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The study of glass from the eastern Mediterranean, south Caucasus and east Africa in the late 8th – 14th centuries AD: an interdisciplinary approach

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Abstract

This study aims to increase our understanding of middle Byzantine, early Islamic, medieval Georgian and east African glasses in the late 8^{th} – 14^{th} centuries AD using typological, archaeological and scientific approaches.

Using EPMA-WDS, 164 glass samples were selected for the chemical analysis: 113 samples come from al-Raqqa in Syria including 76 from the site of Tell Zujaj, 19 from Tell Abu Ali and 17 from Tell Fukhkhar; 9 samples come from Tbilisi in Georgia; 15 samples come from the Pantokrator Church (Zeyrek Camii) in Istanbul; 2 samples from Fustat; 5 samples from Pemba Island in Zanzibar; 6 samples from al-Qadisiyya in Samarra, Iraq; and 14 samples from al-Mina in northern Syria.

The results show that natron glasses continued to be used in al-Raqqa, al-Mina in northern Syria and Tbilisi in Georgia during the late 8^{th} – 10^{th} centuries AD. At the same time, four types of plant ash glasses appeared and produced in northern Syria, Egypt, Iraq and Iran: (1) low MgO-high Al_2O_3 glasses; (2) high MgO-low Al_2O_3 glasses; (3) low Al_2O_3-CaO glasses; (3) low Al_2O_3-MgO-high CaO glasses.

By the 11^{th} – 12^{th} centuries AD, plant ash glasses spread from the Middle East to the Byzantine heartland of Turkey, where a type of plant ash glass from Syria, Israel and Lebanon was found in this study, along with mixed natron-plant ash glasses. This study also shows that high alumina glasses from South-East Asia and East Africa were found in Tbilisi in Georgia and Pemba Island in east Africa.

Finally, using typological, archaeological and scientific approaches, this study shows that the demise of the natron glass industry and the rise of the plant ash glass industry in the Middle East was deeply affected by the political and economic conditions during the late 8^{th} – 14^{th} centuries AD.

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Contents

	Page
Title page	i
Abstract	ii
Acknowledgements	iii
Contents	iv
List of figures and tables	ix
Chapter 1 Introduction	**1**
1.1 The study of Byzantine glass (11^{th} – 12^{th} centuries AD)	2
1.2 The study of medieval Georgian glass (10^{th} – 14^{th} centuries AD)	3
1.3 The study of medieval east African glass	5
1.4 The study of Islamic glass (late 8^{th} – 14^{th} centuries AD)	5
1.5 Glass compositional groups in the Middle East in the late 8^{th} – 14^{th} centuries AD	7
1.6 Research questions	10
1.7 Aims and objectives	12
1.8 Layout of the thesis	13
Chapter 2 Glass as a material	**15**
2.1 Introduction	15
2.2 Definition of glass	15
2.3 Formation of glass	16
2.3.1 Melting of glass	16
2.3.2 Temperature, volume and the formation of glass	18
2.4 The structure of glass	20
2.5 Network formers, modifiers and intermediates	22
2.5.1 Network formers	22
2.5.2 Network modifiers	22
2.5.3 Intermediates	23
2.6 Crystalline theory	23
2.7 The chemistry of glass colouring	24
2.7.1 Ligand field theory	24
2.7.2 Oxidation sate of metal ions	25
2.7.3 The presence of other oxides in the glass batch	26
2.8 Summary	26
Chapter 3 Raw materials	**27**
3.1 Introduction	27
3.2 Alkali source	28
3.2.1 Natron as a flux	28
3.2.2 Definition of natron	28
3.2.3 Locations of natron and mineralogical studies of the material	28
3.2.4 Natron used in the production of Roman and early medieval glass	31
3.2.5 The demise of the use of natron	32
3.2.6 Plant ashes	34
3.2.7 Properties of plant ashes	35
3.2.8 Reh	37
3.2.9 Soda-rich evaporate associated with borax deposits	37

3.3 Silica source 38
3.3.1 Sand 38
3.3.2 Historical references to sand sources and scientific studies of the material 39
3.3.3 Quartz 40
3.4 Lime 41
3.5 Summary 42

Chapter 4 Organisation of glass production and production sites in the eastern Mediterranean, south Caucasia and east Africa in 8th – 14th centuries AD 44
4.1 Introduction 44
4.2 Division of glass production in late antiquity and early Medieval period 44
4.3 Primary glass production centres in the Israeli coast 45
4.3.1 Apollonia, Israel 47
4.3.2 Bet Eli'ezer (Hadera), Israel 48
4.3.3 Bet She'arim, Israel 49
4.3.4 Horbat Biz'a, Israel 50
4.4 Primary glass production centre in Egypt 50
4.4.1 el-Ashmunein 50
4.5 Secondary glass production centres 50
4.5.1 Secondary glass production centres in Israel 51
4.5.2 Secondary glassworkshops in Egypt 51
4.5.3 Secondary glass production centres in the Byzantine Empire 52
4.6 Medieval Georgia glass industry in the 9th – 12th centuries AD 54
4.7 The transportation of natron glass 54
4.8 Alternative glass production model in the 8th – 12th centuries AD? Regional glassmaking and glassworking 55
4.8.1 Scientific evidence of regional glass production in the late 8th – 15th centuries AD 56
4.8.2 Regional glass production centres in Syria 57
4.8.3 Regional glass production centres in Iraq 58
4.8.4 Regional glass production centres in the Byzantine Empire 59
4.8.5 Regional glass production centre in Lebanon 60
4.8.6 Transportation of glass under the regional glass production model 63
4.9 Summary 63

Chapter 5 Archaeological sites 65
5.1 Introduction 65
5.2 al-Raqqa, northern Syria 65
5.3 al-Mina, southern Turkey 70
5.4 al-Qadisiyya (Area N) in Samarra, Iraq 73
5.5 Zeyrek Camii (Pantokrator monastery) in Istanbul, Turkey 77
5.6 Tbilisi, Georgia 79
5.7 Pemba Island, Zanzibar 80
5.8 Fustat, Egypt 81
5.9 Summary 82

Chapter 6 Methodology 83
6.1 Introduction 83
6.2 Sampling technique 83
6.3 Sample preparations 103

6.4 Electron microprobe analysis 103
6.4.1 Beam of electrons 103
6.4.2 Interaction between the electron beam and the sample 104
6.4.3 Wavelength-dispersive X-ray detector and energy dispersive detector 105
6.4.4 Advantages and disadvantages of electron microprobe 107
6.5 Analytical procedure 108
6.6 Description of the samples: Islamic glass in the late 8^{th} – 12^{th} centuries AD 110
6.6.1 Goblets/wine glasses 111
6.6.2 Bottles 111
6.6.3 Bowls 113
6.6.4 Small bottles 114
6.6.5 Islamic glass decoration 115
6.6.6 Mould-blown decoration 115
6.6.7 Cut decoration 118
6.6.8 Diamond-scratched decoration 118
6.6.9 Linear-style decoration 121
6.6.10 Tonged decoration 121
6.6.11 Middle Byzantine glass (9^{th} – 12^{th} centuries AD) 123
6.6.12 Byzantine window glass 123
6.7 Summary 125

Chapter 7 Results **126**
7.1 Introduction 126
7.2 Natron glass 130
7.2.1 al-Raqqa Type 3 131
7.2.2 al-Raqqa Type 5 134
7.2.3 al-Mina VA-19 and 27 134
7.2.4 Tbilisi Geo-09 134
7.2.5 Colourants for natron glass 135
7.3 Plant ash glass 137
7.3.1 al-Raqqa 139
7.3.2 al-Raqqa Type 4 139
7.3.3 al-Raqqa Type 4a (low MgO-high Al_2O_3 glass) 141
7.3.4 al-Raqqa Type 4c (high MgO-low Al_2O_3 glass) 142
7.3.5 al-Raqqa Type 4b (recycling and mixing) 143
7.3.6 Colourants in al-Raqqa Type 4 144
7.3.7 al-Raqqa Type 1 147
7.3.8 al-Raqqa Type 1a 151
7.3.9 al-Raqqa Type 1b 151
7.3.10 Colourants for al-Raqqa Type 1 151
7.3.11 al-Raqqa Type 2 154
7.3.12 al-Raqqa Type 2 colourants 157
7.3.13 al-Raqqa Type 6 159
7.3.14 Colourants for al-Raqqa Type 6 160
7.3.15 Fustat 160
7.3.16 Colourants for the Fustat glass 162
7.3.17 Pemba Island 164
7.3.18 VA-03 and 04 from Pemba Island 164
7.3.19 VA-05 from Pemba Island 165
7.3.20 VA-07 from Pemba Island 165

7.3.21 Colourants for the Pemba Island glass 166
7.3.22 al-Qadisiyya, Samarra 166
7.3.23 VA-08, 09 and 12 from al-Qadisiyya, Samarra 166
7.3.24 VA-10 and 11 from al-Qadisiyya, Samarra 167
7.3.25 VA-13 from al-Qadisiyya, Samarra 167
7.3.26 Colourants for al-Qadisiyya glass 167
7.3.27 Tbilisi, Georgia 168
7.3.28 Geo-03 and 05 from Tbilisi 168
7.3.29 Geo-02, 06 and 07 from Tbilisi 168
7.3.30 Geo-01 from Tbilisi 170
7.3.31 Geo-04 from Tbilisi 170
7.3.32 Colourants for the Tbilisi glass 171
7.3.33 al-Mina 171
7.3.34 al-Mina Group 1 171
7.3.35 VA-15 from al-Mina 172
7.3.36 VA-26 from al-Mina 173
7.3.37 Colourants for al-Mina glass 173
7.3.38 Zeyrek Camii 175
7.3.39 Zeyrek Camii Group 1 176
7.3.40 Zeyrek Camii Group 2 178
7.3.41 High alumina glass (Tbilisi Geo-08 and Pemba Island VA-06) 179
7.4 Summary 180

Chapter 8: Discussion – raw materials, recycling, and the relationships between composition, vessel forms and colours 182
8.1 Introduction 182
8.2 A brief summary of raw materials used for glass production in the late 8^{th} – 14^{th} centuries AD 182
8.3 Raw materials, provenance and glass compositions 184
8.3.1 Natron glass in the Middle East and Southern Caucasus 184
8.3.2 Plant ash glasses in the late 8^{th} - 10^{th} centuries AD 189
8.3.2.1 Low MgO-high Al_2O_3 glass 190
8.3.2.2 High MgO-low Al_2O_3 glass 197
8.3.2.3 Low Al_2O_3-CaO glass 199
8.3.2.4 Low Al_2O_3-MgO-high CaO glass 208
8.3.3 Plant ash glass in the 11^{th} – 12^{th} centuries AD 210
8.3.3.1 Zeyrek Camii Group 1 210
8.3.3.2 Tbilisi Geo-02, 06 and 07 215
8.3.3.3 High alumina glasses (Tbilisi Geo-08 and Pemba Island VA-06) 215
8.4 Evidence of recycling/mixing 219
8.4.1 Evidence of recycling/mixing in natron glass 220
8.4.2 Evidence of recycling/mixing in plant ash glass – Type 4b 220
8.4.3 al-Raqqa Type 2 and al-Mina VA-15 221
8.4.4 Evidence of recycling/mixing in plant ash glass – Zeyrek Camii Group 2 229
8.4.5 Evidence of recycling/mixing in plant ash glass – Tbilisi Geo-03 and 05 230
8.5 Glass compositions and colours 231
8.5.1 Natron glass 231
8.5.2 Plant ash glass 231

8.6 Glass compositions and vessel forms 235
8.6.1 Natron glass 235
8.6.2 Plant ash glass 237
8.7 Summary 240

Chapter 9: Discussion – the social and economic aspects of glass in the late 8th – 14th centuries AD 243
9.1 Introduction 243
9.2 Economy of natron glass 243
9.2.1 Natron glass in the 7th – 9th centuries AD 243
9.2.2 The Byzantine and Umayyad economy and the natron glass industry in the Middle East 245
9.3 Economic and social aspects of plant ash glass (late 8th – 10th centuries AD) 250
9.3.1 Previous explanations on the rise of the plant ash industry 250
9.3.2 'Abbasid economic integration and the (re-) introduction of the plant ash glass in northern Syria 252
9.3.3 Plant ash glasses in Egypt, Lebanon and Israel 260
9.4 Plant ash glasses in East Africa 265
9.5 Organisation of glass production in the Islamic East 266
9.6 Plant ash glasses in the Byzantine Empire 267
9.6.1 The social and religious reasons of why plant ash glasses were used in Byzantine churches 270
9.6.2 Trading of plant ash glass in the 11th – 12th centuries AD 273
9.7 Organisation of glass production in the Byzantine Empire 276
9.8 Medieval Georgian glass industry 277
9.9: Summary 278

Chapter 10: Conclusion and further research 280
10.1 Chemical compositions of glasses, raw materials and production zones in the late 8th – 14th centuries AD 281
10.2 Evidence of recycling/mixing of glass during the late 8th – 14th centuries AD 283
10.3 The relationship between composition and glass vessel types 284
10.4 The social and economic aspects of natron and plant ash glasses 285
10.5 Further work 285

Bibliography 288

Appendix 324

Sample Pictures 333

List of figures and tables

Figures

Figure 1.1: A map showing the findspots of the glass samples in the Middle East (image from Google Map, https://www.google.com/maps).
Figure 2.1: Curve for viscosity in a soda-lime-silica glass melt with viscosity points (from Shelby 2005, 113, Figure 6.1).
Figure 2.2: The diagram shows the transformation from a liquid to a crystalline or glassy state (from Pollard and Heron 2008, 147, Figure 5.1).
Figure 4.1: A diagram showing the organisation of the glass industry in the eastern Mediterranean in late antiquity (Freestone *et al.* 2008, 31, Fig. 3).
Figure 4.2: Plan of a glass furnace in Area N discovered in the 2002 excavations at Apollonia-Arsuf (Tal *et al*. 2004, 57, Fig. 5).
Figure 4.3: A map showing the discovery of primary and secondary glass production centres on the Israeli coast in the 4^{th} – 12^{th} centuries AD. Map is from Gorin-Rosen 2000, 51, Fig. 2.
Figure 4.4: The plan and sections of a furnace from Bet Eli'ezer (Gorin-Rosen 2000, 53, Fig. 3).
Figure 4.5: The glass slab at Bet She'arim (Freestone and Gorin-Rosen 1999, 106, Fig. 1).
Figure 4.6: The plan of Furnace 1 in Tyre (Jennings *et al*. 2001, 224, Fig. 7).

Figure 4.7: The plan of Furnace 2 in Tyre (Jennings *et al*. 2001, 226, Fig. 13).

Figure 4.8: The plan of Furnaces 3 and 4 in Tyre (Jennings *et al.* 2001, 230, Fig. 19).

Figure 5.1: A map showing the location of al-Raqqa (Henderson *et al*. 2004, 440, Figure 1).
Figure 5.2: A map showing the plan of the city of al-Raqqa. It should be noted that no. 31 is Tell Zujaj and no. 32 is Tell Aswad (Heidemann 2006, 36, Map).
Figure 5.3: The plan of the late 8^{th} – 9^{th} century AD glass workshop at Tell Zujaj in al-Raqqa, Syria (Henderson 1999, 227, Figure 2).

Figure 5.4: A plan showing the location of Samarra in the Middle East (Northledge 2005, 96, Fig. 41).
Figure 5.5: The plan of al-Qadisiyya in Samarra (site N1) where glassworks were found (Northledge 2005, 83, Fig. 33).
Figure 5.6: A plan of Zeyrek Camii showing the South Church, North Church and Middle Church (Ousterhout *et al*. 2000, 267, Fig. 1).
Figure 5.7: A photo of the Medieval City Wall in Tbilisi, Georgia (the picture is from Merab Dzneladze from the Georgian National Museum).

Figure 7.1: A bi-plot of K_2O versus MgO for all the analysed samples in this study. The samples are from al-Raqqa, al-Mina, al-Qadisiyya in Samarra, Fustat, Tbilisi, The Pemba Island and Zeyrek Camii in modern day Istanbul.
Figure 7.2: A bi-plot of CaO versus Al_2O_3 for natron glasses from 9th century AD Tell Zujaj and Tell Abu Ali in al-Raqqa, 9th – 10th century AD al-Mina and medieval Tbilisi. Data for al-Raqqa Type 3 glasses: Henderson *et al*. (2004).
Figure 7.3: A bi-plot of TiO_2 versus Al_2O_3 for natron glasses from 9th century AD Tell Zujaj and Tell Abu Ali in al-Raqqa, 9th – 10th century AD al-Mina and medieval Tbilisi. Data for al-Raqqa Type 3 glasses: Henderson *et al*. (2004).
Figure 7.4: A bi-plot of Fe_2O_3 versus Al_2O_3 for natron glasses from 9th century AD Tell Zujaj and Tell Abu Ali in al-Raqqa, 9th – 10th century AD al-Mina and medieval Tbilisi. Data for al-Raqqa Type 3 glasses: Henderson *et al*. (2004).
Figure 7.5: A bi-plot of Fe_2O_3 versus Al_2O_3 for natron glasses from 9th century AD Tell Zujaj and Tell Abu Ali in al-Raqqa, 9th – 10th century AD al-Mina and medieval Tbilisi. It is displayed according to compositional groups and coloration.
Figure 7.6: A bi-plot of MnO versus Fe_2O_3 for natron glasses from 9th century AD Tell Zujaj and Tell Abu Ali in al-Raqqa, 9th – 10th century AD al-Mina and medieval Tbilisi. It is displayed according to compositional groups and coloration.
Figure 7.7: A bi-plot of Al_2O_3 versus MgO for plant ash glasses from 9th century Tell Zujaj and Tell Abu Ali in al-Raqqa, 9th – 10th centuries al-Mina, Islamic period Fustat, Islamic period Pemba Island, 9th century (?) al-Qadisiyya in Samarra and 10th – 14th centuries Tbilisi. Data for al-Raqqa Types 1, 2 and 4 glasses: Henderson *et al*. (2004).
Figure 7.8: A bi-plot of Al_2O_3 versus MgO for al-Raqqa Type 4 glasses from 9th century Tell Zujaj and Tell Abu Ali in al-Raqqa. Data for al-Raqqa Type 4 glasses: Henderson *et al*. (2004).

Figure 7.9: A bi-plot of Fe_2O_3 versus Al_2O_3 for al-Raqqa Types 4a, 4b and 4c glasses from 9th century Tell Zujaj and Tell Abu Ali in al-Raqqa. Data for al-Raqqa Type 4 glasses: Henderson *et al*. (2004).

Figure 7.10: A bi-plot of TiO_2 versus Fe_2O_3 for al-Raqqa Types 4a, 4b and 4c glasses from 9th century Tell Zujaj and Tell Abu Ali in al-Raqqa. Data for al-Raqqa Type 4 glasses: Henderson *et al*. (2004).

Figure 7.11: A bi-plot of CaO versus MgO for al-Raqqa Types 4a, 4b and 4c glasses from 9th century Tell Zujaj and Tell Abu Ali in al-Raqqa. Data for al-Raqqa Type 4 glasses: Henderson *et al*. (2004).

Figure 7.12: A bi-plot of Fe_2O_3 versus Al_2O_3 for al-Raqqa Type 4 glasses from 9th century Tell Zujaj and Tell Abu Ali in al-Raqqa. It is displayed according to colours.

Figure 7.13: A bi-plot of MnO versus Fe_2O_3 for al-Raqqa Type 4 glasses from 9th century Tell Zujaj and Tell Abu Ali in al-Raqqa. It is displayed according to colours.

Figure 7.14: A bi-plot of CaO versus Al_2O_3 for al-Raqqa Types 1a, 1b, 2, 3, 4a, 4b and 4c glasses from 9th century Tell Zujaj and Tell Abu Ali in al-Raqqa. Data for al-Raqqa Types 1, 2 and 4 glasses: Henderson *et al*. (2004).

Figure 7.15: A bi-plot of CaO versus Al_2O_3 for al-Raqqa Types 1a, 1b, 4a, 4b and 4c glasses from 9th century Tell Zujaj and Tell Abu Ali in al-Raqqa. Data for al-Raqqa Types 1 and 4 and subtype 1 glasses: Henderson *et al*. (2004).

Figure 7.16: A bi-plot of CaO versus MgO for al-Raqqa Types 1a, 1b, 4a, 4b and 4c glasses from 9th century Tell Zujaj and Tell Abu Ali in al-Raqqa. Data for al-Raqqa Types 1 and 4 and subtype 1 glasses: Henderson *et al*. (2004).

Figure 7.17: A bi-plot of CaO versus Na_2O for al-Raqqa Types 1a, 1b, 4a, 4b and 4c glasses from 9th century Tell Zujaj and Tell Abu Ali in al-Raqqa. Data for al-Raqqa Types 1 and 4 and subtype 1 glasses: Henderson *et al*. (2004).

Figure 7.18: A bi-plot of Fe_2O_3 versus Al_2O_3 for al-Raqqa Type 1 glasses from 9th century Tell Zujaj and Tell Abu Ali in al-Raqqa. It is displayed according to compositional groups and colours.

Figure 7.19: A bi-plot of MnO versus Fe_2O_3 for al-Raqqa Type 1 glasses from 9th century Tell Zujaj and Tell Abu Ali in al-Raqqa. It is displayed according to compositional groups and colours.

Figure 7.20: A bi-plot of Na_2O versus K_2O for al-Raqqa Types 1a, 1b, 2, 3, 4a, 4b, 4c and 6 glasses from 9th century Tell Zujaj and Tell Abu Ali in al-Raqqa. Data for al-Raqqa Types 2 and 4 glasses: Henderson *et al*. (2004).

Figure 7.21: A bi-plot of Fe_2O_3 versus Al_2O_3 for al-Raqqa Types 1a, 1b, 2, 3, 4a, 4b, 4c and 6 glasses from 9th century Tell Zujaj and Tell Abu Ali in al-Raqqa. Data for al-Raqqa Types 2 and 4 glasses: Henderson *et al*. (2004).

Figure 7.22: A bi-plot of CaO versus Al_2O_3 for al-Raqqa Types 1a, 1b, 2, 3, 4a, 4b, 4c and 6 glasses from 9th century Tell Zujaj and Tell Abu Ali in al-Raqqa. Data for al-Raqqa Types 2 and 4 glasses: Henderson *et al*. (2004).

Figure 7.23: A bi-plot of Fe_2O_3 versus Al_2O_3 for al-Raqqa Type 2 glasses from 9th century Tell Zujaj and Tell Abu Ali in al-Raqqa. It is displayed according to colours.

Figure 7.24: A bi-plot of MnO versus Fe_2O_3 for al-Raqqa Type 2 glasses from late 8th - 9th century Tell Zujaj and Tell Abu Ali in al-Raqqa. It is displayed according to colours.

Figure 7.25: A bi-plot of Al_2O_3 versus MgO for plant ash glasses from 9th century Tell Zujaj and Tell Abu Ali in al-Raqqa, 9th – 10th centuries al-Mina, Islamic period Fustat, Islamic period Pemba Island, 9th – 10th centuries AD al-Qadisiyya in Samarra and 10th – 14th centuries Tbilisi.

Figure 7.26: A bi-plot of Fe_2O_3 versus Al_2O_3 for plant ash glasses from late 8th - 9th century Tell Zujaj and Tell Abu Ali in al-Raqqa, 9th – 10th centuries al-Mina, Islamic period Fustat, Islamic period Pemba Island, 9th – 10th centuries AD al-Qadisiyya in Samarra and 10th – 14th centuries Tbilisi.

Figure 7.27: A bi-plot of CaO versus MgO for plant ash glasses from late 8th - 9th century Tell Zujaj and Tell Abu Ali in al-Raqqa, 9th – 10th centuries al-Mina, Islamic period Fustat, Islamic period Pemba Island, 9th – 10th centuries AD al-Qadisiyya in Samarra and 10th – 14th centuries Tbilisi.

Figure 7.28: A bi-plot of Na_2O versus K_2O for plant ash glasses from late 8th - 9th century Tell Zujaj and Tell Abu Ali in al-Raqqa, 9th – 10th centuries al-Mina, Islamic period Fustat, Islamic period Pemba Island, 9th – 10th centuries AD al-Qadisiyya in Samarra and 10th – 14th centuries Tbilisi.

