sons Ltd, 507–517.

Wilson, D.M., Hurst, D.G., 1962. Medieval Britain in 1961. Medieval Archaeology 6, 306–349.

Woldseth, R., 1973. X-Ray Energy Spectrometry. Kevex Corporation, Burlingame, California.

Zachariasen, W.H., 1932. The atomic arrangement in glass. Journal of the American Chemical Society 54, 3841–3851.

Zecchin, L., 1990. Vetro e vetrai di Murano: studi sulla storia del vetro. Venezia: Arsenale edizioni.