Figure 7.29: A bi-plot of CaO versus Al_2O_3 for plant ash glasses from 10th – 14th centuries Tbilisi.

Figure 7.30: A bi-plot of Fe_2O_3 versus Al_2O_3 for plant ash glasses from 9th – 10th centuries AD al-Mina. It is displayed according to colours.

Figure 7.31: A bi-plot of MnO versus Al_2O_3 for plant ash glasses from 9th – 10th centuries AD al-Mina. It is displayed according to colours.

Figure 7.32: A bi-plot of Fe_2O_3 versus Al_2O_3 for plant ash glasses from 11^{th} – 12^{th} centuries AD Zeyrek Camii. Three glass groups are identified, Zeyrek Camii Groups 1, 2 and 3.
Figure 7.33: A bi-plot of Na_2O vs. CaO for plant ash glasses from 11^{th} – 12^{th} centuries AD Zeyrek Camii. Three glass groups are identified, Zeyrek Camii Groups 1, 2 and 3.
Figure 7.34: A bi-plot of CaO versus MgO for plant ash glasses from 11^{th} – 12^{th} centuries AD Zeyrek Camii. Three glass groups are identified, Zeyrek Camii Groups 1, 2 and 3.
Figure 7.35: A bi-plot of Na_2O versus K_2O for the high alumina glasses from 10^{th} – 13^{th} centuries AD Tbilisi and Islamic Pemba Island, compared with plant ash glasses from al-Raqqa, Tbilisi, al-Qadisiyya in Samarra, al-Mina, Fustat and Pemba Island.
Figure 7.36: A bi-plot of CaO versus MgO for the high alumina glasses from 10^{th} – 13^{th} centuries AD Tbilisi and Islamic Pemba Island, compared with plant ash glasses from al-Raqqa, Tbilisi, al-Qadisiyya in Samarra, al-Mina, Fustat and Pemba Island.

Figure 8.1: A bi-plot of CaO versus Al_2O_3 for natron glasses from 9^{th} century AD al-Raqqa, 9^{th} – 10^{th} century al-Mina and medieval Tbilisi. It is displayed according to composition groups. Data for Levantine I glasses: 6^{th} – 7^{th} centuries AD Byzantine glass weights, Schibille *et al*. (2016). Data for HIMT glasses: 6^{th} – 7^{th} centuries AD Byzantine glass weights, Schibille *et al.* (2016). Data for Levantine II glasses: Bet Eli'ezer, Freestone *et al*. (2000); Data for Egypt I glasses: 6^{th} – 7^{th} centuries AD Byzantine glass weights, Schibille *et al*. (2016). Data for Egypt II glasses: Tell el-Ashmuneun, Bimson and Freestone (1988); Raya N2-b, Kato *et al*. (2009). Data for Foy-2: 6^{th} – 7^{th} centuries AD Byzantine glass weights, Schibille *et al*. (2016).
Figure 8.2: A bi-plot of Na_2O versus CaO for natron glasses from 9^{th} century AD al-Raqqa, 9^{th} – 10^{th} century al-Mina and medieval Tbilisi. It is displayed according to composition groups.
Figure 8.3: A bi-plot of Fe_2O_3 versus Al_2O_3 for natron glasses from 9^{th} century AD al-Raqqa, 9^{th} – 10^{th} century al-Mina and medieval Tbilisi. It is displayed according to composition groups.
Figure 8.4: A bi-plot of TiO_2 versus Fe_2O_3 for natron glasses from 9^{th} century AD al-Raqqa, 9^{th} – 10^{th} century al-Mina and medieval Tbilisi. It is displayed according to composition groups.

Figure 8.5: A bi-plot of CaO versus MgO for low MgO-high Al_2O_3 and high MgO-low Al_2O_3 glasses from late 8th - 9th century AD al-Raqqa, 9th – 10th century al-Qadisiyya in Samarra, Islamic Pemba Island and medieval Tbilisi. It is displayed according to composition groups and sites. Data for al-Raqqa glasses: Henderson *et al*. (2004); Fustat glasses: Brill (1999); glasses from Ctesiphon and Samarra: Henderson *et al*. (2016); Nishapur colourless and coloured glasses: Brill (1995) and Henderson *et al*. (2016); Raya glasses: Kato *et al*. (2010).

Figure 8.6: A bi-plot of Fe_2O_3 versus Al_2O_3 for low MgO-high Al_2O_3 and high MgO-low Al_2O_3 glasses from late 8th - 9th century AD al-Raqqa, 9th – 10th century al-Qadisiyya in Samarra, Islamic Pemba Island and medieval Tbilisi. It is displayed according to composition groups and sites.

Figure 8.7: A bi-plot of Na_2O versus K_2O for low MgO-high Al_2O_3 and high MgO-low Al_2O_3 glasses from late 8th - 9th century AD al-Raqqa, 9th – 10th century al-Qadisiyya in Samarra, Islamic Pemba Island and medieval Tbilisi. It is displayed according to composition groups and sites.

Figure 8.8: A bi-plot of CaO versus MgO for al-Raqqa Type 6 from late 8th - 9th century AD al-Raqqa, Samarra VA-10 and 11 from 9th – 10th century al-Qadisiyya in Samarra. It is displayed according to composition groups and sites. Data for al-Raqqa glasses: Henderson *et al*. (2004); glasses from Ctesiphon and Samarra: Henderson *et al*. (2016); Nishapur colourless and coloured glasses: Brill (1995) and Henderson *et al*. (2016); Raya glasses: Kato *et al*. (2010).

Figure 8.9: A bi-plot of Na_2O versus K_2O for al-Raqqa Type 6 from late 8th - 9th century AD al-Raqqa, Samarra VA-10 and 11 from 9th – 10th century al-Qadisiyya in Samarra. It is displayed according to composition groups and sites.

Figure 8.10: A bi-plot of Fe_2O_3 versus Al_2O_3 for al-Raqqa Type 6 from late 8th - 9th century AD al-Raqqa, Samarra VA-10 and 11 from 9th – 10th century al-Qadisiyya in Samarra. It is displayed according to composition groups and sites.

Figure 8.11: A bi-plot of CaO versus MgO for Types 1a and 1b glasses from late 8th - 9th century AD al-Raqqa, 9th – 10th century, VA-03 and 04 from Islamic Pemba Island and al-Mina Group 1 from 9th – 10th centuries AD al-Mina. It is displayed according to composition groups and sites. Data for al-Raqqa glasses: Henderson *et al*. (2004); glasses from Ctesiphon, Khirbat al-Minya and Samarra: Henderson *et al*. (2016); Nishapur colourless and coloured glasses: Brill (1995) and Henderson *et al*. (2016);

Raya glasses: Kato *et al*. (2010); Tyre glasses: Freestone (2002); Banias glasses: Freestone *et al*. (2000); Serce Limani glasses: Brill (2009).

Figure 8.12: A bi-plot of Na_2O versus K_2O for Types 1a and 1b glasses from late 8th - 9th century AD al-Raqqa, 9th – 10th century, VA-03 and 04 from Islamic Pemba Island and al-Mina Group 1 from al-Mina. It is displayed according to composition groups and sites.

Figure 8.13: A bi-plot of Fe_2O_3 versus Al_2O_3 for Types 1a and 1b glasses from late 8th - 9th century AD al-Raqqa, 9th – 10th century, VA-03 and 04 from Islamic Pemba Island and al-Mina Group 1 from al-Mina. It is displayed according to composition groups and sites.

Figure 8.14: A bi-plot of Fe_2O_3 versus Al_2O_3 for Zeyrek Camii Groups 1, 2 and 3 from 11th – 12th centuries AD Zeyrek Camii, Tbilisi Geo-03 and 05, and Tbilisi Geo-02, 06 and 07 from 10th – 14th centuries Tbilisi. It is displayed according to composition groups and sites. Data for Tyre glasses: Freestone (2002); Banias glasses: Freestone *et al*. (2000); Damascus glasses: Henderson *et al*. (2016); Kariye Camii glasses: Brill (2005), Henderson and Mango (1995); Zeyrek Camii glasses: Brill (2005).

Figure 8.15: A bi-plot of Fe_2O_3 versus Al_2O_3 for Zeyrek Camii Groups 1, 2 and 3 from 11th – 12th centuries AD Zeyrek Camii, Tbilisi Geo-03 and 05, and Tbilisi Geo-02, 06 and 07 from 10th – 14th centuries Tbilisi. It is displayed according to composition groups and sites.

Figure 8.16: A bi-plot of Fe_2O_3 versus Al_2O_3 for Zeyrek Camii Groups 1, 2 and 3 from 11th – 12th centuries AD Zeyrek Camii, Tbilisi Geo-03 and 05, and Tbilisi Geo-02, 06 and 07 from 10th – 14th centuries Tbilisi. It is displayed according to composition groups and sites.

Figure 8.17: A bi-plot of Na_2O versus K_2O for the high alumina glasses from 10th – 13th centuries AD Tbilisi, Islamic Pemba Island and late 8th – 9th centuries AD al-Raqqa. Data for Chaul, Bungule, Musaya and Mtwapa glasses: Dussubieux *et al*. 2010; Tell Abu Sarbut and Khirbat Faris glasses: Boulogne and Henderson 2009; Sardis glasses: Brill (1999) and Brill and Stapleton (2012); Pergamon glasses: Schibille (2011).

Figure 8.18: A bi-plot of K_2O versus MgO for the high alumina glasses from 10th – 13th centuries AD Tbilisi, Islamic Pemba Island and late 8th – 9th centuries AD al-Raqqa.

Figure 8.19: A bi-plot of CaO versus Al_2O_3 for the high alumina glasses from 10th – 13th centuries AD Tbilisi, Islamic Pemba Island and late 8th – 9th centuries AD al-Raqqa.

Figure 8.20: A bi-plot of Fe_2O_3 versus Al_2O_3 for Types 4a, 4b, 4c, 2, and 3 from late 8^{th} – 9^{th} centuries AD al-Raqqa and VA-15 from 9^{th} – 10^{th} centuries AD al-Mina. Data for al-Raqqa glasses: Henderson *et al*. (2004).

Figure 8.21: A bi-plot of Na_2O versus K_2O for Types 4a, 4b, 4c, 2, and 3 from late 8^{th} – 9^{th} centuries AD al-Raqqa and VA-15 from 9^{th} – 10^{th} centuries AD al-Mina. Data for al-Raqqa glasses: Henderson *et al*. (2004).

Figure 8.22: A bi-plot of CaO versus Al_2O_3 for Types 4a, 4b, 4c, 2, and 3 from late 8^{th} – 9^{th} centuries AD al-Raqqa and VA-15 from 9^{th} – 10^{th} centuries AD al-Mina. Data for al-Raqqa glasses: Henderson *et al*. (2004).

Figure 8.23: A bi-plot of Al_2O_3 versus MgO for Types 4a, 4b, 4c, 2, and 3 glasses from late 8^{th} - 9^{th} century AD al-Raqqa and VA-15 from 9^{th} – 10^{th} centuries AD al-Mina. It is displayed according to composition groups and sites. Data for al-Raqqa glasses: Henderson *et al*. (2004); Nishapur colourless and coloured glasses: Brill (1995) and Henderson *et al*. (2016); Serce Limani glasses: Brill (2009).

Figure 8.24: A bi-plot of CaO versus MgO for Types 4a, 4b, 4c, 2, and 3 glasses from late 8^{th} - 9^{th} century AD al-Raqqa and VA-15 from 9^{th} – 10^{th} centuries AD al-Mina. It is displayed according to composition groups and sites.

Figure 8.25: A bi-plot of Na_2O versus K_2O for Types 4a, 4b, 4c, 2, and 3 glasses from late 8^{th} - 9^{th} century AD al-Raqqa and VA-15 from 9^{th} – 10^{th} centuries AD al-Mina. It is displayed according to composition groups and sites.

Figure 8.26: A bi-plot of CoO versus Fe_2O_3 for blue glasses from al-Raqqa Types 2, 4b, 4c and 6 from late 8^{th} – 9^{th} centuries AD al-Raqqa, VA-13 from 9^{th} – 10^{th} centuries AD al-Qadisiyya in Samarra and Zeyrek Camii Group 2 from 11^{th} – 12^{th} centuries AD Zeyrek Camii.

Figure 8.27: A bi-plot of ZnO versus CoO for blue glasses from al-Raqqa Types 2, 4b, 4c and 6 from late 8^{th} – 9^{th} centuries AD al-Raqqa, VA-13 from 9^{th} – 10^{th} centuries AD al-Qadisiyya in Samarra and Zeyrek Camii Group 2 from 11^{th} – 12^{th} centuries AD Zeyrek Camii.

Tables

Table 1.1: A summary of the dates, locations, and number of samples and vessel types analysed in this study.

Table 3.1: Compositional data for the six main groups of 1st millennium AD glass. The data are taken from Abd-Allah 2010, 1867-1868; Brill 1988, 259; Bimson and Freestone 1988, 237-243; Degryse et al. 2006, 494-501; Foster and Jackson 2009, 189-204; Foy *et al.* 2003, 41-85; Freestone 1994, 290; Freestone *et al.* 2000, 72-73; Freestone 2003, 111-112; Freestone 2005, 197, Table 1; Gratuze and Banandon 1990, 159-161; Nenna *et al.* 2000, 97-112; Rehren and Cholakova 2010, 81-96; Rehren *et al.* 2010, 68-79; Schibille *et al.* 2008, 627-642; Schibille 2011, 2939-2948; Schibille *et al.* 2012, 1-25; Silvestri *et al.* 2005, 797-816; Silvestri *et al.* 2012, 2177-2190; Tal *et al.* 2004, 62-63.

Table 6.1: A description of the glass samples analysed in this study. They are displayed according to sites, finds numbers, contexts/excavations, dates, types of vessels, colours and decorations.

Table 6.2: The results of the analysis of the Corning Glass Standard B. The known composition for the Corning Glass Standard B comes from Brill (1999, 544).

Table 7.1: A summary table of all the glass groups found in this study.
Table 7.2: Means and standard deviations of natron glass groups from al-Raqqa and al-Mina.
Table 7.3: Means and standard deviations of plant ash glass group Type 4 from al-Raqqa.
Table 7.4: Means and standard deviations of plant ash glass group Type 1 from al-Raqqa
Table 7.5: Means and standard deviations of plant ash glass group Type 2 from al-Raqqa.
Table 7.6: Means and standard deviations of plant ash glass group Type 6 from al-Raqqa.
Table 7.7: Means and standard deviations of plant ash glass from al-Mina Group 1
Table 7.8: Means and standard deviations of plant ash glass groups from Zeyrek Camii.

Table 8.1: Descriptions of glass types.

Chapter 1: Introduction

In the study of glass, typological analysis has often been employed to investigate different forms of glass vessels and their evolution across space and time. More recently, chemical analysis of glass has been proved beneficial to investigate the technology of glassmaking, glass compositional groups, the types of raw materials used for glassmaking and their distribution patterns. Environmental analysis of the alkali and silica sources of glassmaking yielded valuable information on the types of raw materials used for glassmaking. This study utilises existing chemical data on different types of glassmaking raw materials to investigate the technology of glassmaking. Therefore, a combination of archaeological, environmental, typological and chemical analyses would allow us to investigate the technological, social and economic aspects of ancient glass. This study aims to apply these approaches on the study of glasses from middle Byzantine (10^{th} – 11^{th} centuries AD) Turkey, Islamic Syria, Egypt and Iraq (late 8^{th} – 12^{th} centuries AD) (Figure 1.1), medieval Georgia (10^{th} – 14^{th} centuries AD) and Pemba Island (medieval period).



Figure 1.1: A map showing the findspots of the glass samples in the Middle East (image from Google Map, https://www.google.com/maps).

1.1 The study of Byzantine glass (11th – 12th centuries AD):

With regard to middle Byzantine glass, our understanding on this subject (e.g. production techniques, provenance, organisation of the glass industry) is limited. Many scholarly discussions and debates on middle Byzantine glass have centred on luxury glasses. Painted and enamelled glasses have attracted the most attention, such as the bowl of dark wine-red glass with enamelled and gold-painted decoration, set in Byzantine silver-gilt mounts in the Treasury of San Marco, and the British Museum's bottle of translucent dark purple glass with traces of muffle-fired gold-painted

decoration (Henderson and Mundell Mango 1995, 333; Ristovska 2009, 199; Tait 1995, 146-147). More recently a study of the painted glass, which is considered as a type of Byzantine luxury glass, has shed some light on its production technique and distribution pattern (Ristovska 2009, 199-220).

On the other hand, our understanding of everyday middle Byzantine glass is inhibited by three factors: the inability to identify middle Byzantine glass vessel forms due to their similarity to late Roman/ late antique glass vessels; the lack of stratigraphic recording of some excavated sites; and the lack of excavations on middle Byzantine sites in Turkey (Lauwers *et al*. 2007, 41).

Thus, the chronology and the identification of middle Byzantine glass are confusing. It has been described by Henderson and Mundell Mango (1995) that middle Byzantine glass is 'confusing and obscure' and pointed out by Tait (1995) that even the very few fine glass objects cannot be 'reliably associated with the Empire and its luxuriously endowed capital between the tenth century and 1204' (Henderson and Mundell Mango 1995, 339; Tait 1995, 145). The absence of any archaeological evidence of glass workshops dated to the middle Byzantine period had cast doubts on whether a glass industry existed in the middle Byzantine period.

Nevertheless, recent excavations on a number of Byzantine period sites in Greece and Turkey have increased our understanding of middle Byzantine glasses. A small number of publications on these excavations have dealt with these in detail. For example, Axel von Saldern's (1980) *Ancient and Byzantine glass from Sardis*, G.R. Davidson's (1952) *Corinth XII, The Minor Objects*, J.W. Hayes' (1992) *Excavations at Sarachane in Istanbul volume 2*, and more recently M.A.V. Gill's (2002) *Amorium Reports, Finds I: The Glass (1987 – 1997)*, and A. Megaw's (1963) study on middle Byzantine painted glasses from Zeyrek Camii and Karyie Camii.

In recent years, researchers began to use scientific techniques to analyse middle Byzantine glass, which help us to understand the production technique, provenance and trade of middle Byzantine glass (Wypyski 2005, 186). But such researches are still relatively few and they are mostly discussed in a scientific way with little reference to the historical and archaeological contexts. For instance, researchers failed to ask why

mixed-natron plant ash and plant ash glasses were used to produce a particular type of glass; the organisation of the Byzantine glass industry (using both archaeological and scientific evidence); and why plant ash glasses became available in the empire during this period.

Therefore, by using archaeological and scientific approaches to study some of the window glasses and glass vessels from Zeyrek Camii in Istanbul, the author attempts to determine the origin(s) of the glass, the chemical compositions of the glass and the materials used to produce them, the relationship between glass vessel forms and compositional groups, the organization of the Byzantine glass industry and the economics of glass in the Mediterranean during the middle Byzantine period.

1.2. The study of medieval Georgian glass (10^{th} – 14^{th} centuries AD):

The study of medieval Georgian glass, at least in the English-speaking archaeological community, is lacking. As far as the author is aware, there are only a very limited number of publications that deal with medieval Georgian glass published in English. For instance, early Byzantine glass vessels from the southwestern littoral of Georgia were published in a symposium *Late Antique/Early Byzantine glass in the eastern Mediterranean* in 2009 (Shalikadze and Kakhidze 2009, 369-377); late Antique and early Medieval glass were found in the settlement site of Taman (Sorokina 1963, 134-169); glass finds were also excavated in a settlement in Vashnari (Chkhaidze 1975, 107-114). And recently, the 2008 – 2009 excavations at Samtavro, near Tbilisi in Georgia, have revealed a large necropolis dated from the third millennium BC to the late antique period. A large number of glass vessels which were grave goods associated with the tombs was excavated (Sagona *et al.* 2010, 1-136). These glass vessels were dated to an earlier period, rather than to the late 8^{th} – 14^{th} centuries AD.

But because there are no known archaeological and scientific studies on medieval Georgian glass, it is an opportunity for the author to undertake this particular area of research in order to get a better understanding of glass production and trade between Georgia and its neighbours. Nine fragments of glass dated to the 10^{th} – 14^{th} centuries AD from two different excavations in Tbilisi were chosen to be studied and analysed

in this study. The author attempts to extract any scientific and archaeological information from these glasses as our first step in the study of medieval Georgian glass.

1.3. The study of medieval east African glass:

In terms of east African glasses, recently Lankton and Dussubieux (2006), Dussubieux *et al*. (2008 and 2010) have studied some of the glasses from Kenya in east Africa. They have successfully identified that these glasses were probably made with the alkali source *reh* and have high alumina compositions (Dussubieux *et al*. 2008, 806-811; 2010, 1649; Lankton and Dussubieux 2006, 127-132). As far as the author is aware, no glasses from Pemba Island in Zanzibar were studied and analysed. Therefore, it is an opportunity to investigate these glasses from Pemba Island to identify their chemical compositions and their relationship with east African, Middle Eastern, Georgian and Byzantine glasses.

1.4. The study of Islamic glass (late 8th – 14th centuries AD):

Compared with middle Byzantine, medieval Georgian and east African glasses, Islamic glass is better understood by archaeologists through decades of research. This is largely helped by scholars' interest in Islamic arts which took place against the background of Orientalism, a fascination with the Near East that inspired European artists in the nineteenth century (Whitehouse 2001a, 8-9). In the early twentieth century scholars began to study Islamic glass systematically, both everyday and prestigious objects. This was started by the Swedish scholar Carl Johan Lamm who had published *Das Glas von Samarra* (Lamm 1928), his doctoral thesis *Mittelalterliche Glaser und Steinschnittarbeiten aus dem Nahen Osten* (Lamm 1929-1930), *Glass from Iran in the National Museum, Stockholm* (1935) and subsequently *Oriental Glass of Medieval Date Found in Sweden and the Early History of Lustre-Painting* (1941). These publications, after more than 70 years, remain useful in the study of Islamic glass.

Archaeological excavations have been an important medium for archaeologists to research Islamic glass. Several major archaeological excavations were carried out in various parts of the Middle East over the years, especially in Israel and Jordan, which have provided scholars with a better understanding of the production and evolution of

Islamic glass. For instance, Islamic glass vessels from Ramla, Tiberias and Bet Shean in Israel and Fustat in Egypt have provided us invaluable information on the chronology of Islamic glasses and various types of glass vessels in the Middle East. And we were able to reconstruct the economic and cultural interactions between regions through the study of glass vessel forms (Gorin-Rosen 2010, 2012; Hadad 2005; Jackson-Tal 2012; Lester 2004; Scanlon and Pinder-Wilson 2001).

Scientific analysis of Islamic glass has yielded valuable information in provenancing Islamic glasses, the identification of raw materials and production zones, and changes in glassmaking technology. For instance, in a paper published by Sayre and Smith (1961), they identified that early Islamic glass (8^{th} – 10^{th} centuries AD) had higher magnesium (MgO) and potassium (K_2O) concentrations than earlier Roman glass, and were very similar to glasses from Egypt and Mesopotamia that were dated to the second millennium BC. This indicates that plant ashes were the main alkali flux in this period (Sayre and Smith 1961, 1826). Gratuze and Barrandon (1990) analysed Islamic glass weights and found that the change from the use of natron to plant ash occurred in the mid-9^{th} century AD, as confirmed by the increase of MgO and K_2O levels in their Group 3 (Gratuze and Barradon 1990, 161-162).

The analysis of late 8^{th} and 9^{th} centuries AD glasses from the glassworkshop at Tell Zujaj in al-Raqqa, Syria has provided the cleariest evidence that plant ash replaced natron as the main alkali flux of glassmaking in Syria (Henderson 1995, 433-442; Henderson 1999, 225-240; Henderson 2002, 594-602; Henderson 2003, 109-123; Henderson *et al.* 2004, 439-468). Chemical analysis of the al-Raqqa glasses also produces possible evidence of experimentation in the use of different types of plant ash. This is shown in the Type 4 glasses. And subsequently a new type of plant ash glass (Type 1) was probably produced as a result of this experiment and was produced for over 600 years in the region such as Tyre and Banias (10^{th} – 13^{th} centuries AD) (Freestone 2002, 67-77; Henderson *et al.* 2004, 457-459).

Using data from the chemical analyses of Iraqi and Iranian, Syrian and Egyptian glasses of the early Islamic period, it is possible to identify different production zones with different chemical fingerprints. For instance, Iraqi/Iranian glasses are characterized by lower CaO and higher MgO levels than Syrian and Levantine glasses; and Egyptian

glasses (such as glasses from Fustat) have higher concentration of Al_2O_3 than Syrian and Levantine glasses (Brill 1995, 213-230; Henderson 2013, 292-295). Therefore, the use of major and minor elements in ancient glasses helps us to identify the characteristics of different glass production zones.

However, previous research was focused on early Islamic glasses from Syria, Israel and Lebanon and very little research is done on the Iraq/Iranian and Egyptian region. Therefore, it is a privilege and an opportunity to sample glasses from Iraq, Egypt and Syria that are housed in the Victoria and Albert Museum in London in order to gain further knowledge on Islamic glasses from the Middle East.

And much research is focused on the technological aspect of Islamic glass production and the date at which plant ashes were adopted in the Middle East. There is very little research using both scientific analysis and archaeology to study the social and economic aspects of early Islamic plant ash glasses. For instance, very little research looks at the relationship of chemical compositions and early Islamic glass vessel forms. The most systematic research on this topic is done by Kato *et al*. (2010) in their study of early Islamic glasses from Raya in Egypt and by Henderson (2013) who looked at such relationship using different forms of glass vessels from across the Middle East (Henderson 2013, 290-296; Kato *et al*. 2010, 1392-1394).

And as Swan (2012) has pointed out, there are no publications on *why* plant ash was adopted in Syria, Israel and Lebanon during the late 8^{th} - 10^{th} centuries AD, an important question that has been neglected in the study of plant ash glasses (Swan 2012, 349). And we should also begin to use both scientific and archaeological evidence to study the organisation of the glass industry and the trading of glass during the early Islamic period.

1.5 Glass compositional groups in the Middle East in the late 8^{th} – 14^{th} centuries AD:

Two types of glass can be identified in the Middle East during this period: (1) natron glass; (2) plant ash glass. Natron glass was produced and distributed in Syria, Israel and Egypt during the 7^{th} – 9^{th} centuries AD. In recent years, researchers have identified

different composition of natron glass produced in the Middle East, namely Levantine I and II, Egypt I and II and HIMT glasses (Bimson and Freestone 1988; Foy 2003, 84-86; Freestone 2003, 19-32; Freestone *et al*. 2000, 70-72; 2005).

Levantine I glasses were thought to be produced in the 5th – 7th centuries AD. This group of glass is characterised by a relatively high levels of Al_2O_3 (2.5% - 3%) and CaO (8% - 9%) (Freestone *et al.* 2000, 72; Schibille *et al*. 2008, 635). It is thought to have been produced in primary glass production centres such as Apollonia and Dor in Israel. Levantine I glasses were exported to places outside Israel, such as Pergamon and Sardis in Turkey, Butrint in Albania, Maroni Petrea in Cyprus, Aquilia in Italy and Britain (Brill 1999b, 106-107, Table V K; Gallo *et al.* 2014; Rehren *et al.* 2015, 273; Schibille 2011, 2945). But by the 7th and 8th centuries AD, Levantine I glasses ceased to be produced in the Levantine region.

In the 7th – 8th centuries AD, Levantine II glasses appeared and replaced the Levantine I glasses in the region. This type of glass is markedly different from Levantine I glasses and is characterised by lower concentrations of CaO and Na_2O and a higher level of SiO_2. Bet Eli'ezer in Israel was a major production centre of Levantine II in this period (Freestone *et al*. 2000, 71; Schibille *et al*. 2008, 635). The distribution of Levantine II was also very small. A recent study by Phelps *et al*. (2016) on early Islamic glasses in Israel shows that Levantine II glasses were mainly distributed in southern Israel and it rarely distributed in northern Israel or beyond (Phelps *et al*. 2016, 59-61).

In Egypt, HIMT glasses, thought to be produced in the 4th – 6th centuries AD, were characterised by high level of Fe_2O_3, MnO and TiO_2 and a strong correlation between Fe_2O_3 and TiO_2. Also, this glass type has a high concentration of Na_2O (18% - 19%), MgO and lower CaO (about 6%) (Conte *et al*. 2014, 7; Foster and Jackson 2009, 192; Freestone 1994, 290; Freestone *et al*. 2005, 153-154). It is not yet known where HIMT glasses were produced but one of the places of production could have been Egypt. Nenna (2014) suggests that Nilotic sands in Egypt with its high concentrations of TiO_2 and Fe_2O_3 might have been one of the possible sources to have produce HIMT glasses (Nenna 2014, 187). It is unlikely that MnO derived from the sands as analysis of Nilotic sand from Egypt shows that it has low level of MnO (Nenna 2014, 187). HIMT glasses

were widely found in Britain, Butrint, France, Carthage, Italy, Cyprus and Egypt during late antiquity (Conte *et al*. 2014, 8; Freestone 1994, 290; Freestone *et al.* 2005, 154).

By the 7^{th} – 9^{th} centuries AD, HIMT glasses were replaced by two regional glass groups, Egypt I (7^{th} – 8^{th} centuries AD) and II (8^{th} – 9^{th} centuries AD). Egypt I was first identified by Gratuze and Barrandon (1990) in their study of Islamic glass weights (Group 1) dated to the Umayyad and early 'Abbasid period (Gratuze and Barrandon 1990, 159-161). It was subsequently identified by Kato *et al.* (2009) in Raya (Group N2-a2) which consists of glass weights, a bottle and a beaker (Freestone *et al.* 2000, 72; Kato *et al.* 2009, 1705). This group of glass is characterised by low level of CaO and high levels of Al_2O_3, Fe_2O_3, TiO_2 and MnO (Kato *et al*. 2009, 1705). Based on the current evidence, this glass group was mainly distributed in Raya, south Sinai in Egypt only (Gratuze and Barrandon 1990, 162, Figure 9; Kato *et al.* 2009, 1700, Table 1).

Evidence for the manufacture of Egypt II glasses was found in the primary and secondary glass workshop at Tell el Ashmunein in Egypt. This glass type appears to have been produced in Egypt in the 8^{th} – 9^{th} centuries AD. Sixty percent of the 500+ glass assemblage in Raya belong to this group (Kato *et al.* 2009, 1705). This group is charactersied by low level of Al_2O_3 and K_2O and a high concentration of CaO (up to 11%) (Freestone *et al*. 2002, 168; Kato *et al*. 2009, 1705).

In terms of plant ash glass, it appears that since the Sassanian period (3^{rd} – 7^{th} centuries AD), plant ash glasses with low level of Al_2O_3 (<2.50%) and high levels of MgO (up to 8%) and CaO (up to 9%) were produced in Iraq such as Veh Ardasir and Ctesiphon (Mirti *et al*. 2008, 438-440; Mirti *et al*. 2009, 1064). This type of glass continued to be produced in Iraq such as Samarra and Iran such as Nishapur the early Islamic period (8^{th} – 10^{th} centuries AD) and were exported to places such as Raya in Egypt, where Iraqi and Iranain glasses with low levels of Al_2O_3 and CaO were found (Kato *et al*. 2010, 1392). Trace element analysis shows that hey tend to have a highe Li/K ratios (Henderson *et al.* 2016, 142).

By the late 8^{th} – 9^{th} centuries AD, plant ash glasses started to appear and produced in regions previously doinated by natron glass. Henderson *et al*. (2004) analysed early Islamic glass from al-Raqqa in northern Syria and found glasses (Type 4) with high

MgO and CaO and varied levels of Al_2O_3 (1% - over 4%) (Henderson *et al*. 2004, 457). Subsequently, by the 9th and 10th centuries AD, a type of plant ash glass that is relatively homogenous and characterised by low levels of Al_2O_3 and MgO and a relatively high CaO content dominated Syria, Israel and Lebanon (Henderson *et al.* 2004, 454). One of the earliest examples of this type of plant ash glass is found in al-Raqqa (Type 1) identified by Henderson *et al.* (2004). And they were later identified in Tyre (10th – 11th century AD), Banias (11th – 13th centuries AD), Damascus (12th – 14th centuries AD) and Beirut (12th – 14th centuries AD) (Freestone 2002, 70-71; Freestone *et al*. 2000, 78; Henderson *et al*. 2016, 140).

Another type of glass present in the Middle East and Turkey in this period is high alumina glasses. They were thought to have been originated from India, East Africa, Sri Lanka and southeast Asia dated to the 9th – 19th centuries AD (Boulogne and Henderson 2009, 71; Dussubieux *et al*. 2008, 798; 2010, 1646; Henderson 2013, 297-300; Schibille 2011, 9). The only Middle Eastern example of high alumina glasses was reported by Boulogne and Henderson (2009) in their study of Mamluk-Ottoman period bracelets from Tell Abu Sarbut and Khirbat Faris in Jordan.

Further west in the Mediterranean, Dussubieux *et al*. (2010) and Schibille (2011) have reported that high alumina glasses were found in Sardis and Pergamon in western Turkey (Dussubieux *et al*. 2010, 1652; Schibille 2011, 9-10). The glasses from Pergamon are also accompanied with elevated levels of B_2O_3 which are not found in other high alumina glasses from India, East Africa, Sri Lanka and southeast Asia (Schibille 2011, 10). This suggests western Turkey was one of the area where high alumina (with elevated level of B_2O_3) glasses were produced during the 9th – 15th centuries AD.

1.6. Research questions:

Samples from al-Raqqa in Syria, Tbilisi in Georgia, Istanbul in Turkey, al-Qadisiyya in Samarra in Iraq, al-Mina in Syria, Fustat in Egypt and Pemba Island in East Africa (Table 1.1) were chemically and archaeologically analysed to answer a series of questions (technological, social and economic) on Islamic, Byzantine, east African and Georgian glasses dated to the late 8th – 14th centuries AD.

Sites	Dates	Contexts	Material types	Number of samples
Tell Zujaj (Al-Raqqa, Syria)	Late 8th – 9th centuries AD	Primary and secondary glassworkshop	Glass vessels, raw glass, window glass	76
Tell Abu Ali (Al-Raqqa, Syria)	9th century AD	Settlement and glassworkshop	Glass vessels	19
Tell Fukhkhar (Al-Raqqa, Syria)	11th century AD	Glassworking Tell	Glass bracelets and raw glass	18
Tbilisi (Georgia)	10th – 14th centuries AD	Medieval city wall and Ormotsmotsameta Church	Glass vessels, bracelets and a ring	9
Zeyrek Camii (Istanbul, Turkey)	11th – 12th centuries AD	Medieval church (now a mosque)	Glass vessels, window glass, glass cakes and chunks	15
Fustat (Egypt)	Islamic period	Fustat excavation	Frit and furnace glass	2
Al-Qadisiyya (Samarra, Iraq)	9th – 10th centuries AD	Glass furnace	Tank furnace glass and glass wasters	6
Pemba Island (Zanzibar)	Islamic period	Museum collection	Glass vessels	5
Al-Mina (Hatay, Turkey)	9th – 10th centuries AD	Circular pits	Glass vessels	15

Table 1.1. A summary of the dates, locations, and number of samples and vessel types analysed in this study.

The research question, aims and objectives of this study are as follows.

- What are the chemical compositions of glass in the Byzantine empire, medieval Georgia, medieval east Africa and the Islamic Middle East during the late 8th – 14th centuries AD?

- What raw materials were used to produce glass in the Byzantine empire, medieval Georgia, medieval east Africa and the Islamic Middle East in this period?

- Are there any visible changes in the use of raw materials in the production of glass during this period? If so, why did they occur in a specific period and region?

- Is there any evidence of recycling/mixing of glass during the late 8th – 14th centuries AD?

- Are there any relationships between chemical compositions and glass vessel types, and the relationship between chemical compositions and colours?

- Can we identify glass production zones using the chemical compositions of glasses, specifically their major and minor elements?

- Can we use archaeological and scientific evidence to look at the organisation of the glass industries within the Byzantine empire, medieval Georgia, medieval east Africa and the Islamic Middle East during this period?

- And finally, can we use an archaeological and scientific approach to study the trading of glass between these four regions during this period?

1.7. Aims and objectives:

- To use the electron microprobe to analyse a range of glass samples from the eastern Mediterranean, south Caucasus and east Africa provided by excavators and museum curators.

- To characterise the compositions of the glass samples and to investigate the types of raw materials used.
- To investigate and to interpret any technological changes in the political and economic contexts in the late 8^{th} – 14^{th} centuries AD.
- To investigate the relationship between compositional groups and vessel forms and their implications.
- To investigate recycling and/or mixing of glass.
- To identify production zones and to investigate the organisation of the glass industry in the late 8^{th} – 14^{th} centuries AD using scientific and archaeological evidence.
- To discuss the trade of glass in the late 8^{th} – 14^{th} centuries AD.

1.8. Layout of the thesis:

In Chapter 2 the properties of glass will be discussed. It is important to understand the chemistry of glass before we look at the composition of the glasses because if we do not understand these basic theories, we will not be able to fully understand the technological aspect of glass such as its manufacture process, raw materials and the colouring mechanisms. In Chapter 3 the raw materials of glass production in the late 8^{th} – 14^{th} centuries AD will be discussed. This chapter will discuss the alkali, lime and silica sources for glassmaking in this period. These have been discussed and studied extensively by scholars.

In Chapter 4 the organisation of the glass industry in the eastern Mediterranean and south Caucasia in the late 8^{th} – 14^{th} centuries AD will be looked at using both scientific and archaeological evidence. Chapter 5 will look at the history of the archaeological sites where the glass samples were found.

Chapter 6 will provide a detailed account of the glasses selected for this study and the methodology that has been employed to analyse the samples. These procedures follow strictly the international guidelines on the analysis of glass, using the electron microprobe fitted with wavelength dispersive spectrometer to analyse the samples. The EMPA-WDS was calibrated against a combination of certified standard reference

materials include mineral and synthetic standards to show the laboratory errors of the analysis.

Chapters 7 will present the results of the chemical analysis of the glass samples, a series of graphs will be produced in order to illustrate the author's arguments and interpretations of the data. Chapters 8 and 9 will discuss the technological, social and economic aspects of glass in the late 8^{th} – 14^{th} centuries AD using a multi-disciplinary approach. Finally, Chapter 10 will provide an overview of this study and whether the outcome of the analysis has achieved the aims and objectives of this study. It will also discuss future research on Islamic, Byzantine, east African and Georgian glasses.

Chapter 2: Glass as a material

2.1 Introduction:

Before we discuss the production and trading of Byzantine, Islamic, Georgian and east African glass in the late 8th – 14th centuries AD, we will look at what glass is as a material. We need to understand how glass is formed, how does glass behave under different temperatures, what is the structure of glass, and how colours are produced in glass. This will be the sort of questions that concerned glassmakers and glassworkers. Through the understanding of the properties and behaviour of glass, we will begin to understand how glassmakers would experiment with different raw materials and production techniques to produce glass that is suitable for use, and valuable enough to be traded across the Middle East and beyond. Therefore, this chapter will focus on the science of glass.

2.2 Definition of glass:

The American Society for Testing and Materials has defined glass as 'an organic product of fusion which has cooled to a rigid condition without crystallising' (Pollard and Heron 2008, 145). Paul (1990) states that 'glass is a state of matter which maintains the energy, volume and atomic arrangement of a liquid, but for which the changes in energy and volume with temperature and pressure are similar in magnitude to those of a crystalline solid' (Pollard and Heron 2008, 145). Zarzycki (1991) wrote that 'glasses are essentially *non- crystalline solids* obtained by freezing supercooled liquids' (Zarzycki 1991, 1). Doremus (1994) has described it as 'an amorphous solid; it has no long-range order, that is, when there is no regularity in the arrangement of its molecular constituents on a scale larger than a few times the size of these groups' (Doremus 1994, 1).

2.3 Formation of glass:

2.3.1 Melting of glass:

When most liquids are cooled their atomic structure will change at a particular temperature. If the cooling to any temperature below the melting temperature of the liquid, crystallization occurs with the formation of a long-range, periodic atomic arrangement (Frank 1982, 2; Shelby 2005, 3-4).

On the other hand, glass never crystallises. In order to achieve a glassy or vitreous state, the liquid has to be cooled at a sufficiently rapid rate to avoid crystallisation and the cooling has to be below the melting temperature of the liquid (Shelby 2005, 4; Zarzycki 1991, 1-2). Thus, the molecules in the liquid cannot form the long-range order that is required to form the crystal lattice structure. Therefore, glass is also described as a 'supercooled' liquid (Frank 1982, 2; Shelby 2005, 4).

The viscosity of the liquid will gradually increase when the temperature is lowered and finally it turns into a 'solid' (Frank 1982, 2; Zarzycki 1991, 2). Viscosity is dependent on the melting temperature and is used to describe the various stages of glass-forming process (Zarzycki 1991, 263). It is also used to determine a number of things in glass-forming: (1) to determine the melting conditions necessary to form a bubble-free glass; (2) to determine the homogeneity of the glass melt; (3) the temperature range used to form the glass; (4) the temperature of annealing to remove internal stress; (5) the conditions under which devitrification may occur (Pollard and Heron 2008, 146; Shelby 2005, 111).

Different glass formers will show different temperature dependencies of their viscosity (Rossler *et al.* 1998, 208). Here we will only consider the viscosity of soda-lime-silica glass. Reference points are noted by scientists to highlight their importance in the glass-forming melts. Viscosity is expressed in the units of poise (Pa s) with dimensions (g $cm^{-1}s^{-1}$) (Pollard and Heron 2008, 146). Figure 2.1 shows a typical curve for viscosity in a soda-lime-silica glass melt with various viscosity points.

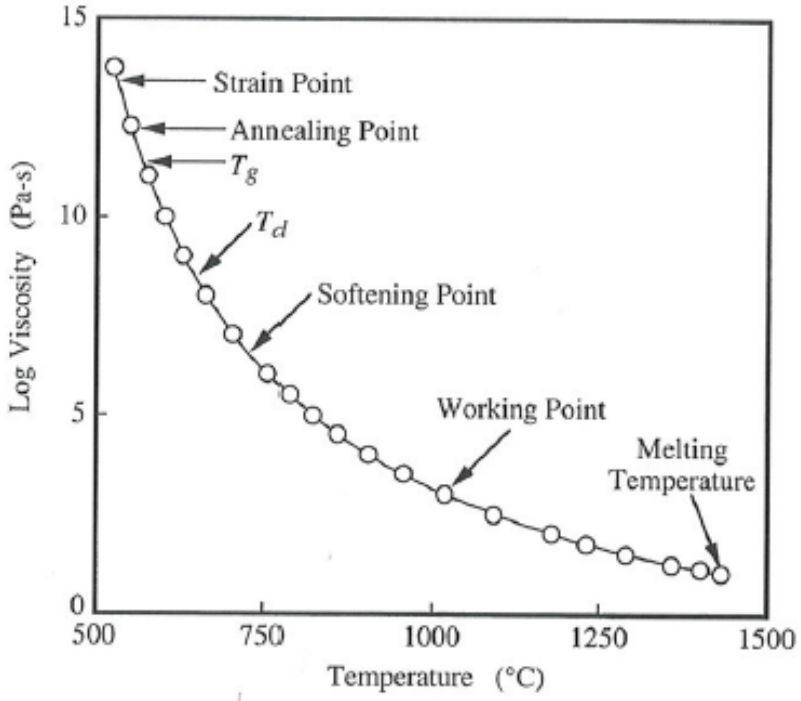


Figure 2.1. Curve for viscosity in a soda-lime-silica glass melt with viscosity points (from Shelby 2005, 113, Figure 6.1).

Glass does not have a fixed melting point but a processing temperature, which is between 700 ^{o}C and 1300 ^{o}C (Shelby 2005, 112-113). When the temperature reaches 1000 ^{o}C (which could be achieved with ancient glass furnaces), the viscosity of the liquid is at 10^4. The liquid will form into a gob which can be worked into various shapes by blowing (Pollard and Heron 2008, 146, Table 5.1; Shelby 2005, 113; Zarzycki 1991, 266). At a viscosity of $10^{7.6}$ the liquid will stop deforming under its own weight and this is known as the softening point (700 ^{o}C). The temperature range between the working point and the softening point is called the working range (Pollard and Heron 2008, 146, Table 5.1; Shelby 2005, 113).

When the object is formed, its internal stress can be reduced by annealing and this only requires a few minutes. To achieve this the viscosity of the object has to be at $10^{13.4}$ and at a temperature of 510 ^{o}C (Pollard and Heron 2008, 146, Table 5.1; Shelby 2005, 114). The object has reached its straining point at a viscosity of $10^{14.5}$ and at a temperature of 470 ^{o}C where stress is substantially relieved in several hours (Pollard and Heron 2008, 146, Table 5.1; Shelby 2005, 114).

Melts with longer working range are called long glasses which are suited to blowing processes where the precise control of temperature cannot be obtained (Zarzycki 1991, 266). Therefore, ancient glasses can be described as long glasses. This is because glassmakers and glassworkers were unable to control the melting temperature as precisely as modern glassmaking and glassworking, thus the glasses would have a longer working time and wee suitable for the glass-blowing process. On the other hand, melts with shorter working range is described as short glasses which are achieved by mechanised processes that require a shorter working time (Zarzycki 1991, 266).

2.3.2 Temperature, volume and the formation of glass:

The transformation of liquid to non-crystalline solid is best described using the temperature and the specific volume of the glass. In Figure 2.2, the liquid is melted at a high temperature, which is above 1250 ^{o}C and at a viscosity of <_10 Pa (Figure 2.1). The liquid contracts once the temperature is lowered to T_1. This temperature is called the liquidus temperature. Two things can happen: (1) if the liquid is allowed to cool too slowly, the liquid will crystallise and its specific volume experiences a sharp drop as the phase transition from a liquid to a crystalline solid takes place, a silicate can be produced which consists of a series of crystals (which is demonstrated by the solid line) (Figure 2.2); (2) by cooling the glass at an appropriate rate, crystallisation is avoided, and it follows the dashed line and the liquid enters the supercooled state (Figure 2.2) (Henderson 2000, 24; Holloway 1973, 5; Kalogeras and Lobland 2012, 70; Pollard and Heron 2008, 147; Zarzycki 1991, 11). Doremus (1994) notes that silica is cooled rapidly from above the melting point to below 900 ^{o}C and no amount of crystalline cristobalite is formed and the silica becomes a stable glass (Doremus 1994, 19).

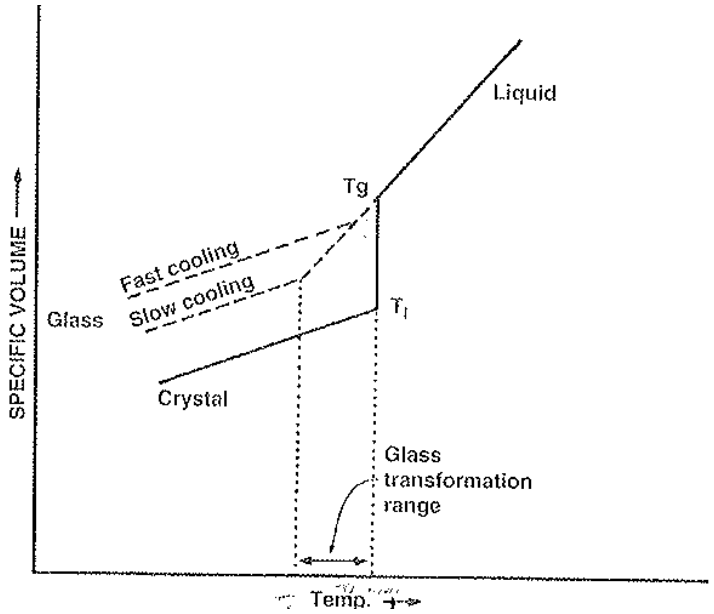


Figure 2.2. The diagram shows the transformation from a liquid to a crystalline or glassy state (from Pollard and Heron 2008, 147, Figure 5.1).

Depending on the rate of cooling, at a temperature below T_l the glass reaches its metastable state. At the temperature T_g the supercooled liquid turns into a glass and this is called the glass formation temperature (Mysen and Richet 2005, 35-36; Pollard and Heron 2008, 147; Zarzycki 1991, 12). Below the temperature T_g the glass becomes too viscous for its molecules to rearrange into a lattice like structure (Frank 1982, 5; Henderson 2000, 24-25; Kalogeras and Lobland 2012, 70, Figure 1a; Pollard and Heron 2008, 147). It will then transform into glass, a solid with a disordered atomic arrangement (Mysen and Richet 2005, 35). It is estimated that the average value of viscosity of the melt at T_g is $10^{11.3}$ Pa s (Shelby 2005, 114). Depending on the rate of cooling, the temperature of T_g varies among glass with the same composition.

Experiments show that the temperature of T_g is higher for higher cooling rates or shorter experimental time scales. This effect shows the kinetic, non-equilibrium nature of glass transition (Holloway 1973, 5; Mysen and Richet 2005, 36). It is estimated that this temperature covers a range of about 20 - 50 ^{o}C in soda-lime-silica glass and it is called the glass transformation range (Frank 1982, 5; Pollard and Heron 2008, 147; Zarzycki 1991, 12-13, Table 2.1). Once the glass is formed, the process of annealing facilitates the structural relaxation process. The structure of the glass is allowed to explore lower energy minima, allowing a progressive shift to a more stable state (Kalogeras and Lobland 2012, 71).

2.4 The structure of glass:

What does the structure of glass look like after it was formed? The atomic structure of glass shares many common features with crystal. Both materials can be considered a three-dimensional arrangement of the oxygen coordination polyhedra of cations (Mysen and Richet 2005, 69-70). This was first suggested by W.H. Zachariasen in 1932 when he wrote that the mechanical properties of glass are comparable to those of crystals but glass lacks periodicity. And 'therefore it is necessary to assume that the atoms in glass are linked together by forces essentially the same as in crystals' (Zachariasen 1932, 3842).

The theory of the structure of glass is conventionally based on vitreous silica glasses (Shelby 2005, 72). Zachariasen (1932) had compared the behaviour of crystalline with vitreous silica and found that the difference between crystal and glass is the presence and absence of periodicity respectively (Zachariasen 1932, 3843). Also, Zachariasen noticed that each unit cell in a crystal must contain an integral number of stoichiometric molecules. On the other hand, the unit cell in glass is infinitely large and has no restrictions on the relative numbers of chemically different atoms (Zachariasen 1932, 3843).

Based on this observation he proposed four rules for those oxides that are capable of forming glasses and it is called *the random network theory* (Doremus 1994, 21; Paul 1982, 10; Pollard and Heron 2008, 148; Rao 2002, 23; Shelby 2005, 73, Table 5.1; Zachariasen 1932, 3847):

(1) Each oxygen atom is linked to no more than two glass-forming cations.

(2) The oxygen coordination number of the glass-forming atoms is small.

(3) Oxygen polyhedra share only corners, not edges or faces.

(4) At least three corners of each oxygen polyhedron are shared in order to form a three-dimensional network.

These rules only allow the following oxides to be glass formers: B_2O_3, SiO_2, GeO_2, P_2O_5, As_2O_5, P_2O_3, As_2O_3, Sb_2O_3, V_2O_5, Sb_2O_5, Nb_2O_5 and Ta_2O_5 (Doremus 1994, 21; Paul 1982, 8; Pollard and Heron 2008, 149).

Experimental works on vitreous silica by Warren (1937) and Warren and Biscoe (1938) had supported this theory (Pollard and Heron 2008, 149; Shelby 2005, 74). The crystalline and glass forms of silicate are a network of SiO_4 tetrahedra, in which silicon is the central atom and four oxygen atoms surround it to form a tetrahedron (Doremus 1994, 25; Holloway 1973, 11; Rasmussen 2012, 2; Zachariasen 1932, 3845; Zarzycki 1991, 38). Using X-ray diffraction Warren and co-workers were able to calculate the average distance between silicon and oxygen which is 1.62 Å. Oxygen – oxygen distance within the tetrahedron is 2.65 Å; the silicon-silicon distance is 3.12 Å; the silicon-oxygen-silicon bond distance is 4.15 Å; the oxygen-second oxygen and silicon-second silicon distance is 5.1 Å; at about 6.4 Å is the result of the silicon-third oxygen contribution (Doremus 1994, 31; Pollard and Heron 2008, 149; Polyakova, 2014, 200).

Zachariasen (1932) had also proposed to look at the structure of glass using a single structural crystal unit for silica in a two dimensional form (Zachariasen 1932, 3845). Using a hypothetical oxide structure A_2O_3, it is shown that the corners of these tetrahedra are linked to form a continuous three-dimensional network in both the crystalline and vitreous forms of A_2O_3 (Frank 1982, 8; Shelby 2005, 81). However, what is different is that the crystalline structure is built by the same A_2O_3 units and they are bonded together in the same direction, which makes it impossible to introduce disorder into the structure (Frank 1982, 8; Zachariasen 1932, 3845; Zarzycki 1991, 38).

On the other hand, the glass form is an open, three-dimensional network in which each oxygen is shared by only two neighbouring tetrahedra (Frank 1982, 8; Mysen and Richet 2005, 72; Zachariasen 1932, 3845). This is in line with Zachariasen's random network theory and because of its open and three-dimensional network, glass-forming oxides are divided into network formers, network modifiers and intermediates (Pollard and Heron 2008, 152). This can be applied to ancient soda-lime-silica glass.

2.5 Network formers, modifiers and intermediates:

2.5.1 Network formers:

The network formers are those that can be formed into a vitreous state on their own as pure substances, these include SiO_2, B_2O_3, GeO_2, P_2O_5 and As_2O_5 (Pollard and Heron 2008, 152). SiO_2 is the main network former in ancient glasses. It can be found in sand, quartz and cherts. In order for it to melt alone it will require a temperature of over 1700 ^oC, which would not be achievable by ancient glassmakers (Frank 1982, 8). Therefore, it is necessary to introduce network modifiers to lower the melting temperature.

2.5.2 Network modifiers:

Network modifiers include alkali metal oxides (Na_2O, K_2O) and alkali earth oxides (CaO, MgO) that can disrupt the glass network and cause a decrease of the Si/O ratio, which subsequently leads to the breakup of the Si-O-Si bonds and the formation of Si-O^- terminations (i.e. the structure is depolymerised) (Holloway 1973, 13; Pollard and Heron 2008, 152; Mysen and Richet 2005, 72; Rao 2002, 25; Zarzycki 1991, 40-41). Thus, the polyhedra cannot share all corners and the network modifiers have created spaces in the network (Newton and Davison 1989, 6; Rao 2002, 24).

This also significantly lowers the viscosity of the melt and leads to the reduction of the glass transformation temperature (Frank 1982, 10; Shelby 2005, 83). Experimental work shows that in sodium silicate glasses, an increase in the Na_2O content leads to a decrease in the content of the unreacted silica (Vedishcheva and Wright 2014, 288).

The introduction of network modifiers has led to an increase of oxygen ions in the glass. As each network-forming atom is accompanied by three oxygen atoms, it is not possible for every oxygen ion to be bonded to two silicons (Holloway 1973, 13; Newton and Davison 1989, 6). Thus, we see some of the oxygen atoms bond to two silicon atoms, while others bond to only one (Newton and Davison 1989, 6; Pollard and Heron 2008, 152). The former are referred to as bridging oxygens, while the latter are called non-bridging oxygens (Pollard and Heron 2008, 152-153; Shelby 2005, 83; Zarzycki 1991, 41). The non-bridging oxygen is negatively charged and to balance the two negative

charges of the oxygens, the positively charged alkali ion are located in the interstices in the network to compensate the negative charges (Frank 1982, 10; Newton and Davison 1989, 6; Shelby 2005, 83; Zarzycki 1991, 41).

2.5.3 Intermediates:

Intermediates are oxides that can be network formers and network modifiers. However, they cannot form glasses themselves (Mysen and Richet 2005, 73; Pollard and Heron 2008, 152). These include Al_2O_3, TiO_2 and ZrO_2 (Pollard and Heron 2008, 152). This can be illustrated by Al_2O_3. It is the most important element in this category and its ionic radius (r=0.47 Å) is comparable to the ionic radius of Si_4 (r=0.34 Å). But because it has only a formal charge of 3^+, it cannot therefore form into a tetrahedron like silicate which has 4^+ formal charge of Si. Thus it needs to be associated with a neighbouring charge-compensating cation to achieve the 4^+ formal charge of Si (Mysen and Ridchet 2005, 73).

2.6 Crystalline theory:

Apart from the random network theory, the Russian scientist A. A. Lebedev had proposed the crystalline theory in 1921. This theory suggests glass is made up of small crystalline regions with various sizes from 10 Å to 300 Å (Pollard and Heron 2008, 154; Porai-Koshit 1990, 2). It suggests that the structure of glass is inhomogeneous on the sub-micron to micron scale, contradicting the random network theory which assumes glass is homogenous. Also, the random network theory has been proven to not agree with the chemically inhomogeneous structure of binary and more complex glasses (Porai-Koshits 1985, 80; 1990, 4). This is due to phase separation of a liquid type in these glasses (Porai-Koshits 1985, 82).

Experimental work in the past few decades using the SAXS (small angle x-ray scattering) technique have found that many two- and three-component glasses such as SiO_2-B_2O_3 and GeO_2-B_2O_3 contain crystallites or crystal-like regions and inhomogeneous regions in multi-component glasses (Pollard and Heron 2008, 154-155; Porai-Koshits 1977, 98, 110; 1985, 84; 1990, 4; Towle 2002, 42). It is found that these regions have a different chemical composition from the rest of the glass. This can occur

in ancient glasses, especially when magnesia is present. Thus, this can affect the properties of glass, especially their durability because the separated phases could be either more durable or less durable (Newton and Davison 1989, 7).

2.7 The chemistry of glass colouring:

Glass colouring is an important process in ancient and modern glass production. The colour of glass is the result of the absorption and emission of the electron clouds of its constituent ions (Vogel 1994, 223). It is now known that colour in transparent glass is the result of the presence of either small amounts of transition metal ions (e.g. iron, cobalt, manganese, copper etc.) or metallic atoms (e.g. gold, copper, silver etc.) in the structure of glass (Pollard and Heron 2008, 157).

Transition ions are especially important and are more commonly found to be used as glass colourants. They are present either as impurities in raw materials or they are deliberately added to the glass batch by glassmakers and/or glassworkers (Sanderson and Hutchings 1987, 99). Glass opacifiers such as antimony and tin were used by ancient glassmakers and/or glassworkers to opacify the glass (Henderson 1985, 285).

2.7.1 Ligand field theory:

The generation of colour in transition metal ions can be explained using the ligand field theory. The theory describes the colour of the transition metal ions as the result of interaction between the outer orbital electrons of the transition metal and the electric field created by the presence of co-ordinating ligands (Pollard and Heron 2008, 159; Vogel 1994, 226). A simpler version of this is called the crystal field theory.

When this theory is applied on the study of glass colour, it shows that colouring ions can either exist as interstitial network-modifiers or as substitutes for the silicon in the network, i.e. as a network-former (Pollard and Heron 2008, 162; Vogel 1994, 227-228). Interstitial ions have six or more oxygens surrounding them and are octahedrally co-ordinated. On the other hand, some colouring ions such as Fe^{3+} can substitute the silicon in the network and will therefore have four times the oxygen co-ordination as the interstitial ions (Pollard and Heron 2008, 161-162).

Those ions in fourfold coordination acted as a network former while those in a sixfold coordination act as a network modifier. For instance, Co^{2+} ion in the fourfold coordination will impart a deep blue colour. On the other hand, if it appears in a sixfold coordination it will impart a pink and rather less intense absorption (Sanderson and Hutchings 1987, 102). This shows that the colour of the glass will change if the oxygen co-ordination changes from four to six, even if it is from the same colouring ions (Pollard and Heron 2008, 162).

2.7.2 Oxidation sate of metal ions:

An important influence in the colouring of glass is the oxidation state of the metallic ions. The transition metal ions and metal atoms can be present in different oxidation states. When a metal is oxidised, it loses an electron to the empty 2p orbitals of the oxygen atom; on the other hand, if the metal is reduced, it gains an electron from the oxygen atom (Paul 1982, 148). Several factors affect the oxidation state of the metal ions (Henderson 1985, 278; Paul 1982, 160; Pollard and Heron 2008, 163-164; Sanderson and Hutchings 1987, 99):

(1) The redox conditions in the furnace, which means the oxidation or reduction conditions in furnace.

(2) The redox reactions between the various transition metal ions present in the melt, such as iron and manganese, iron and sulphur (Brill 1988, 273-274, 277; Schreurs and Brill 1984, 199, 207-208; Newton 1978, 59; Newton and Davison 1989, 8; Schofield *et al.* 1995, 90; Weyl 1976, 116-117).

(3) The extent to which the electrochemical equilibrium is established before the glass is cooled from the melt.

(4) The temperature of the furnace can affect the redox equilibrium in glass. The oxidation-reduction equilibrium in glass usually moves toward the reduced condition when the temperature inside the furnace increased.

(5) The firing time and the type of fuel used are also important influences on the final colour of the glass.

2.7.3 The presence of other oxides in the glass batch:

Another factor that affects the colouring of glass is the presence of other network modifiers. They can influence the colouring ions due to the mutual polarization effects between ionic partners that have considerable influence on the absorption behaviour of a compound (Vogel 1994, 228). The colouring ions in glasses where only soda is present as alkali may produce different colours from glasses with potash as the only alkali (Pollard and Heron 2008, 162).

2.8 Summary:

Glass is a very complex material. The above discussion shows that glass is a non-crystalline solid that is formed by rapidly cooling the liquid to avoid crystallisation. The structure of glass is an open, three-dimensional network and each oxygen is shared only by two neighbouring tetrahedra.

Glass-forming oxides can be divided into network formers that can be formed into a vitreous state on their own, network modifiers that can disrupt the glass network and redcues the glass transformation temperature and intermediates can be network formers and network modifiers.

It also shows that the colour in glass is the result of the absorption and emission of the electron clouds of its constitutent ions. The presence of transition metal ions or metallic atoms in the structure of glass helps to colour transparent glass.

Chapter 3: Raw materials

3.1 Introduction:

This chapter discusses the raw materials that were used to produce glass in the late 8th – 14th centuries AD. Research has shown that major technological change in glassmaking occurred in this period. This is a period when glassmakers began to experiment with different raw materials to produce a new type of glass (plant ash glasses) (Henderson *et al.* 2004, 439).

Recent advance in the study of ancient glass using various scientific techniques has helped us to determine the composition of ancient glasses, which helps us to determine what sort of raw materials were used to make glass.

It is widely accepted in the archaeometric community that most glass was made using a two-ingredient recipe in this period (Degryse *et al*. 2014, 228). These are the alkali sources (natron and plant ash) which provide sodium oxide (Na_2O) and act as network-modifier to flux silica and to lower its melting temperature; silica source (sand and quartz pebbles) which is the network-former in glass; and lime, which is the network-stabiliser that is derived from both plant ash and sand.

As we shall see, glassmakers would need to understand the properties of these raw materials and the environments in which they were procured to determine whether they are suitable for glass production. Therefore, choices would have to be made and this determines the final composition of the glass. By studying the compositions of glasses, we can attempt to determine what raw materials were used and the provenance of these materials.

3.2 Alkali source:

3.2.1 Natron as a flux:

Between 800 BC and AD 800, a mineral-based material was the principal alkali source for glassmaking. Sayre and Smith (1961) have analysed ancient glasses dated to the 4th century BC to the 9th century AD and found that they have low levels of MgO and K_2O which are below 1.5% and there is a correlation between the two elements (Sayre and Smith 1961, 1825-1826). This suggests a mineral source, such as natron, was used to flux and dissolve sand or quartz grains (Brill 1988, 258-259; Freestone *et al.* 2000, 69-70; Henderson 1985, 271-273; Henderson 2000, 26; Henderson 2013, 51).

3.2.2 Definition of natron:

Natron is a term that is used by archaeologists to describe the mineral and its deposits. In fact, its mineral name is sodium carbonate 10-hydrate ($Na_2CO_3.10H_2O$), in which sodium carbonate bicarbonate 2-hydrate ($Na_2CO_3.NaHCO_3.2H_2O$), i.e. trona, is the dominant carbonate in the deposits (Brill 1988, 268; Henderson 1985, 273; Henderson 2000, 26; Shortland *et al.* 2006, 521). It provides a relatively pure source of sodium carbonate and is relatively free of chlorides and sulphates (Shortland 2004, 497). Glass made from natron would have behaved more predictably when worked. Also, it was denser and generally had higher alkali concentrations than plant ash (Henderson 2013, 51). For convenience, the term natron will be used in this study.

3.2.3 Locations of natron and mineralogical studies of the material:

The Roman author, Pliny the Elder (AD 23 – AD 79), had noted in his *Natural History* that Egyptian soda was preferable to use for glass production (*Natura Hisory* XXXVI: 193). He had also noted that there were two sources of soda in Egypt that were used for glassmaking: Naucratis and Memphis (*Natural History* XXXI: 111). It is now generally agreed that the Wadi Natrun in Egypt (i.e. Pliny's Memphis) was the main source of natron for the production of glass between 800 BC and AD 800 (Jackson *et al.* 2016, 2). It lies in a geographical depression some 100 km north-west of Cairo (Henderson 2013, 51; Shortland 2004, 497; Shortland *et al.* 2006, 521). In the bottom of the Wadi

Natrun depression, there are a series of evaporitic lakes of different sizes. They contain water in the winter and in the summer this evaporates to dryness to produce deposits of carbonates, sulphates and chlorides of sodium, whose amounts are varied due to different amount of water in different lakes (Shortland 2004, 498; Shortland *et al.* 2006, 524).

The mineralogical analysis of the lakes in the Wadi Natrun (Lakes Fazda, Umrisha, Ruzunia, Hamra, Zug, Beida, Khadra, Ga'ar and Barnuj I and II) shows that the lakes are dominated by halite and burkeite throughout most of the year. They contained very little sodium carbonate, i.e. in the form of trona. It is a reactive compound in glass melting (Jackson *et al*. 2016, 2). However, it was never a pure mineral, and is associated with a significant amount of chloride and/or sulphates (Shortland 2004, 512-513, Figures 3 and 4; Shortland *et al.* 2011, 922). Trona is very rare and can only be exploited at certain time of the year, may be in summer (Pliny the Elder suggested natron was collected in Macdeonia when the dog star rises, which is summer in Greece (*Natural History* XXXI: 107) and/or winter - spring (Nenna 2015 suggests it was likely collected between mid-November and mid-March). It also depends on the climate of that particular year (Jackson *et al*. 2016, 4; Nenna 2015, 17; Shortland 2004, 514; Shortland *et al.* 2006, 525).

Pliny the Elder also mentioned that the natron deposit at Naucratis was exploited for glass production in antiquity (*Natural History* XXXI: 109). Recent research has suggested that el-Barnugi near the Nile Delta in Egypt was Naukratis, a thriving trading post from the 7th century BC unti Roman times (Jackson *et al*. 2016, 2). Mineralogical analysis of the natron sample from el-Barnugi shows that trona made up 40% of the sodium compounds, with halite (sodium chloride) and thenardite (sodium sulphate) making up the remainder sodium compounds, sometimes with halite dominant (Jackson *et al*. 2016, 6). Experimental work by Jackson *et al*. (2016) using natron from el-Barnugi shows that the reactive soda component in the natron could produce glass with a chemical composition similar to a typical Roman glass (Jackson *et al*. 2016, 7). This suggests natron from el-Barnugi could also have been used to produce glass in the Roman period.

As trona was never a pure mineral, Pliny the Elder in his *Natural Histroy* mentioned that natron could be purified by mixing the salts with calcium carbonate and heating, which may have induced a chemical reaction that converted sodium sulphate to sodium carbonate by leaving a by-product of calcium sulphide (*Natural History* XXXI: 111, 114; Shortland *et al.* 2011, 925-926). Shortland *et al.* (2011) have carried out an experiment on this and found that it is possible to convert sodium sulphates, like burkeite, into sodium carbonate using something similar to the 'Le Blanc process' in which sulphate salt is converted to carbonate by calcining lime with charcoal (Shortland *et al.* 2011, 926-928). However, at present, there is no archaeological evidence, such as waste products of calcium sulphide, to show that such refinement was carried out by ancient glassmakers (Shortland *et al.* 2011, 927).

Recent experimental work by Jackson *et al*. (2016) shows that glass can be produced at a temperature of 1100 ^{o}C using natron without any pre-treatment (Jackson *et al*. 2016, 6-7). It shows that sodium sulphate and sodium chloride in natron do not react in the glass melt even in high melting temperatures. Only trona (sodium carbonate) reacts in the glass melt. The batch with a larger proportion of trona produced a fully formed glass (Jackson *et al*. 2016, 6). They also found that sodium chloride played a crucial role in glass formation. It helps to produce a homogenous, transparent glass free from crystalline phases or surface residue (Jackson *et al*. 2016, 8).

Elsewhere, there are various locations where natron could have been exploited for glassmaking. Pliny the Elder mentioned that Lake Pikrolimni, near the city of Chalastra/Clitae in Macedonia, was a source of natron (*Natural History* XXXI, 107; Dotsika *et al.* 2009, 133; Ignatiadou *et al.* 2003, 64-66). Geochemical analyses by Dotsika *et al.* (2009) and Ignatiadou *et al.* (2003) have found that alkaline Na-Cl brines were formed in the lake, and the evaporating conditions that occurred in the lake provided trona, halite and burkeite which are typical minerals found in the Wadi Natrun lakes (Dotiska *et al.* 2009, 142).

Ignatiadou *et al.* (2003) had demonstrated that the sequence of salts upon evaporation is as follows: burkeite-> trona-> halite (Ignatiadou *et al.* 2003:64-66), which is very similar to the sequence found in the lakes of the Wadi Natrun. However, there is no archaeological evidence, such as a primary glass production centre(s) in the region, to

support the fact that natron was collected from Lake Pikrolimni to produce glass in antiquity.

Other lakes including Lake Van in Turkey, the al-Jabbul salt lakes in northern Syria, Fezzan in Libya and Sebket al Melah in Tunisia have been suggested for the exploitation of natron (Shortland *et al.* 2006, 527). However, it is uncertain whether they were used in ancient times for glassmaking, and they have not been investigated geochemically to determine whether they produce common salt or natron (Devulder and Degryse 2014, 89).

3.2.4 Natron used in the production of Roman and early medieval glass:

Throughout the Roman period, natron was the primary alkali source for glassmaking. A large amount of literature has been devoted to the study of Roman glass. Typical Roman glasses from the 1st century BC – 3rd century AD has low levels of K_2O and MgO, mainly at a range of 0.50% - 1.1% and 0.38% - 0.84% respectively. Jackson (1992) showed that the mean concentrations of K_2O and MgO of the typical blue-green Roman glass are 0.8% and 0.6% respectively, which gives a potash : magnesia ratio for Roman glass at 1.3 : 1 (Jackson 1992, 451). Even in the late Roman and the early Medieval period, the levels of K_2O and MgO are fairly consistent, except for Egypt II glass which has a relatively low level of K_2O of 0.1% - 0.2% (Table 3.1).

	Levantine I	Levantine II	Egypt I	Egypt II	HIMT 1	HIMT 2
Na_2O	14 – 17%	10 – 13%	21.4%	14.7 – 15.3%	19.11%	19.12%
K_2O	0.5 – 1.8%	0.35 – 0.58%	0.34%	0.1 – 0.2%	0.79%	0.41%
MgO	0.4 – 0.8%	0.5 – 0.92%	0.9%	0.3 – 0.6%	1.2%	1.23%

Table 3.1: Compositional data for the six main groups of 1st millennium AD glass. The data are taken from Abd-Allah 2010, 1867-1868; Brill 1988, 259; Bimson and Freestone 1988, 237-243; Degryse *et al*. 2006, 494-501; Foster and Jackson 2009, 189-204; Foy *et al*. 2003, 41-85; Freestone 1994, 290; Freestone *et al*. 2000, 72-73; Freestone 2003, 111-112; Freestone 2005, 197, Table 1; Gratuze and Banandon 1990, 159-161; Nenna *et al*. 2000, 97-112; Rehren and Cholakova 2010, 81-96; Rehren *et al*. 2010, 68-79; Schibille *et al*. 2008, 627-642; Schibille 2011, 2939-2948; Schibille *et al*. 2012, 1-25; Silvestri *et al*. 2005, 797-816; Silvestri *et al*. 2012, 2177-2190; Tal *et al*. 2004, 62-63.

3.2.5 The demise of the use of natron:

From the late 8th and 9th centuries AD onwards, the Muslims had (re-) introduced plant ashes as the principal alkali flux for glassmaking in Syria, Israel, Lebanon and Egypt. Previously plant ashes were used by the Sassanians to produce glass during the 3nd – 7th centuries AD in Iraq and Iran (Mirti *et al*. 2009, 1061). The natron glass industry went into decline and natron glass gradually replaced by plant ash glass in the Middle East and wood ash glass in Western Europe (Barkoudah and Henderson 2006, 298; Freestone *et al.* 2000, 70; Henderson 2002, 596; Henderson 2013, 97-108; Sayre and Smith 1961, 1826).

Chemical analyses of glasses from the 6th – 9th centuries AD have shown that glass made in the Levantine area has lower Na_2O concentrations than previous Roman natron glass. The level of Na_2O in early Roman glass was about 17% - 20%; however, a lower concentration of Na_2O was found in Levantine I (14% - 17%), and Levantine II glasses (10% - 13%) in the 4th – 8th centuries AD (Brill 1988, 266-267, Tables 9-6, 9-7; Freestone *et al.* 2000, 71; Freestone 2003, 111-112; Freestone 2005, 197, Table 1; Henderson 2002, 597-598, Table 1; Henderson 2013, 96-97, Figure 4.2; Jackson 2005, 769, Table 2; Silvestri 2008, 1494). This could due to the limited availability of natron in the early medieval period, or the scale of glass production in which glassworkers had to produce larger volume of glass (Henderson 2002, 598), thus a lesser amount of natron was required.

Archaeologists and archaeological scientists have proposed several theories and reasons as to why the supply of natron decreased during the 7th – 9th centuries AD:

1. Shortland *et al.* (2006) and Whitehouse (2002) have proposed the effect that a series of political events in Egypt and the Levant had on the supply of natron:

In Egypt, the Wadi Natrun and trading port Alexandria (the principal port of Egypt), were affected by foreign invasions by the Persians and the Muslims, and civil wars during the 7th – 9th centuries AD, causing disruption in the Mediterranean trade (Shortland *et al*. 2006, 527-528; Whitehouse 2002, 194). These affected the supply of natron to glassmakers outside Egypt, and they were forced to adapt to such

circumstances by lowering the proportion of natron used. This lowered the concentrations of Na_2O in glasses, causing the melting temperature of glass to increase and the glass had shorter time to be worked, along with an increased demand for fuel (Henderson 2013, 99-100). Eventually, the civil wars and revolts in the 9th century caused widespread destruction in the Nile Delta region. This led to a temporary shortage of labour for the extraction of natron and the transport of this mineral. Despite a period of recovery and state control over the supply of natron in AD 865, this business had become less organised and on a smaller scale compared to the Roman period (Shortland *et al.* 2006, 528). In the end, glassmakers had to experiment with other raw materials to produce glass in order to supply the glass industry with alkali flux.

2. Henderson (2013) suggests a cultural explanation for the replacement of natron by plant ash:

The reason natron was not replaced by plant ash earlier than the 9th century AD is because the Umayyad caliphate and its retinues were not especially interested in developing arts and crafts that could be defined as 'Islamic', as opposed to the Roman, Christian or Jewish industries that were so well established centuries before. It was the 'Abbasid caliphate which had initiated the rise of the Islamic art industry. They tried to justify their rule in Islamic terms through the use of arts and crafts, which formed an innate part of every aspect of life under the 'Abbasids. Islamic religion and culture were expressed in arts and crafts and using these media to create a sense of belonging to Islamic society. This was more pronounced under the reigns of Harun al-Rashid and his son al-Ma'mum when the caliphate was becoming centralised. Therefore, this constituted an industrial revolution in the glass industry, and it is not surprising that this occurred in major political centres such as Baghdad, Samarra and al-Raqqa where the centre of government was located (Henderson 2013, 266).

3. Foy and Nenna (2001) proposed that climate change in the 8th and 9th centuries AD had decreased the supply of natron:

They suggested that the increased rainfall in the 8th century AD in the regions of the Sahara desert could have affected the natron supply in the region (Foy and Nenna 2001, 26). As we have discussed above, temperature and seasons of the year would have

affected the formation of trona in the evaopritic lakes. Therefore, a reduction in temperature or an increase in rainfall could have affected the evaporation process that occurred in the salt lakes, and on the total amount of natron that was produced due to slow rate of evaporation. As a result, the supply of natron to glassmaking centres decreased (Henderson 2013, 98; Shortland *et al.* 2006, 527). However, as Shortland *et al.* (2006) have pointed out, there is no evidence to suggest that severe climate change occured in the late 8th and 9th centuries AD that could have affected the formation of natron in Egypt (Shortland *et al*. 2006, 527). Therefore, we cannot emphasise too much this factor in the explanation of the demise of the natron glass industry.

Despite the lack of natron, there are increasing evidence to suggest that old natron glass was recycled and used until the 12th century AD in the western Mediterranean. Analysis of the mosaic glasses from the basilica of Torcello in the Venetian lagoon (7th – 13th centuries AD) shows that old natron glass was recycled and used alongside plant ash glass throughout the 7th – 12th centuries AD. Plant ash glass would not fully replace natron glass until the 12th century AD. (Andreescu-Treadgold *et al.* 2006; Henderson 2013, 100; Verita *et al.* 2002, 264). Chemical analyses of glasses from Rocca di Asolo in Northern Italy show that natron glass was in used until the 10th century AD until it was replaced by plant ashes from the 11th century AD onwards (Gallo and Silvestri 2012, 1028, Table 2). Therefore, the replacement of natron glass by plant ash glass was a gradual process, with the Islamic east being the first region to have adopted it in the late 8th and early 9th centuries AD.

3.2.6 Plant ashes:

From the 4th millennium BC plant ashes were the principal alkali source for the production of faience in the Middle East. From about 1500 BC onwards glassmakers also made use of this organic source for glassmaking (Brill 1970, 109-111; Henderson 2002, 595; Sayre and Smith 1961, 1824-1826; Tite *et al.* 2006, 1284). Although natron glass replaced plant ash glass from about 800 BC, regions that were controlled by the Sasanian Empire (about AD 200 – 600) used plant ashes as the principle alkali flux for glass production. And it was (re-) introduced to Syria, Lebanon, Israel and Egypt by the Muslims during the Islamic period (about late 8th – 14th centuries) and to Venice by the Venetians in the 13th – 17th centuries AD.

3.2.7 Properties of plant ashes:

Previous studies on plant ashes by Turner (1956), Brill (1970), Tite *et al.* (2006) and Barkoudah and Henderson (2006) have shown that plant ashes can be divided into three categories: sodium rich, potassium rich and mixed alkali plants (Brill 1970, 105-128; Barkoudah and Henderson 2006, 311; Tite *et al.* 2006, 1287, Table 2; Turner 1956, 286-287, Table VI). Halophytic plants grow in semi-desert and desert regions, coastal and salt marsh regions, and inland salinas. They are salt resistant and can tolerate highly alkaline environments, and by photosynthesis alkaline salts such as sodium carbonate will concentrate in their tissues (Henderson 2013, 23; Tite *et al.* 2006, 1285).

Halophytic plants that are suitable for glassmaking must have alkalis (sodium and potassium) that are in the form of carbonates, bicarbonates, sulphites, sulphides and hydroxides, and must be present in sufficient quantities to react with silica (Turner 1956, 291). It is sodium carbonates (Na_2CO_3) that are most important to glassmakers as they would lower the melting temperature of silica from 1710 - 1730 ^{o}C to 1100 – 1200 ^{o}C, which could be achieved using ancient furnaces (Henderson 2013, 23).

Plant genera that are sodium rich are suitable for glassmaking. These include *Anabasis*, *Arthrocnemum*, *Halopeplis*, *Hammada* (*Haloxylon*), *Salicornia* and *Salsola.* They belong to the halophytic plants of the Chenopodiaceae family. Many of which are found in the Middle East. Their levels of Na_2O range from 14.20% to 48.2% (Barkoudah and Henderson 2006, 297; Henderson 2013, 23; Rehren 2008, 2566; Tite *et al.* 2006, 1286-1287, Tables 1 and 2).

The factor that determines the alkali level in plant ashes is likely to be the plant's physiognomy, not its geological environment. For instance, *Salsola jordanicola* from the Balikh valley and *Salsola vermiculata* from the Jabul evaporate deposit have very similar soda to potash ratios of 2.67 and 2.42 respectively (Barkoudah and Henderson 2006, 306-307, Table 2; Henderson 2013, 41).

Apart from the level of Na_2O, CaO is also crucial in determining whether a plant species is suitable for glassmaking. Soda-rich species have CaO values between 1.63% and 23.10%. Only certain species such as *Halopeplis sp*. from Heracla, *Salsola kali* from

the Levant, *Salsola* and *Suaeda* from Wadi Natrun and Barnug in Egypt could have provided the CaO level found in plant ash glass (Barkoudah and Henderson 2006, 306, Table 2; Tite *et al.* 2006, 1286-1287, Tables 1 and 2). While the rest of the soda-rich plant species analysed including *Anabasis syriaca*, *Salsola jordanicola*, *Salsola vermiculata* and *Arthrocnemum strobilaceum* are unable to provide enough CaO to the glass.

Therefore, a separate lime source may be needed to enhance the CaO level in glass. There is evidence that the CaO level in Type 4 al-Raqqa glasses could have been increased by the use of bone ash to compensate the lack of CaO in plant ashes (Barkoudah and Henderson 2006, 315; Henderson 1999, 235; Henderson 2000, 89; Henderson 2002, 599; Henderson 2013, 38; Henderson *et al.* 2004, 459).

It should be noted that the level of CaO in plant ashes is likely determined by the geological background of the plants, not the plant's physiognomy (Barkoudah and Henderson 2006, 317; Henderson 2013, 41). For instance, two *Salsola sp.* (*sueda*?) which were grown in the gypsiferous limestone area northeast of al-Raqqa up the Balikh valley contain nearly twice the amounts of CaO than the rest of *Salsola* species found in other parts of Northern Syria (Barkoudah and Henderson 2006, 317).

Barkoudah and Henderson (2006) also found that there is a positive correlation between MgO and CaO in the soda-rich *Salsola* genus. This suggests MgO in plant ash glasses was not necessary the result of the use of dolomitic limestone. It could have come from the plant ash itself and it reflects the limestone environments in which the plants grow (Barkoudah and Henderson 2006, 311-313).

On the other hand, the potassium-rich *Chenopodium* genus was not used for glassmaking. Apart from its low Na_2O and high K_2O levels, this genus did not display any correlations between K_2O, MgO and CaO, which suggests that this genus may not have been used for glass production (Barkoudah and Henderson 2006, 319). Also, there is no evidence to suggest that mixed-alkali plant ashes were used to produce glass in the late 8^{th} – 14^{th} centuries AD.

3.2.8 Reh:

Reh is an alkali rich mineral that is commonly found in south and southeast Asia such as India and continued to be used in 1990s (Henderson 2013, 53). It contains sodium carbonate, sodium sulphate and sodium chloride. Brill (1999a and 199b) analysed a sample of *reh* from a field 12 km southeast of Shikohabad in India and found that it contained 52.9% of Na_2O, 0.10% of K_2O, 0.10% of CaO and 0.40% of Al_2O_3 (Brill 1999a, 212; 1999b, 481). *Reh* contributes high levels of Al_2O_3 (about 10%), Na_2O (up to 36%) and K_2O (3% - 6%) but relatively low levels of MgO (about 1%) and CaO (about 3%) to the glass (Boulogne and Henderson 2009, 72; Lankton and Dussubieux 2006, 132-133; Henderson 2013, 53).

Reh was possibly used to produce high alumina glasses that were found in south and southeast Asia such as India, Sri Lanka, Bangladesh, Vietnam, Malaysia and Thailand, and east Africa such as Kenya. Mineral high alumina glasses are dated to the 3rd century BC – 19th century AD (Dussubieux *et al*. 2008, 801; 2010, 1647).

3.2.9 Soda-rich evaporate associated with borax deposits:

Recent chemical analysis of raw glasses and glass vessels from Pergamon, Sardis and Aphrodisias in western Turkey shows that glassmakers in the region may have used a different alkali source for glass production in the middle and late Byzantine period (Brill 1968; Dussubieux *et al.* 2010, 1649, Table 3; Schibille 2011, 12). It is characterised by high alumina and boron contents (Brill 1968; Dussubieux *et al.* 2010, 1649, Table 3; Schibille 2011, 8-9).

Chemical analysis of thermal waters from hot springs and wells in western Turkey shows that hot springs with Na-HCO_3 water type (in which HCO_3 is the dominant anion) could have been used to produce high boron glasses in western Turkey (Tite *et al*. 2016, 63). Comparison between the chemical compositions of the hot springs from western Turkey and the high boron Byzantine glasses shows that the Afyon-Gazligol and Urganli hot springs could have been used to produce this type of glass in western Turkey. They show similarities in terms of their Na/B, B/Li and Na/K ratios (Tite *et al*. 2016, 64).

It is noted that Afyon-Gazligol and Afyon-Karahisar (Imperial edicts dated to AD 1590 and AD 1608 requested the supply of *bora*, a term used by the Ottomans to cover borax, soda and potash, from Afyon-Karahisar) hot springs in western Turkey could have been used to produce Iznik glazes from the 15th century AD onwards based on their similarities in Na/K, Na/Mg, Na/Ca and Na/B ratios (Tite *et al*. 2016, 62-64).

3.3 Silica source:

Silica acts as a glass-former in ancient soda-lime-silica glasses. Silica is a polymorph that has three principal crystalline forms with the same chemical composition: quartz, tridymite and cristobalite. Quartz is the most common crystalline form that forms 12% of the earth's crust. The latter two occur rarely in certain volcanic rocks and they can be produced by heating quartz to high temperatures. With a temperature higher than 1470 ^{o}C, quartz can be converted to cristobalite, which in turn can be formed to tridymite at a temperature between 870 ^{o}C and 1470 ^{o}C (Henderson 2013, 56).

3.3.1 Sand:

The most common source of silica for glass production in antiquity and early medieval period was sand. It is especially valuable for the production of natron glass. It provides SiO_2, CaO and Al_2O_3 for the glass. As mentioned above, natron does not contribute CaO into the glass to stabilise it, as opposed to plant ashes. Thus, the majority of CaO in natron glasses came from sand.

Sand contains heavy minerals including magnetite (iron oxide), ilmenite (iron titanites) and feldspars (alumina). All of which provide characteristic elements (Fe_2O_3, TiO_2 and Al_2O_3 respectively) which help us to identify different sand sources. However, it is found that feldspars can be sodium- or potassium-rich. They can be formed chemically in a continuous series between two members (Henderson 2000, 27; 2013, 60). For instance, plagioclase feldspars have albite (high level of sodium) and anorthite (high levels of calcium) as end members. Also, olivine, chromite, epidote, ilmenite, sphene or titanite, mica, calcite and zircons can all be found as impurities in sands. They contribute iron, chromium, titanium, alumina and calcium as oxides into the glass (Henderson 2000, 27; 2013, 59-60).

3.3.2 Historical references to sand sources and scientific studies of the material:

Pliny the Elder mentioned that sand was used for the production of glass (Degryse *et al*. 2014, 224). In his *Natural History*, he specifically mentioned the beach near the mouth of the Belus River (the modern River Naaman, running into the Bay of Haifa in northern Israel), which meets the sea near Ptolemais (the city of Akko in northwest Israel), as the major source of sand for glass production (*Natural History* XXXVI: 190). The sediments of the coast of Israel are derived from the Nile (Brill 1988, 266; Foy and Nenna 2001, 21; Freestone 2006, 10; 2008, 85; Henderson 2013, 62; Turner 1956, 279).

Several scientific studies have been conducted to determine the mineralogy of the Belus River sand and its suitability for glass production. Brill (1988) analysed the sand from the Belus River in the context of the 4th century glass workshop at Jalame in Israel. The mean compositions of the seven samples of clean sand show that they contained 79.90% of SiO_2, 8.93% of CaO, 0.80% of K_2O, 0.50% of MgO, 2.98% of Al_2O_3, 0.33% of Fe_2O_3, 0.04 of TiO_2 and 0.03% of MnO. The presence of the shells in sand would explain the high concentration of CaO which would provide sufficient lime source for the glass (Brill 1988, 266-267, 270, Table 9-9). Freestone has suggested that the calcium carbonate content of the sand in the Bay of Haifa is around 15% and would have provided a level of about 8.4% CaO to a typical natron glass (Freestone 2006, 10; 2008, 87), which further confirms that the Belus River was the source of sand for glassmaking as noted by Pliny the Elder in antiquity.

The Bay of Haifa would not be the only source of sand in the Israeli coast. It is very likely that other sand sources along the Israeli coast were also used for glass production. This is supported by the discovery of primary glass production centres along the coast and the chemical analyses of the glasses found in these factories. All have different chemical compositions which suggests different sources of sands were used by different production centres. These include Apollonia, Bet Eli'ezer and Beth She'arim in Israel and all are dated to the 6th – 9th centuries AD (Gorin-Rosen 2000, 52-56; Freestone and Gorin-Rosen 1999, 105-106; Freestone *et al.* 2008, 67-68; Tal *et al.* 2004, 55-61).

3.3.3 Quartz:

Quartz pebbles are believed to have been used for the production of some Syrian glasses during the 9^{th} – 12^{th} centuries AD (Henderson *et al*. 2004, 455). They come from various environmental deposits, including crushed, riverine and coastal sand deposits, or inland geological deposits (Henderson 2013, 56-57). Quartz, especially that with high purity, can exist in two forms:

(1) Vein quartz is an intrusion of silica magma in igneous and metamorphic rocks. It can be colourless, milky white or pink. In terms of its microstructure, it is characterised by water-filled vacuoles.

(2) Rock crystal is found in fill cavities. It is the result of the precipitation of silica-rich (hydrothermal) groundwater. It is colourless and its microstructure is microcrystalline aggregates (Henderson 2013, 56-57).

Quartz is purer than sand sources, with low concentrations of impurities such as Al_2O_3, Fe_2O_3, TiO_2 and CaO. This can be found in some plant ash glasses which have a low Al_2O_3 concentration of 1% – 1.7%. Also, the silica source can also be carbonate-free sand, presumably from inland sources (Leslie *et al.* 2006, 262). The CaO in plant ash glasses is likely to have come from the plant ashes as we have mentioned before.

Strontium and oxygen isotopes were used to determine the source of quartz used for the production of Islamic plant ash glasses. It was found that plant ash glasses generally have a lower ^{18}O than natron glasses, which may suggest glassmakers used a different silica source for the production of plant ash glasses (Henderson *et al.* 2005, 672). Henderson *et al.* (2005) found that if quartz pebbles were used for glass production, they would introduce a lower amount of Sr into the glass. This is found in the analyses of two quartz pebble samples near the glassmaking site at al-Raqqa in northern Syria, which contain 26 ppm and 0.26 ppm of Sr, and have high isotopic values of 0.716 and 0.718 respectively (Henderson *et al.* 2005, 669). This suggests most of the Sr came from plant ashes and the isotopic signatures of the plant ash glasses are similar to those of the plant ash collected from near al-Raqqa (about 0.7080) (Henderson *et al.* 2005, 670, Figure 3).

Leslie *et al.* (2006) have used oxygen isotope analysis to study the plant ash glasses from Banias (northern Israel) and Tyre (southern Lebanon) and show that they both have similar ^{18}O values of 11.8 – 12.9, while the al-Raqqa samples appear to have higher ^{18}O of about 13.1 – 13.7. This is because glasses from Banias and Tyre were made with sands that were geologically related and were possibly from the same region, while glasses from al-Raqqa were made with a different silica source from a different geochemical background (Henderson *et al.* 2005, 669, Table 1; Leslie *et al.* 2006, 259-263, Table 2 and Figure 2).

Neodymium isotope analysis of glasses also helps us to identify whether a purer source of silica was used to produce glass and its possible origins. Nd isotope analysis of plant ash glasses from al-Raqqa shows that Type 2 glasses have the highest concentrations of Nd (about 8 ppm – 12 ppm), which suggests a rather impure source of silica (possibly sand) was used to make this type of glass. On the other hand, some of the Type 4 glasses from al-Raqqa have the lowest Nd contents (<5 ppm) and this may suggest a purer source of silica (possibly quartz) was used to produce some of the glasses in Type 4 (Henderson *et al*. 2009, 422). Comparison between al-Raqqa glasses and glasses from Tyre and Banias using Nd isotope analysis shows that they are markedly different from each other. Tyre and Banias glasses have $^{143}Nd/^{144}Nd$ value below 0.5120. On the other hand, al-Raqqa glasses have $^{143}Nd/^{144}Nd$ value between 0.5120 and 0.5122 (Henderson *et al*. 2009, 423).

It is noted that if Belus-type coastal sand was combined with calcium-rich plant ashes, the glass would have devitrified. This occured in the Bet She'arim glass slab. This is because coastal sand would have contributed excessive lime into the glass (Freestone and Gorin-Rosen 1999, 110, Table 1).

3.4 Lime:

Lime is an essential component in the production of glass. It helps to stabilise the glass, making it more durable and resistant to water attack. The lime comes from calcium carbonates which can be found in sand sources and plant ashes. As we have mentioned before, it appears that the calcium in natron glass comes from sand sources, since natron does not contribute any calcium into the glass.

However, it has been claimed by Wedepohl and Baumann (2000) that shell fragments could have been added to increase the lime content, based on strontium isotopic analyses (Wedepohl and Baumann 2000, 129). Such a practice is also backed up in Pliny's *Natural History* who mentioned that shells were added to the glass melt separately (*Natural History* XXXVI: 192; Henderson 2013, 64). However, Freestone *et al.* (2003) have shown that the strontium isotopic signatures between Wedepohl and Baumann's glass from Germany and glasses from the Middle East have similar values and are very close to the Belus River value (Freestone *et al.* 2003, 27). Therefore, the question of whether a separate lime source was added in the production of glass remains uncertain. But if a separate lime source was added to the glass melt, the glass would have a different Sr isotopic signature (Brems *et al.* 2013, 229-231). Therefore, it is unlikely that lime was added separately to the glass melt for the majority of the natron glasses in antiquity and the early medieval period.

For plant ash glasses, CaO possibly comes from the plant ashes themselves, since glassmakers used a purer silica source, quartz, which contains less Al_2O_3 and carbonate-free than sand. Another characteristic in plant ash glasses that suggests CaO comes from plant ash is phosphorus. Natron glass has lower phosphorus level because it was aragonite in seashells that provided the CaO and natron is relatively free of phosphorus (Henderson 2013, 286). On the other hand, plant ash glasses have a much higher level of phosphorus which comes with plant ashes which provide CaO in the glass (Henderson 2013, 286, Figure 10.5). It has been demonstrated that different plant species will have different levels of CaO, depending on their geological environments (Barkoudah and Henderson 2006, 306, Table 2). Therefore, glassmakers would require a certain knowledge as to which plants to use that can provide the required level of CaO in the glass.

3.5 Summary:

One of the aims of this study is to identify the raw materials that were used to produce glasses in the late 8^{th} – 14^{th} centuries AD. This chapter shows that through the use of scientific analysis, archaeological and historical evidence, we can investigate what sort of raw materials were used to produce glasses. This is something that cannot be determined using typological analysis to study glasses.

Between 800 BC and AD 800, natron was the main alkali source of glass production in Syria, Israel and Egypt. The Wadi Natrun and el-Barnugi in Egypt were the main sources of natron. However, by the late 8th and 9th centuries AD, the Muslims began to (re-) introduce plant ashes as the principal alkali flux for glassmaking in Syria, Lebanon, Israel and Egypt. It was suggested that the supply of natron was affected by political events, cultural and climatic changes in the region during this period.

Plant ashes were widely available in the Middle East and plant genera that are sodium rich are suitable for glassmaking. It also provides sufficient level of CaO to stabilise the glass. Other alkali sources, such as *reh* and soda-rich evaporate, were also exploited for glass production in southeast Asia and western Turkey respectively during this period.

The main type of silica source for natron glass production was sand. It contains heavy minerals and provides SiO_2, CaO and Al_2O_3 in the glass. On the other hand, quartz was the main silica source for plant ash glasses and is purer than sand sources, with lower concentrations of impurities.

While scientific analysis could provide us with information on the compositions of glasses and raw materials, it cannot tell us how the glass industry was organised, how glasses were traded, why a specific raw material was adopted, and the dissemination of glass production techniques. It will be beneficial to use both scientific techniques and archaeology to find out these answers.

Chapter 4: Organisation of glass production and production sites in the eastern Mediterranean, south Caucasia and east Africa in 8th – 14th centuries AD

4.1 Introduction:

This chapter will look at the organisation of glass production in the eastern Mediterranean, east Africa and south Caucasia in the 8th – 14th centuries AD. It is accepted that the organisation of the glass industry in late antiquity was based on the division of glass production model, which is supported by both the scientific and archaeological evidence. However, as we shall see, a second model of glass production began to emerge in the Middle East in the late 8th and early 9th century AD: regional glass production centres supplied raw glasses to local glassworkshops and these are generally found in Islamic capitals and urban cities. This is also supported by both chemical and archaeological evidence.

We will also look at the archaeological evidence for glass production in the regions. But as we shall see below, only in a limited number of cases did archaeologists discover the physical remains of primary and secondary glass workshops. Most of the time we will have to rely on circumstantial evidence such as glassworking debris, the homogeneity and number of glass vessels and raw glass to determine whether a primary and/or secondary glass production centre existed.

4.2 Division of glass production in late antiquity and early Medieval period:

Since the late Roman period, the glass industry in the eastern Mediterranean was already operating on industrial level. The current consensus is that the structure of the natron glass industry in the 4th – 9th centuries AD was divided into primary glass production centres and secondary glass production centres (Freestone *et al.* 2002, 259; 2008, 31; Henderson 2013, 266). A large amount of raw glasses (measured in tons) was produced in Israel and Egypt in order to supply local glass workshops with glasses across the Mediterranean and Europe.

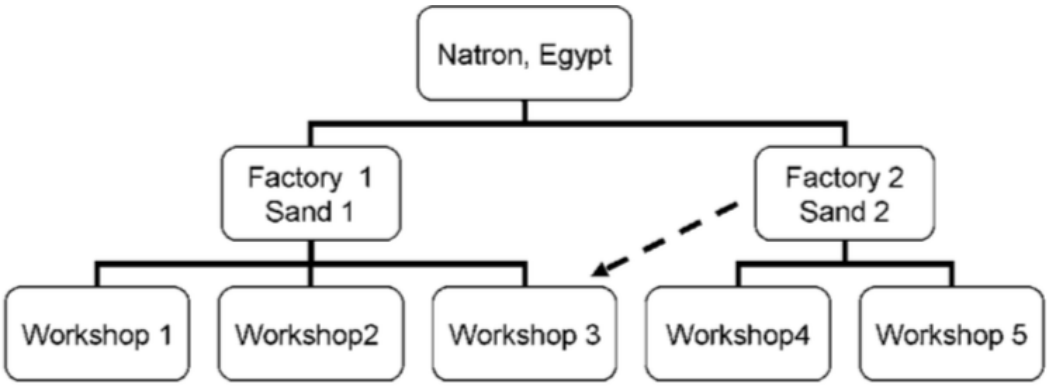


Figure 4.1. A diagram showing the organisation of the glass industry in the eastern Mediterranean in late antiquity (Freestone *et al.* 2008, 31, Fig. 3).

Figure 4.1 shows the structure of the glass industry in late antiquity. Glassmakers in primary glass production centres were responsible for sourcing suitable raw materials and mixing them into raw glass through fritting and melting, and might also be involved in the colouring of glass. This process is called primary glassmaking. Raw glass was then exported to secondary glass workshops across the Mediterranean and Europe (Fontaine and Foy 2007, 236; Freestone *et al*. 2008, 30-31; Freestone 2003, 111; Nenna 2007, 125). Here, glassworkers worked raw glass into glass vessels through glass-blowing. Glass decorations (hot and cold) and glass colouring were also involved in this stage. These processes are collectively called glassworking or secondary glassmaking (Degryse *et al*. 2005, 289).

Recent archaeological excavations in the eastern Mediterranean and historical sources have located a number of primary and secondary glass production centres. Many of these are dated to the 6^{th} – 9^{th} centuries AD. This suggests the division model of glass production continued into the early Medieval period. Chemical analysis of glass and raw materials also help to deduce the possible primary glass production zones. All of these provide strong evidence for the division of glass production model in the eastern Mediterranean in the early medieval period.

4.3 Primary glass production centres in the Israeli coast:

The majority of the primary production centres are located in the Israeli coast outside the cities and villages in the 6^{th} – 8^{th} centuries AD (Figure 4.3). The reason why so

many primary glass production centres were located on the Israeli coast is because of their close proximity to fuel (wood) and raw materials (Gorin-Rosen 2000, 62; Tal *et al*. 2004, 60-61). As mentioned in Chapter 2, sand along the Israeli coast was suitable for glass production, especially for the production of natron glass. By locating near to the coast, this allowed the glassmakers to have easy access to sand and reduced the cost of transportation. The proximity to ports along the Israeli coast would also allow an easy access to natron (possibly from Egypt) at a lower cost.

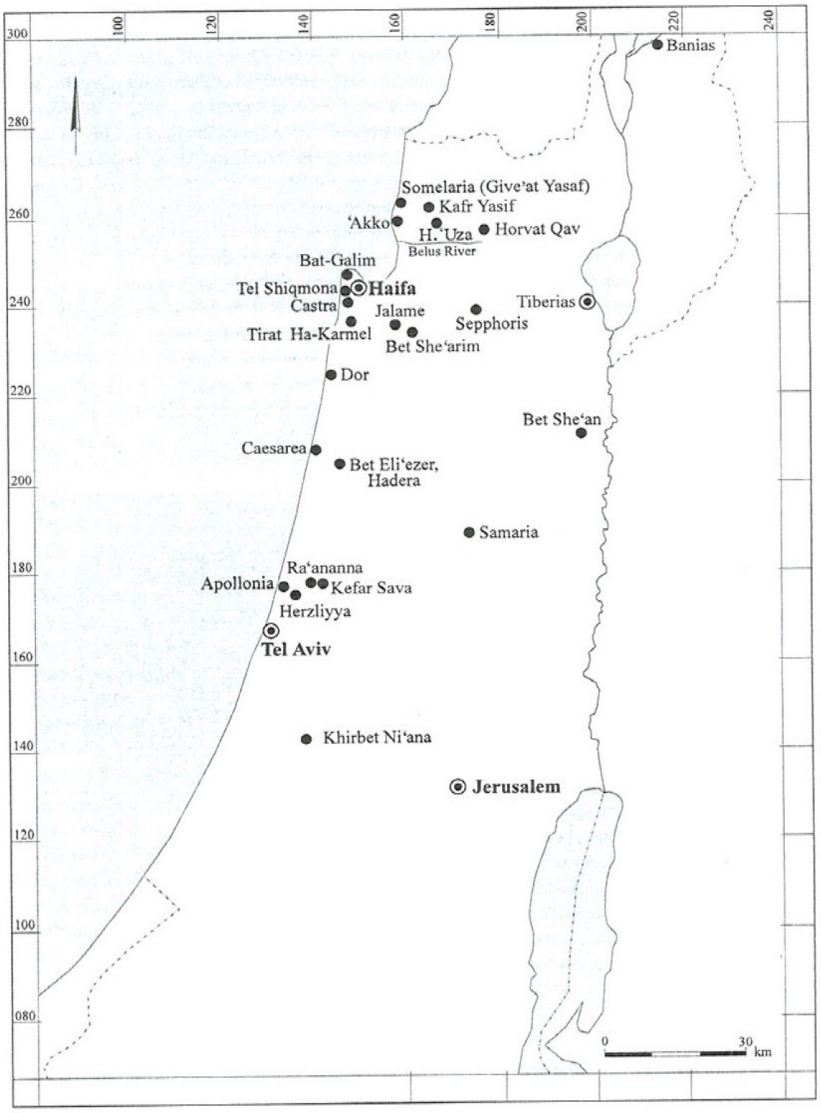


Figure 4.3. A map showing the discovery of primary and secondary glass production centres on the Israeli coast in the 4th – 12th centuries AD. Map is from Gorin-Rosen 2000, 51, Fig. 2.

4.3.1 Apollonia, Israel:

Four glass furnaces dated to 6th – 7th century AD were found in Apollonia in central Israel. Two glass furnaces were discovered by Pinchas Kahane in 1950: (a) one glass furnace in Area N was installed within the courtyard in the southern part of a rectangular building. The glass furnace consisted of the furnace (the firing area) and the glass floor (the melting chamber). (b) Another glass furnace with a square glass floor was found further to the east in Area A in the 1950 excavation (Tal *et al*. 2004, 54-55).

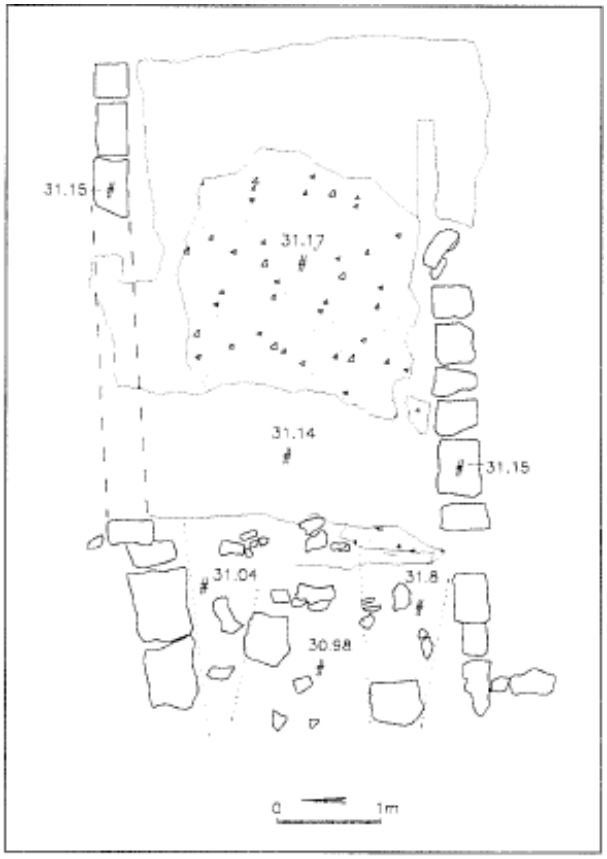


Figure 4.2. Plan of a glass furnace in Area N discovered in the 2002 excavations at Apollonia-Arsuf (Tal *et al*. 2004, 57, Fig. 5).

The third glass furnace (Figure 4.2) was found in Area N in the 2002 excavation which revealed a glass furnace consisted of a firing area with two conical firing chambers which opened onto a melting chamber (Tal *et al*. 2004, 56). The firing chambers were facing west to take advantage of sea winds and to facilitate the airflow in the firing chambers (Tal *et al*. 2004, 58). A glass slab was found in the furnace located in Area N and raw glasses of various colours including transparent blue and greenish blue, yellowish green and yellowish brown were found (Tal *et al.* 2004, 54-58).

Later in the 2006 excavation, the remain of a raw glass furnace was found in Area O. The furnace was built adjacent to a mosaic floor from an industrial installation and was probably dismantled to extract raw glass in the furnace. Only the remains of its southern section were revealed. This furnace was very similar to the one found in Area N. Chunks of raw blue glass were found (Freestone *et al*. 2008, 70).

4.3.2 Bet Eli'ezer (Hadera), Israel:

At Bet Eli'ezer (Hadera) in Israel, 17 glass furnaces of 6th – 8th centuries AD and hundreds of tons of raw glass were discovered. The furnaces (Figure 4.4) were built in the same manner and are similar to the furnace found in Area N in Apollonia: each furnace consists of a firing chamber divided into two compartments with two separate openings and a melting chamber. The openings of the furnaces all face southwest to utilise seasonal winds for circulation in the firing chambers. The fire in the firing chamber spread into the melting chamber where raw materials were mixed and placed beforehand.

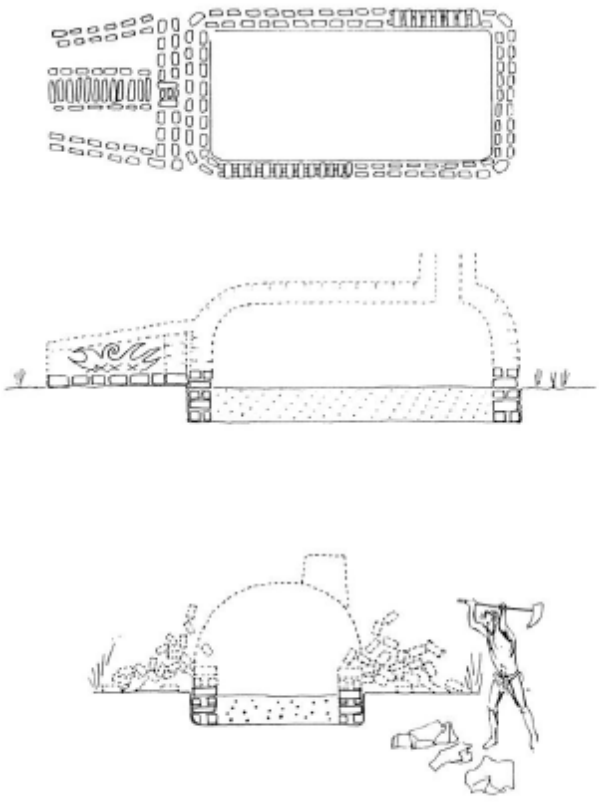


Figure 4.4. The plan and sections of a furnace from Bet Eli'ezer (Gorin-Rosen 2000, 53, Fig. 3).

To extract raw glasses the furnaces would have been dismantled, hence all the furnaces at the site were found destroyed (Gorin-Rosen 2000, 52-54). Much raw glass from Bet Eli'ezer was found in shipwrecks along the coast of Israel, at Caesarea and northward (Gorin-Rosen 2000, 52-54).

4.3.3 Bet She'arim, Israel:

At Bet She'arim in Israel, a tank furnace with a glass slab measuring 3.80 m X 1.95 m X 0.45 m and weighing about 9 tons were discovered in 1958 (Figure 4.5) (Freestone and Gorin-Rosen 1999, 105; Gorin-Rosen 2000, 55). The glass slab and the furnace are dated to the early 9th century AD (Freestone and Gorin-Rosen 1999, 113-116).

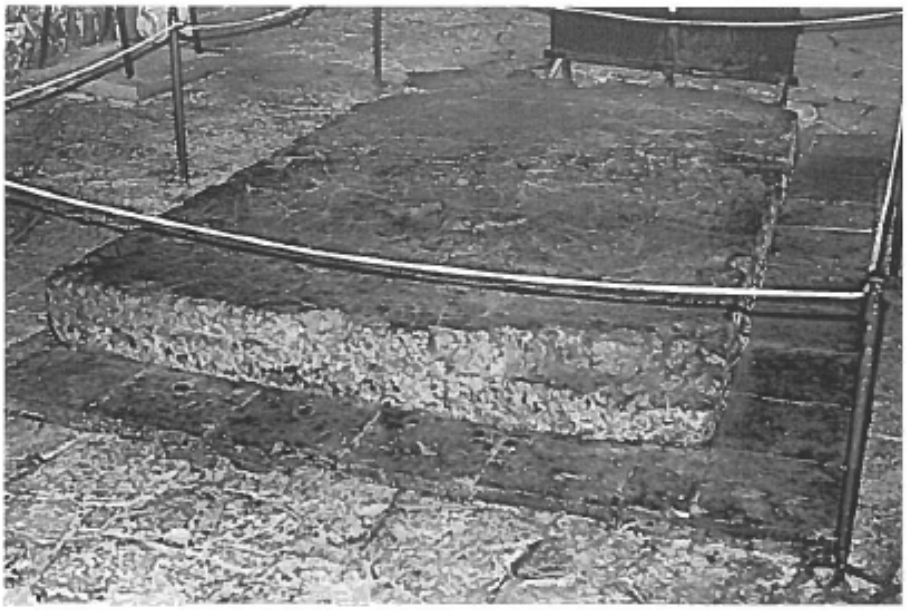


Figure 4.5. The glass slab at Bet She'arim (Freestone and Gorin-Rosen 1999, 106, Fig. 1).

Gorin-Rosen (2000) has suggested that the furnace that was used to produce this glass slab is likely to have a melting chamber with one side used to introduce fuel and the other side with a chimney to enable circulation of hot air in the melting chamber (Gorin-Rosen 2000, 55). It was located inside a cave and the opening of the fire chamber must have faced the entrance of the cave and the chimney was probably located below the hole in the cave ceiling (Gorin-Rosen 2000, 55).

4.3.4 Horbat Biz'a, Israel:

More recently, excavation at Horbat Biz'a, 7 km east of Bet Eli'ezer in Israel, has found evidence of both primary and secondary glass production in a single workshop. The evidence for primary glassmaking was found in Areas A, B and C. This is mainly debris from glass furnaces which includes fragments of glazed bricks, which are probably from the furnaces' walls (similar to those from Bet Eli'ezer), and raw glass chunks. Large amounts of glass vessels and wasters were also found. This suggests secondary glassworking was also carried out in here. These are dated to the late Byzantine – early Umayyad periods (Gorin-Rosen 2012, 49, 59-60). Further research on the site and its materials are needed to see how important Horbat Biz'a was in the Israeli coast, what compositional group(s) of glass it produced and to determine if the workshop produced glasses for regional and/or interregional consumptions.

4.4 Primary glass production centre in Egypt:

There is evidence that primary glass production centre(s) also existed in Egypt and was located close to major rivers such as the Nile. This helped glassmkaers to gain easy access to raw materials and fuel.

4.4.1 el-Ashmunein:

Excavations at el-Ashmunein (the Roman city of Hermopolis Magna) in Egypt have found a 5^{th} - 7^{th} centuries AD glassmaking site at an Antonine period building lying to the north of the main east-west road of Hermopolis (Bimson and Freestone 1988, 237). No remains of glass furnaces were found on the site, but there is evidence of great heat that calcined the limestone floor-slabs and glass waste penetrated the calcined limestone, which suggest it could be a glassmaking site (Bimson and Freestone 1988, 238).

4.5 Secondary glass production centres:

Secondary glass production workshops were responsible for turning raw glasses into glass vessels. Unlike primary glass production centres, many of them were in industrial areas of cities or markets. Glassworkers could easily supply the inhabitants in cities with tableware, lamps, cosmetic containers and windowpanes (Gorin-Rosen 2000, 50). Many examples are found in inland and coastal regions in the Middle East and Turkey.

Excavations in Israel, Turkey, Greece and Egypt have found remains of secondary glass production workshops. However, many are dated to the late Roman and early Byzantine periods. Many more sites are thought to have evidence of secondary glass production based on the discovery of glassworking debris. Nonetheless these provide us with evidence that the natron glass industry was organised according to the division of production model.

4.5.1 Secondary glass production centres in Israel:

In Sephhoris, Israel, archaeologists have found possible remains of a glass furnace, along with glass wastes and vessel shards within a peristyle building. They are dated to the late 6th – early 7th centuries AD (Fischer and McCray 1999, 894; Gorin-Rosen 2000, 57). At Bet She'an (Scythopolis) in Israel, a glass workshop was excavated intact and was located in a row of shops and stalls along the main street. Remains of a glass furnace, glass debris and vessels were found inside the workshop (Gorin-Rosen 2000, 59). At Ramla, Israel, remains of a furnace in the form of glazed and unglazed fired mud bricks were found dated to 6th – 7th centuries AD. Glass working debris, raw glasses and glass vessels were found on site (Tal *et al.* 2008, 81-83). At Somelaria, northern Israel, a complete furnace from the Crusader period (12th and 13th centuries AD) was found. Inside the furnace there were pottery vessels which contained melted glass, which suggest secondary glass production (Gorin-Rosen 2000, 60). At Tiberias, Israel, the excavations did not find any remains of a secondary glass production workshop, but the presence of glass waste and cullet suggests secondary glass production might have been carried out in Tiberias during the Umayyad and 'Abbasid periods (Lester 2003, 158).

4.5.2 Secondary glassworkshops in Egypt:

So far there is only one site where physical remains of a secondary glass workshop was found in Egypt. At el-Ashmunein a primary and secondary glass production workshop existed in the city (Bimson and Freestone 1988, 238). Archaeological excavations in Fustat carried out by the American Research Centre in Egypt discovered numerous fragments of Islamic glass (Pinder-Wilson and Scanlon 1973, 12-30; Pinder-Wilson and Scanlon 1987, 60-71; Scanlon and Pinder-Wilson 2001, 1-134). These finds were

dated to the 8th - 12th centuries AD based on typological analysis. Since many of the pits were disturbed by later activities, it was difficult to secure a definite chronology (Scanlon and Pinder-Wilson 2001, 13-14). No remains of a glassworkshop was found. But medieval Jewish manuscripts (11th – 13th centuries AD) in the Cairo Geniza (a repository where medieval Jewish manuscripts were kept and the room was attached to a synagogue in Fustat) mention that in AD 1125 there was a store for the manufacture of glass and it was located in the 'Street of the Coppersmiths' of Old Cairo, i.e. Fustat (Goitein 1996, 1-2, 83). It is possible that a secondary glass workshop existed in the city of Fustat, or even primary glassmaking was carried out in/around the city based on the discovery of a frit (VA-01) and a raw glass chunk (VA-02).

4.5.3 Secondary glass production centres in the Byzantine Empire:

We have archaeological evidence and historical references that suggest secondary glass production centres existed in the Empire during the 6th – 8th centuries AD. Glass workshops of modest size could have existed in cities in the Byzantine Empire to provide inhabitants with everyday glass objects. On the other hand, large-scale glass production was likely taken place in large workshops in an industrial level.

At Sardis in western Turkey, the discovery of raw glasses, crucibles and drippings in the early Byzantine contexts in the areas of the Synagogue and the Byzantine Shops have suggested that one or more secondary glassworkshop(s) existed during this period, and the workshop could be in the vicinity of this area (von Saldern 1980, 95-96). During the 7th – 8th centuries AD the glassworkshop ceased to operate. Excavations show that it was not until the late 10th century that a glassworkshop(s) began to operate and it continued into the 14th century AD (von Saldern 1980, 98). However, its scale of operation was reduced and restricted to the production of glass bracelets and window glass. The discovery of raw glass in the middle Byzantine context is believed to be used for the production of these products (von Saldern 1980, 101).

Another Turkish site that can provide us with evidence of possible local secondary glass production is Amorium in western Turkey. Again, there were no physical remains of a glass workshop found in the excavations. Only a kiln with evidence of the production of glaze was found (Gill 2002, 264). The excavators believed that the glass workshop,

if one did exist, should be near a pottery workshop (Gill 2002, 264). Several fragments of raw glass, wasters and a rim of a crucible (?) were found in Amorium dated to the early Byzantine period (Gill 2002, 105). They could be used for the production of glass bracelets (Gill 2002, 105).

The Sarachane and Sirkeci excavations in Istanbul have failed to find any remains of glass workshop(s) in the Byzantine capital. Hayes (1992) has suggested that the evidence of glassworking in Constantinople was 'one of discontinuity, with good evidence of 'local' production only in the late Roman period, around the 12th century, and from the late 16th century onwards' (Hayes 1992, 399). But despite the lack of archaeological evidence there is plenty to suggest the city was a major secondary glass production centre in the early Byzantine period. Considering Constantinople was a metropolitan city that was famous for its production of White Glazed Ware which was exported to other regions, and the fact that glaze and glass technology are related to each other, and also considering the size of its population, it is likely a glass workshop did exist in Constantinople to supply glass to its huge population and did not solely rely on imports from other regions for glass vessels (Dark 2001, 65).

Literary evidence such as the miracle collection of St. Photeine (dated to the 11th or 12th century AD) mentioned a glass workshop existed inside Constantinople in the middle Byzantine period. It referred to a glass workshop that caught fire in Constantinople. It describes a fire that started in a glass smelting workshop (*ergasterion huelopsestikon*) on the broad uphill street that led from the Strategion to Hagia Sophia and the Milion and then spread to the area of copper workshops around the Chalkoprateia church (Mango 2000, 202; Talbot 2005, 141). The text suggests a secondary glass workshop existed within the city during 11th – 12th century AD or earlier.

This would explain the production of the large decorated panes in the windows of the Pantokrator Church and the large number of mosaics being produced and exported to Kiev for the cathedral of St. Sophia and to Sicily (Kaplan 2008, 163).

The remains of a 9th century AD glassworkshop was found at Thessaloniki in Greece (Antonaras 2009, 85). The workshop was located inside the ruins of monumental

buildings and is very close to the place where the residence of the governor was in the Byzantine period (Antonaras 2009, 85).

4.6 Medieval Georgia and Pemba Island glass industry in the 10th – 14th centuries AD:

For Medieval Georgia and Pemba Island in east Africa, we currently do not possess much information on whether there were any primary and/or secondary glass production centres in the regions. The glass from these regions is heavily understudied in the study of ancient glass. Therefore, by studying some of the medieval glass finds from Tibilisi and Pemba Island, the author hopes to shed some light on whether glass artisans used local raw materials from Georgia and Pemba Island to produce glass, or relied on imports from the Byzantine Empire, the Islamic East or beyond in the 10th – 14th centuries AD.

4.7 The transportation of natron glass:

According to the division of production for natron glass, after the raw glasses were produced, they were broken up into blocks and transported to secondary glass workshops in the Mediterranean and Europe (Foy *et al.* 2000, 51). Maritime trade was the principle form of glass distribution. Archaeological evidence of shipwrecks has shown that raw glass and/or cullet was transported from primary production centres to secondary glass production centres by ships. Such a practice existed in the Roman period. For instance, tons of raw glasses, along with glass vessels, were found in the late 2nd or early 3rd century AD Embiez shipwreck that was found at the coast of Provence near the archipelago of Embiez in France; raw glasses, recycling glasses and cullets were found in the late 2nd or early 3rd century AD shipwreck at the bay of Ajaccio, Corsica; and the 1st century AD shipwreck of Milet in Croatia was found to have more than 100 kg of blue-green raw glasses (Foy et al. 2000, 52; Fontaine and Foy 2007, 235, 240-242). Many other shipwrecks that contained raw glasses for export were thought to be located along the Israeli coast from Ashkelon to the borders of Lebanon (Bass 2009b, 500).

The most important shipwreck that supports the division of production model of natron glass production in the medieval period is the 10th century AD Serce Limani shipwreck. It contained about three matric tons of glass cullet, in which two tons were raw glass and two-thirds of the other ton were cullets that were misshapen or cracked before they were broken into pieces for transport (Bass 1984, 65; van Doorninck Jr. 1990, 58-59; van Doorninck Jr. 2009, 4). The excavators suggest they were never loaded on the ship in complete vessel forms, but they were cullets to be shipped off to glassworkshops (Bass 1984, 67; Bass 2009a, 18; van Doorninck 1990, 59). Those that were intact and can be reconstructed in complete vessel forms probably belonged to the merchants on board and were used on the ship (Bass 2009a, 18).

The chunks of raw glasses were probably loaded onto the ship as ballast with other heavy merchandise. On the other hand, the broken glasses on the ship were likely to have been carried in baskets as some of it was grouped together in lumps in the shapes of basket interiors (Bass 2009b, 500). It is probable that they were the usual methods of carrying glasses on ships (Bass 2009b, 500).

This also suggests ports were acted as key hubs for the supply of glass during the Roman period (Wilson *et al.* 2012, 377). Many of these port cities, such as Alexandria in Egypt, Beth She'arim, Apollonia, Beth She'an, Caesarea Maritima and Jalame in Israel, and Aquileia and Puteoli in Italy have found evidence of secondary glass production workshops (Wilson *et al.* 2012, 379).

4.8 Alternative glass production model in the 9th – 12th centuries AD? Regional glassmaking and glassworking:

There is evidence that glass production had become decentralised from the early 9th century AD onwards in the Middle East (Henderson *et al.* 2016, 141). Raw glasses were made using local raw materials and glass vessels were either produced in the same workshop or in workshops within the same region as the primary production centres. This model has been described by medieval and early modern writers. This model suggests that the glass vessels from these workshops would have a specific chemical fingerprint and their sources of materials can be identified (Freestone *et al*. 2008, 30).

Many of these regional glass production centres were located in inland area and in major cities or ‘Abbasid capitals.

4.8.1 Scientific evidence of regional glass production in the late 8th – 15th centuries AD:

Recent trace element analysis of plant ash glasses dated to the late 8th – 15th centuries AD by Henderson *et al*. (2016) provides evidence of the decentralisation of glass production in the Middle East. They show that plant ash glasses were produced in different regional production zones with production sub-zones associated with urban centres. Many of these were in inland regions. Israel was no longer the only region that produced raw glasses. The various concentrations of Cr, Fe, La, Zr and Ti (mainly derived from sand) in glasses provide a clear distinction between glasses found and made in the Israel, Syria, Egypt, Iraq and Iran (Henderson *et al*. 2016, 141).

For instance, Iranian and Iraqi glasses (e.g. 9th – 10th centuries AD Nishapur and Samarra respectively) tend to have higher Li/K ratios than the Levantine glasses. Many of these samples were colourless cut decorated vessels and the analysis confirms the aged-old argument by archaeologists that cut decorated vessels were produced in these regions (Henderson *et al.* 2016, 142). It has also been noted that Egyptian glasses (e.g. Cairo) have a higher Cs/K ratio than glasses from Lebanon (e.g. Beirut) and Syria (e.g. Damascus). And it also confirms that the 14th – 15th century AD Egyptian mosque lamps, which were attributed to a Cairo production, were made from raw materials in Egypt (Henderson *et al*. 2016, 142). The decentralisation of plant ash glass production might relate to the fact that plant ashes were more readily available to local glassmakers in inland regions than natron, which could only be found in specific areas in Macedonia (e.g. Lake Pikrolimni), Egypt (e.g. Wadi Natrun) and Turkey (e.g. Lake Van) and would require glassmakers to import it by maritime transport. Therefore, glassmakers of natron glass in the Levantine region, especially coastal regions, would have had easier access to natron due to their proximity to ports.

4.8.2 Regional glass production centres in Syria:

The most concrete archaeological evidence of this model comes from al-Raqqa in Syria. Its glassworkshop was located inside the industrial zone. Scientific and archaeological evidence suggest that al-Raqqa had both primary and secondary glass production centres, supplying raw glass and glass vessels to the 'Abasid capital. Both raw glasses and glass vessels were produced on the same site. Strontium analysis of plant samples and glasses from al-Raqqa shows that they were made with local plant ashes (Henderson *et al.* 2005, 419). It is likely that many of these glasses were intended for local consumption. As we shall see in Chapters 7 and 8, many of the glass vessels from Tell Abu Ali, a settlement with a glassworkshop inside al-Raqqa, have identical chemical compositions to glasses from the workshop at Tell Zujaj in al-Raqqa.

Aleppo is thought to have a primary glass production centre during the Ayyubid period (12^{th} – 14^{th} centuries AD). An inhabitant of Aleppo, Yaqut, mentioned that glassmakers in Aleppo in the 12^{th} - 13^{th} centuries AD had used fine white sands from Jabal Bishri, which is located on the south side of the Euphrates between al-Rasafa and Palmyra, to produce raw glasses (Henderson 2013, 267). It is also thought that secondary glassworkshop(s) also existed in Aleppo. The cosmographer mu'jam al-buldan mentioned that the suq al-marzuqin (market of enamellers) sold amazing decorated objects (Henderson 2013, 267). Glasswares such as cylindrical beakers decorated with applied thread decoration, and enamelled glasses were thought to be made in Aleppo, along with other Syrian cities such as Damascus, Hama and al-Raqqa (Carboni 2001, 184, 323-324, 329, 331). At present there is no archaeological evidence to suggest a glassmaking centre was present in Aleppo during the Ayyubid period.

In Hama, excavations have found a large quantity of 12^{th} – 14^{th} centuries AD glasses, which could suggest the presence of local glass production (Henderson 2013, 267-268). Damascus is thought to have a primary and/or secondary glass production centre. Trace element analysis of glasses from Damascus suggests Damascus glasses have higher Cr/La and lower 1000Zr/Ti ratios. These are distinguished from glasses produced in northern Syria such as al-Raqqa, which have an even higher Cr/La ratio (Henderson *et al*. 2016, 139-141).

4.8.3 Regional glass production centres in Iraq:

The Arab geographer Ibn Khordadbeh (AD 820 – 912) mentioned that a city named al-Qadisiyya was located on the left bank of the Tigris River and was three *farsakhs* (about 9 miles) from Samarra. In the 13th century AD, another Arab geographer, Yaqut al-Hamawi (AD 1179 – 1229), mentioned that al-Qadisiyya was 'a large village… where glass is made' (Barthold 1984, 201-202; Northledge 2005, 93). In the 1986 archaeological survey evidence of glassworking (glass waste and glass vessels) has been discovered in site N1, which was a Tell and was located on the bank of the Tigris (Northedge and Falkner 1987, 149; Northedge 2005, 82-83, Fig. 33). The site is dated from the Sassanian period to the 13th or 14th centuries AD (Northledge 2005, 93). It has also been noted that a glass kiln existed in al-Qadisiyya during the Sassanian period (Northledge and Kennet 2015, 498).

Brigadier General R. Pope Hennessy found seven pieces of furnace glass (C.396-1919; C.396A-1919; C.396B-1919; C.396C-1919; C.396E-1919; C.396F-1919) from an ancient kiln and they were given to the Victoria and Albert Museum as a gift. The museum curator B. Rackham wrote in 1919 that these glasses were 'proof of the site of an ancient (Islamic?) glassworks near Samarra'. The historical and archaeological evidence suggest al-Qadisiyya (Area N) in Samarra was a primary glass production centre dated as early as the Sassanian period and continued to operate in the 13th /14th centuries AD. It is very likely that the furnace glasses found by Pope Hennessy were dated to the Islamic period (possibly 9th – 10th centuries AD).

Recent trace element analysis of glasses from Samarra shows that a unique chemical composition of the glasses (high Li/K ratio, low Cs/K ratio), almost certainly made in Samarra, was used to produce mould-decorated, cameo decorated, scratch decorated and pinch decorated vessels and wall plaques. They are distinctive from glasses made in Nishapur in Iran, the Levantine region, Egypt and Syria (Henderson *et al*. 2016, 139). Although no remains of Islamic glass furnace(s) were discovered in the city, based on the evidence of glass waste and vessel fragments, the unique composition of the glasses and the fact that the city had designated industrial zones (Milwright 2010, 146), it is possible that Samarra was a major centre of glass production during the 9th – 10th centuries AD.

In Nishapur, in the northeastern province of Khurasen, numerous glass finds were found during the excavations. Although no remains of a glassworkshop was found in the city, at Qanat Tepe an industrial zone where pottery and glaze kilns were found to be in operation until the end of 12th century AD. Wasters, lumps of transparent glass or glaze, spurs and alkaline-glazed wares were found to be associated with glaze production (Kröger 1995, 16-17). This could suggest a glassworkshop was probably present in the region.

Nishapur was an important city in the eastern part of Iran on the Silk Road during the Islamic period. This could also increase the possibility that a glass production centre existed in the region (Henderson 2013, 268; Kröger 1995, 9). Moreover, the homogeneity of the glass fabrics, the vessel shapes, the similarities in design and style of wheel-cut vessels, and the styles of calligraphy on the inscribed glass may indicate that they were all produced in one region (Kröger 1995, 20). Recent trace element analysis confirms that the glasses used to made the colourless cut and pinch decorated vessels in Nishapur came from the eastern zone in Iraq/Iran (Henderson *et al*. 2016, 142).

4.8.4 Regional glass production centres in the Byzantine Empire:

At present, there is no archaeological evidence to suggest that primary glass production centre(s) existed within the Byzantine Empire. However, recent chemical analysis of raw glasses and glass vessels from Pergamon, Sardis and Aphrodisias in western Turkey shows that glassmakers in the region may have used a completely different alkali source for glass production in the middle and late Byzantine period (Brill 1968; Dussubieux *et al.* 2010, 1649, Table 3; Schibille 2011, 12). It is characterised by high alumina and boron contents (Brill 1968; Dussubieux *et al.* 2010, 1649, Table 3; Schibille 2011, 8-9).

Tite *et al.* have suggested that the hot springs in western Asia Minor, namely Afyon-Gazligol and Urganli, which are charactersied by elevated boron contents, could have been exploited for the production of coloured and colourless glass in Pergamon in the middle and late Byzantine period (Tite *et al.* 2015, 63-64). This implies a primary and secondary glass production centre probably existed in Pergamon (or its surrounding

region) in the middle and late Byzantine periods (Schibille 2011, 12). Further research is needed to determine whether Pergamon was a major glass production centre that supplied glasses to cities in western Turkey during this period.

4.8.5 Regional glass production centre in Lebanon:

Textual sources in Arabic, Hebrew and Latin mentioned Tyre in southern Lebanon as a major centre of glassmaking in the 10^{th} – 13^{th} centuries AD (Carboni *et al.* 2003, 139-147). The 1940s – 1950s and subsequent excavations at Tyre have revealed four glass furnaces within a walled complex at the south and east of the main colonnade, which was located north-west of the Roman bath. The southern wall of the complex was built atop the wall that formed the north perimeter of the main Roman bath complex (Aldsworth *et al.* 2002, 49-51, Figs. 1-2).

Furnace 1 (Figure 4.6) consists of a melting chamber with a rectangular base of a mortar-lined tank and part of a 'loading floor'. The 'loading' floor was the area where raw material required for the melt was collected and loaded into the tank, and also as a staging area for glass extracted from the tank. A possible firing chamber(s) was located at the east end of the melting chamber and was truncated by a modern path (Aldsworth *et al*. 2002, 51-52). The stone walls and earth fills helped to support the furnace and to retain heat generated in the firing chamber (Aldsworth *et al*. 2002, 62).

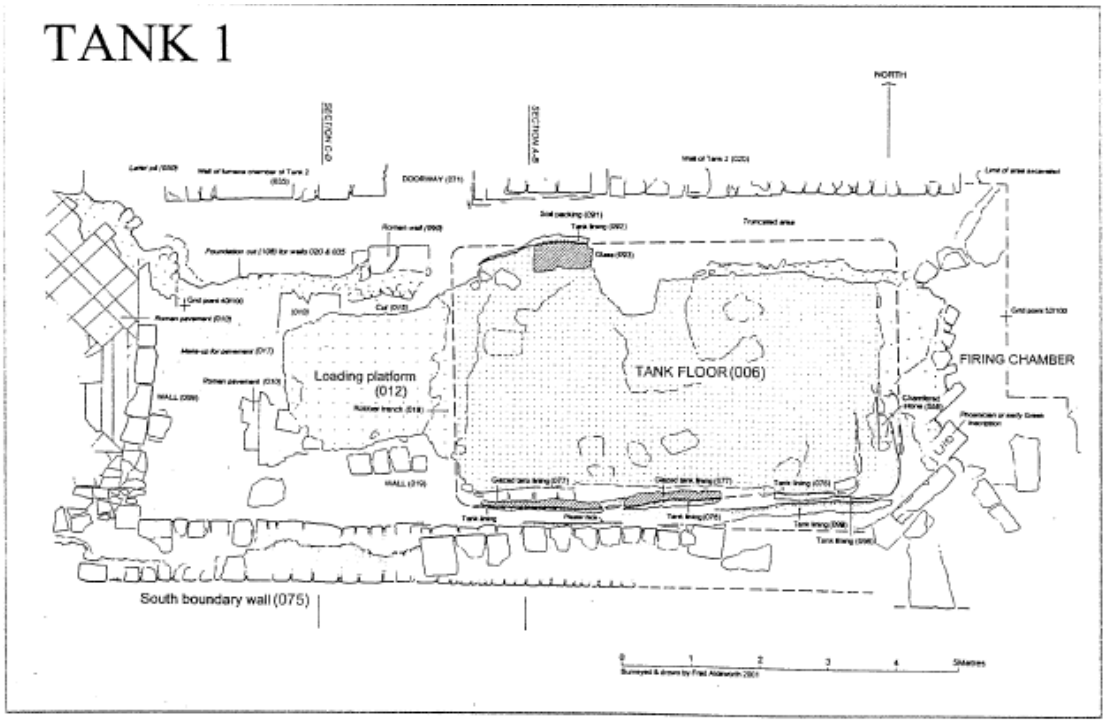


Figure 4.6. The plan of Furnace 1 in Tyre (Jennings *et al*. 2001, 224, Fig. 7).

Furnace 2 (Figure 4.7) consists of a melting chamber with an almost complete tank floor. Two firing chambers were located at the western side of the melting chamber. The presence of a mortar spread containing small glass lumps on top of Wall 020 suggests the presence of a 'loading floor' at the eastern side of the melting chamber (Aldsworth *et al*. 2002, 55-59).

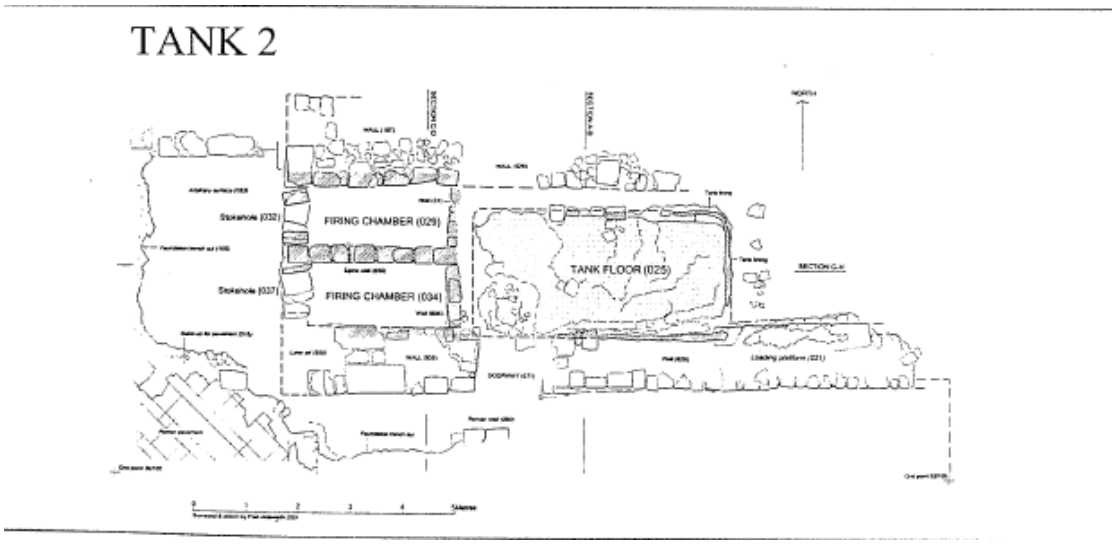


Figure 4.7. The plan of Furnace 2 in Tyre (Jennings *et al*. 2001, 226, Fig. 13).

Furnaces 3 and 4 (Figure 4.8) were located at the west side of the complex. Very little of these furnaces survived. Remains of the melting chambers with tank floors were

found. Neither of the furnaces has any evidence of firing chambers and loading floors (Aldsworth *et al*. 2002, 59-61).

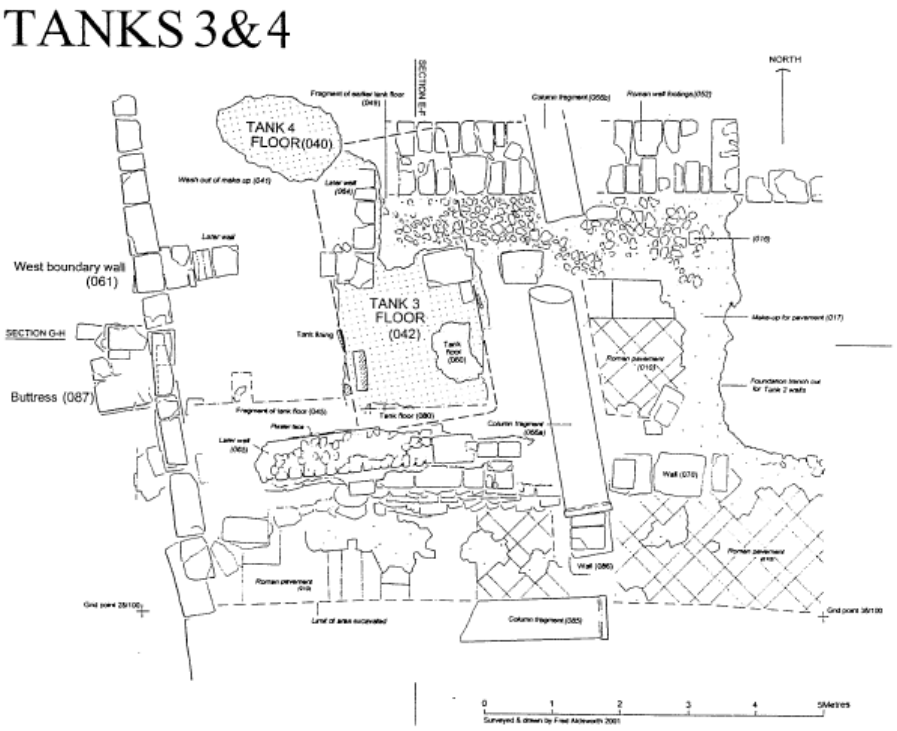


Figure 4.8. The plan of Furnaces 3 and 4 in Tyre (Jennings *et al.* 2001, 230, Fig. 19).

Glassmaking waste was also found at the north and west of the main colonnade (Aldsworth *et al.* 2002, 49-50, Fig. 1). Many of the raw glasses (weight about one-third of a ton) found at Tyre were produced locally in a one-stage melt (Aldsworth *et al.* 2002, 64). No glass vessels were found to be made on the site, which suggests Tyre was a primary glass production centre in the region (Aldsworth *et al.* 2002, 65). The furnaces were dated to the 10th – 11th centuries AD or earlier (Aldsworth *et al.* 2002, 66). Recent chemical analysis of the furnace raw glasses suggests they were made using plant ashes as a source of soda, which suggests the glass factory was in operation after the 9th century AD and not earlier (Freestone 2002, 68). The chemical composition of the glasses is unique when compared with glasses from Syria such as the 11th century AD Tell Fukhkhar from al-Raqqa: the former has a higher concentration of CaO than the latter (Freestone 2002, 70-71).

4.8.6 Transportation of glass under the regional glass production model:

Most of the regional glass production centres in the Middle East and Turkey were located in inland regions. In order to export raw glasses to secondary glass production centres, alternative transport would have to be used. Transportation in inland regions would have involved the use of river networks to transport raw glasses and glass vessels. Also, road and pilgrimage routes, such as the Damascus – Hijaz route, were used for commerce and pilgramage. Pack animals such as camels and mules appeared to be the main types of inland transport for goods. Wagons and carts were rarely used (Walmsley 2009, 465). Caravans would also have been an alternative way of transporting glass between cities and regions. It was used as an alternative transport and trade during winter when the sea was closed to the ships. Caravans were used in summer as ships used to sail in convoys mainly in spring and autumn. Medieval Jewish manuscripts in the Cairo Geniza recorded that at least three caravans used to set out for the East from Qayrawan in Tunisia during winter and a caravan from Alexandria in Egypt to Qayrawan in Tunisia in late August (Goitein 1996, 277).

4.9 Summary:

This chapter shows that in the 4th – 9h centuries AD the structure of the natron glass industry was divided into primary glass production centres and secondary glass production centres. The primary glass production centres were mainly located on the Israeli coast outside cities and villages (e.g. Apollonia, Dor, Bet She'arim), allowing them to have easy access to fuel and sand, and natron from Egypt. Raw glasses were produced these centres and were broken up into blocks and transported to secondary glass production centres in the Mediterranean and Europe via maritime trade routes. This is shown by shipwrecks with raw glasses, recycling glasses and cullets.

By the 9th century AD, glass production became decentralised in the Middle East. Regional primary glass production centres, usually located in urban cities in inland regions, supplying raw glasses to secondary glass production centres located in the same regions.

Regional glass production centres appeared in Syria (e.g. al-Raqqa, Aleppo and Damascus), Lebanon (e.g. Tyre), Israel (e.g. Banias), Iraq (e.g. Samarra and Nishapur)

and Byzantine western Turkey (e.g. Pergamon and Sardis).

Raw glasses were made using local raw materials and glass vessels were either produced in the same workshop (e.g. al-Raqqa in northern Syria) or in workshops within the same region as the primary glass production centres.

Chemical analysis of glass from Syria, Israel, Lebanon, Iraq/Iran, Egypt and western Turkey seems to support this model. It shows that glass production centre in each region produced glasses with a unique composition. It will be interesting to see if different regional glass production centres produced different glass vessels with unique chemical compositions.

Chapter 5: Archaeological sites

5.1 Introduction:

The samples that are used in this thesis came from a number of archaeological sites which are located in the eastern Mediterranean in modern Turkey, Syria, Egypt and Iraq. Some also derive from sites in modern Georgia in the Caucasus and Pemba Island in Zanzibar. By studying glasses from these sites the author hopes to answer the research questions stated in Chapter 1.

5.2 al-Raqqa, northern Syria:

Al-Raqqa is the most well-known and well-excavated site that has produced evidence of both primary and secondary glass production dated to the early Islamic period. The site is located in north-central Syria on the left bank of the middle Euphrates, at the junction of its tributary the Nahr *al*-Balikh (Figure 5.1) (Challis *et al.* 2004, 140; Henderson 1999, 225; Henderson *et al.* 2004, 440; Meinecke 1995). It was briefly an imperial residence for the 'Abbasid caliph Harun al-Rashid (AD 796-808). Like Samarra, it had been divided into different industrial zones to include pottery and glass production and lasted until its abandonment in the mid-13th century AD when the Mongols invaded Syria (Heidemann 2006, 38-43; Henderson *et al.* 2005, 130-131).

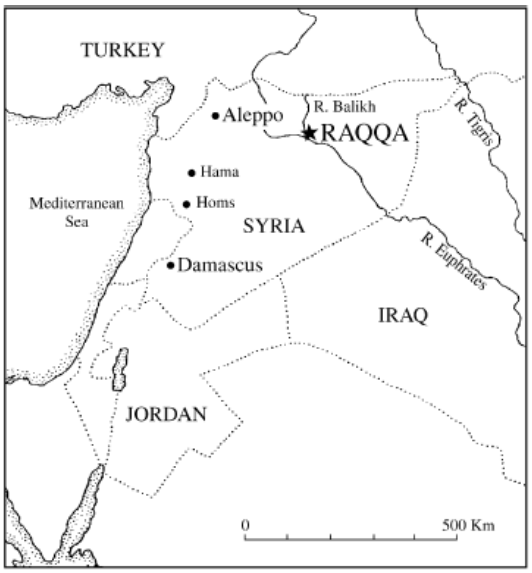


Figure 5.1. A map showing the location of al-Raqqa (Henderson *et al*. 2004, 440, Figure 1).

The excavations at the 3 km industrial area between al-Raqqa and al-Rafika (Figure 5.2) revealed a series of tells: Tell Aswad (late 8th and 9th centuries AD), Tell Zujaj (late 8th - 9th century AD), Tell Fukhkar (11th century AD), Tell Belor (12th century AD) and Tell Abu-Ali (9th century AD). A large quantity of archaeological materials including glass, pottery and glazed-pottery were found in these tells (Heidemann 2006, 40; Henderson 1999, 226; Khalil and Henderson 2011, 237-238). At Tell Zujaj, a glass workshop dated to the late 8th - 9th century AD was discovered. Three phrases of activity were found. The later phase represents the later workshop. The excavators have found a partly-destroyed plaster floor at the south-east of the site and the foundations of two small vitrified structures at the northern end of the site, which could have functioned as glass fritting ovens (Henderson 1996, 60; 1999, 229; 2000, 78).

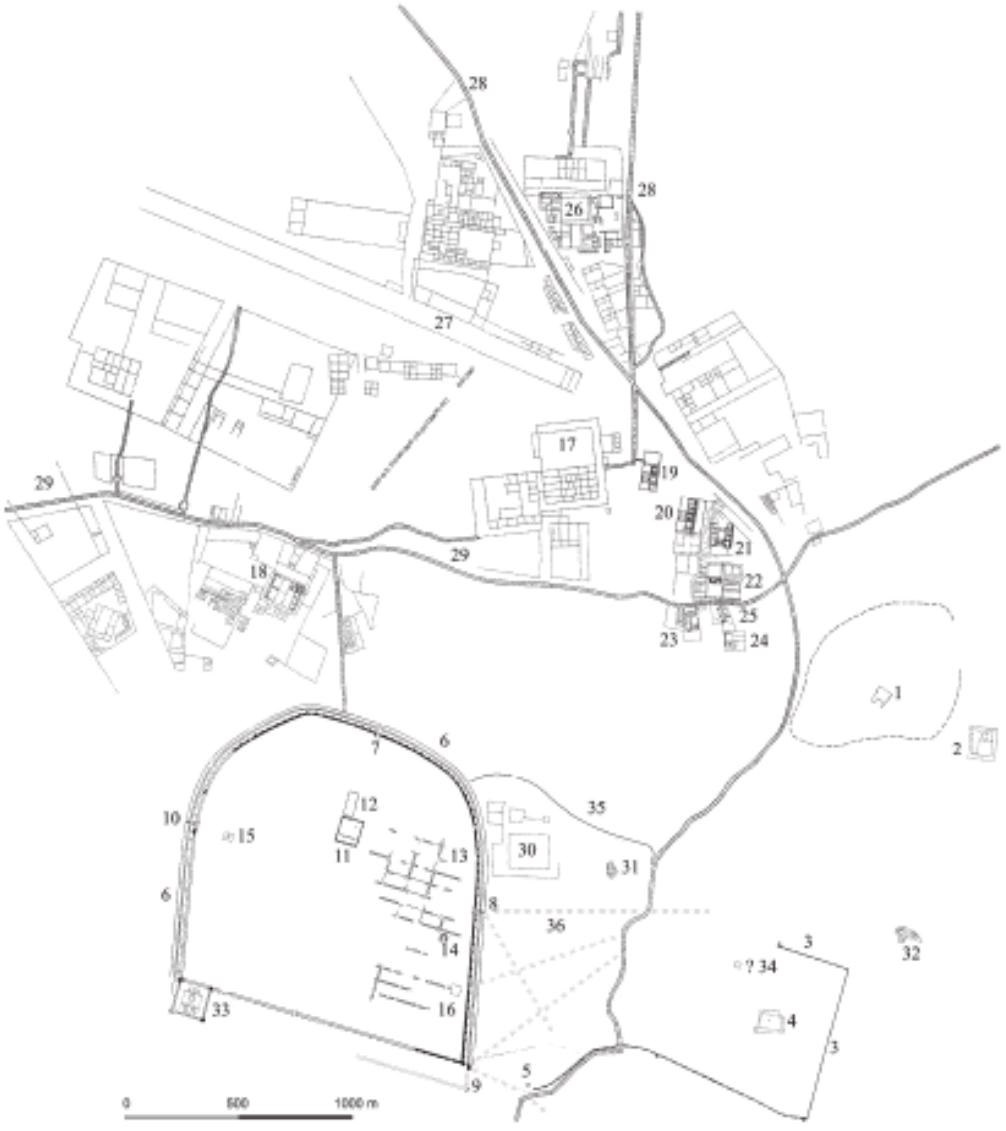


Figure 5.2. A map showing the plan of the city of al-Raqqa. It should be noted that no. 31 is Tell Zujaj and no. 32 is Tell Aswad (Heidemann 2006, 36, Map).

A glass furnace of the later phase was found to be located on the site. In the robbed pit a range of materials include charcoal, soot, burnt bone and glass fragments (some melted) was found and they could belong to the lowest chamber of the glass furnace. This was probably a single chamber glassworking furnace. Other furnaces were destroyed, and their remains, which include destroyed furnaces (furnace bricks), glass dribbles, glass moils, glass frits and possible evidence of glass casted into blocks of at least three different sizes, were found in pits located in the central, eastern and southern parts of the site: these were the remains of tank furnaces with raw glass still attached to the tons of furnace bricks discovered (Henderson 1996, 60; 1999, 226; 2000, 78). The discovery of glass frit, frit ovens and evidence of glassworking (moils and dribbles) suggests the workshop at Tell Zujaj was a primary and secondary glass workshops (Henderson 2000, 38; 2013, 18).

The middle phase of activity is characterised by the presence of a glass workshop (Figure 5.3). The remains of four furnaces were found in the north-west, north-east and south-east of the workshops (Henderson 1996, 60-61, Fig. 7.2; 1999, 226-227, Figure 2). Each of the furnaces was small with an internal diameter of 75 cm. It was suggested that if all the furnaces were operated at the same time, a large amount of glasses could be worked in these furnaces. The large amount of glass finds on site suggested that the glassworkers were able to control the production of glass efficiently using these furnaces (Henderson 1996, 61; 1999, 228; 2000, 80). Furnace 1 is located in the south-east corner of the room and it was a three-chambered glass furnace. Part of the clay dome belonging to the roof of the upper chamber and the remains of the floor of the upper and middle chambers were found. The lower chamber (firing chamber) was characterised by a charcoal-rich black fill mixed with ash. An annealing chamber in the shape of a semi-circle was located at the back of the furnace (Henderson 1996, 60; 1999, 226; 2000, 78).

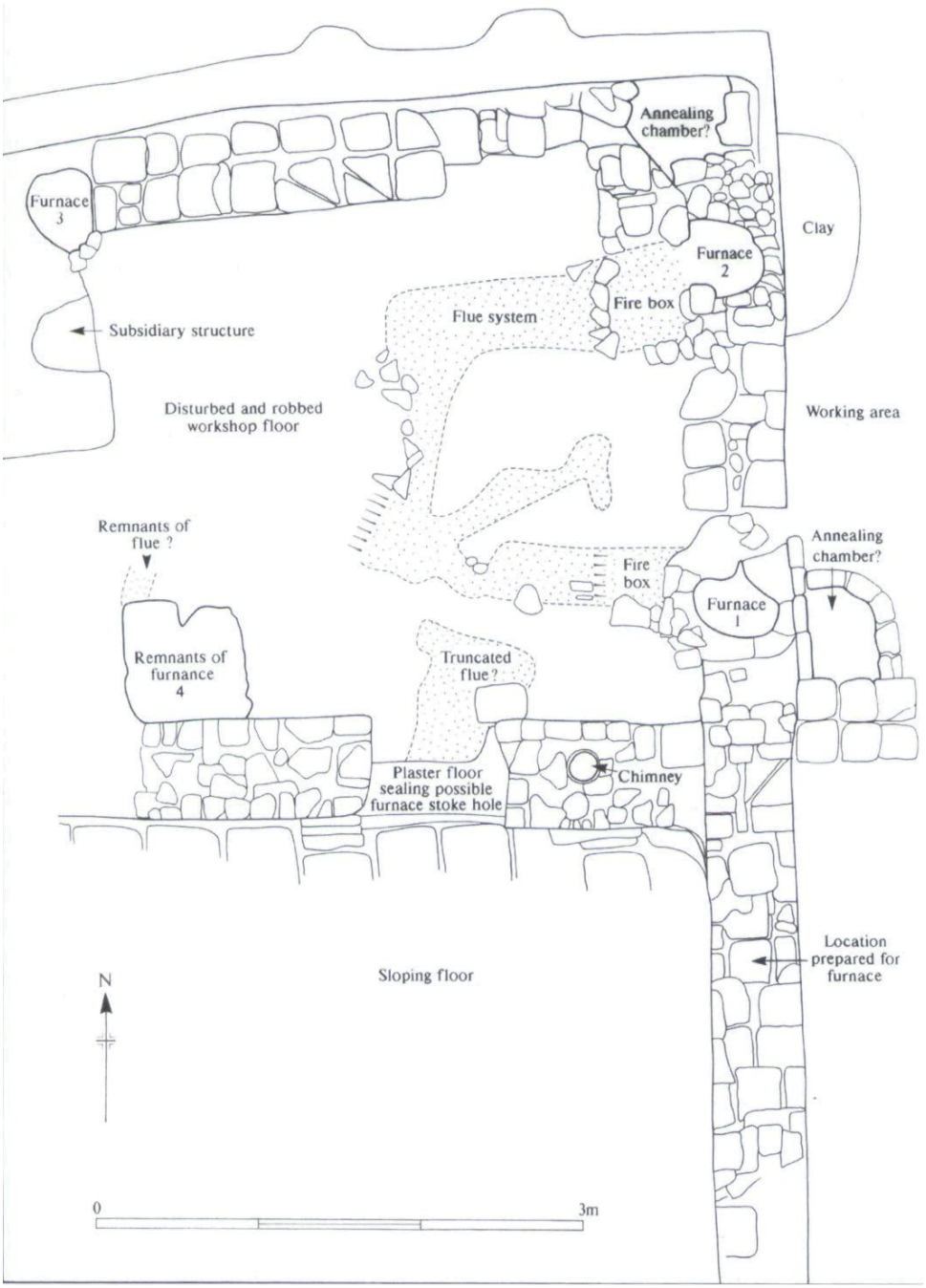


Figure 5.3. The plan of the late 8th – 9th century AD glass workshop at Tell Zujaj in al-Raqqa, Syria (Henderson 1999, 227, Figure 2).

Furnace 2 is located in the north-east corner of the sie (Figure 5.3). The excavators believed that it was a beehive-shaped furnace. An annealing chamber was also found adjacent to Furnace 2 (Henderson 1996, 60; 1999, 226, 228, Fig. 3; 2000, 80). Furnace 3 (Figure 5.3) is a three-chambered furnace that was located in the north-west corner of the workshop. A subsidiary structure was found south of the furnace and thought to be a firing chamber (Henderson 1996, 60; 1999, 226-228, Fig. 2; 2000, 80). Furnace 4

(Figure 5.3) is located at the south-western corner of the workshop and only the foundation of the furnace was discovered (Henderson 1996, 61; 1999, 228; 2000, 80). A possible furnace was found to be located in the centre of the southern wall (Henderson 2000, 78). Apart from the furnaces, a centralised flue system for the furnaces was found. A flue system allows the furnace to retain a temperature as high as 1000 ^{o}C. In addition to a flue system, a bellows emplacement was found in front of the fire box of Furnace 1. This allowed the glassworkers to raise the temperature of the furnace to above 1000 ^{o}C if required (Henderson 2000, 81).

The early phase of the site was the hypocaust where *pilae* (floor supports) were found. Therefore, the subsequent glassworkshops were built on top of this hypocaust system (Henderson 1996, 62; 1999, 229). Hundreds of glass vessel fragments, pulls of glass, rods of glass, dribbles, drops, moils, frit and raw glass were found in Tell Zujaj (Henderson 1995, 435; Henderson 1999, 226-230).

Glass fragments of 9th century AD were discovered at Tell Belor, with 11th century AD raw furnace glasses being recovered at Tell Fukhkhar (Henderson *et al.* 2004, 441). Recent rescued excavations at Tell Abu Ali in 2010 have found an *in situ* rectangular tank glass furnace and a possible circular glass furnace (Khalil and Henderson 2011, 238). The site is dated to the 9th century AD and is located at the eastern end of the industrial complex. The remain of the tank furnace measured 3.7m x 2m. Slabs with translucent green and purple glasses were used on the walls and floor of the rectangular furnace. This rectangular furnace appears to be the first to be discovered in the Islamic world (Henderson 2013, 271; Khalil and Henderson 2011, 238-239).

Two phases were found in the tank furnace. This is represented by two courses of flooring slabs in different sizes. It is possible the phase 1 floor slab was melted and removed before the phase 2 floor was built (Khalil and Henderson 2011, 239). Also, the phase 2 floor was covered with raw glasses adhering to the top and bottom surfaces. This is because glass from the upper surface of the lower floor was melted onto the lower side of the upper floor. Therefore, we have two phases of activity in the rectangular furnace (Henderson 2013, 271; Khalil and Henderson 2011, 239).

During phase 1 a forced draft system was probably installed and below the phase 1 floor a chamber was built for fuel, charcoal fragments and olive stones were found in the chamber (Khalil and Henderson 2011, 240). Phase 2 of the furnace is different from phase 1 because a downdraft system was used in the furnace. A large heating chamber underneath the floor of the furnace provided the heat which came up between the two walls of the furnace using a chimney. The walls were acted as a flue and the heat was reflected off the roof of the furnace down onto the surface of the glass batch (Khalil and Henderson 2011, 240).

A possible circular glass furnace was found in a level above the floor of the tank furnace (Khalil and Henderson 2011, 241). The floor was also made from slab like the rectangular tank furnace. The excavators suggest that the remains could be part of a circular furnace or an apsidal-ended of the tank furnace. If it is a circular furnace, it could be a beehive-shaped three-chambered furnace that was used to reheat raw glass inside crucibles for secondary glassworking (Henderson 2013, 272; Khalil and Henderson 2011, 241). However, deep purple and green raw glasses were found attached to the furnace floor of the circular furnace and there was no sign that it was used for burning fuel. Therefore, it has been suggested that the furnace was used to heat glasses. It is even possible that raw materials were fused to make raw glasses in this furnace (Henderson 2013, 272-273; Khalil and Henderson 2011, 242).

The above evidence suggests that al-Raqqa was a centre for both primary and secondary glass production, supplying glass for local consumption and further afield during the late 8th – 12th centuries AD with its glassworkshops at Tell Zujaj and Tell Abu Ali. This was made possible as the ‘Abbasid caliph al-Rashid had made al-Raqqa the capital of the caliphate in the early 9th century AD. Thus, glassmakers and glassworkers were brought in from different regions to the new capital to produce glasses and facilitating the changing use of raw materials, experimenting with the use of plant ash as the alkali source to replace natron.

5.3 al-Mina, southern Turkey:

Al-Mina is located in the modern day Hatay province of southern Turkey. It was an important medieval site and was excavated by Sir Leonard Woolley in 1936 and 1937

(Lane 1938, 19; Woolley 1937, 4; Vorderstrasse 2005, 1). The word al-Mina literally means 'the harbour' in Arabic and was first used by Sir Leonard Woolley in 1938 (Lehmann 2005, 61). In 1936 Sir Leonard Woolley had begun to excavate at the site of Tal Sheikh Yusuf, a small mound at the mouth of the Orontes and found an important harbour site dated to the Iron Age (Lehmann 2005, 61).

Under the 'Abbasid caliphate al-Mina functioned as a river port on the Orontes and was connected to the city of Antioch and was near to the city of Aleppo in the 6th and 7th centuries AD. It was vital for distributing goods to Aleppo and Antioch (Lane 1938, 21; Vorderstrasse 2005, 12, 30). The excavators believed that the port went out of use after the Islamic Conquest in the mid-7th century AD.

It has been suggested by Leonard Woolley that the site was not occupied throughout the 8th century AD and only reoccupied in the mid-9th century AD. Buildings of 9th – 10th century AD were found and were probably located south of the limits of the excavations. These buildings were of a simple type with an irregular layout (Lane 1938, 25; Vorderstrasse 2005, 69). Judging by the increased quantities of glazed pottery (unglazed pottery was discarded by Woolley and Lane during the excavations) and glasses found in al-Mina, the site was larger than the excavated area and economically active during this period (Vorderstrasse 2005, 69).

Several circular rubbish-pits of 9th – 10th and 13th centuries AD were found. It is not known if these pits were rubbish pits or used for other purposes such as storage or ritual activity. These pits could have been in used for hundreds of years (Vorderstrasse 2005, 21). Finds from these pits include glazed pottery such as the glazed relief ware of Coptic, Persian and Chinese influences, unglazed pottery and fragments of glass vessels that were dated to as late as the 12th century AD. Many of these are now in the British Museum and Victoria and Albert Museum in London, United Kingdom and the Antakya Museum in Turkey (Lane 1938, 25, 31, 33-34; Woolley 1937, 5; Vorderstrasse 2005, 20).

Pottery and glass found in al-Mina can help us to understand the relationship between al-Mina and other regions in the 'Abbasid Caliphate in the 9th – 10th centuries AD. According to Lane (1938) a greenish-yellow type of lustre-ware, splashed ware from

Iraq and Iran were found in the excavations, which shows that trade between Iraq, Iran and al-Mina started from the 9th century AD and continued into the 10th century AD. It could have been purchased by local elites who could not afford Chinese pottery and bought locally produced (such as unglazed white ware) wares and imported Chinese influenced glazed pottery from Iraq to identify themselves with the 'Abbasid court (Lane 1938, 21, 28,36; Vorderstrasse 2005, 75-77).

In terms of the glassware, Lane (1938) has reported that the majority of the glass was found in a layer where sgraffiato- and lustre-ware of the 'Abbasid period and pottery of Samarra types were found, suggesting that these glasses are dated between AD 850 and 968. One rubbish-pit in square E2 contained large number of broken fragments which could be dated to this period (Lane 1938, 61).

The glass assemblages from al-Mina have an unusually high quantity of decorated glasses (the majority of Islamic sites have 60% - 70% of undecorated glasses). Vorderstrasse (2005) suggests Woolley and Lane did not retain many undecorated glasses from the excavations (Vorderstrasse 2005, 79). Many of these decorated glasses are of Islamic influence. The cut and facet decorated glasses in al-Mina, such as molar flasks, came from Iraq and Iran. Tonged and mould-blown decorated glasses are a substitute for cut glasses. Many of them were found in al-Mina, such as the bowls, beakers and cups decorated with birds and geometric designs, and parallels of tonged and mould-blown glasses can be found in Syria, Iraq and Iran (Vorderstrasse 2005, 80-81). This suggests the trading of different glass types were widespread inside the Caliphate during the 9th – 10th centuries AD (Vorderstrasse 2005, 82). Ten of these tonged and mould-blown decorated glasses from the Victoria and Albert Museum were studied and analysed in this study.

Despite the political turmoil in the region between the late 9th and 10th centuries AD instigated by the Tulunids from Egypt, the Hamdanids from Aleppo and Mosul and the Byzantines, trade passing through the port of al-Mina to Antioch did not suffer (Lane 1938, 21). However, after the Byzantine invasion of northern Syria in the late 10th century AD, al-Mina began to decline, trade passing through al-Mina decreased and it continued to exist in a reduced size as a naval station with only a few buildings along the edge of the river (Lane 1938, 22). It is true that the number of finds from al-Mina

had decreased when compared to the previous period. The number of glass finds dated to this period is relatively small compared to the previous period (Vorderstrasse 2005, 86, 97). Excavations show that only 18 coins were found ranging from Michael IV to Nikephorus II, and the excavators suggested that the Byzantine invasion of Northern Syria in AD 968 – 969 is the *terminus post quem nihil* for the finds and the settlement in this period (Lane 1938, 22). However, it is still unclear if the Byzantine invasion of northern Syria and the subsequent economic downturn Lane had suggested had any significant impact on al-Mina.

5.4 al-Qadisiyya (Area N) in Samarra, Iraq:

Samarra was founded by the 'Abbasid caliph al-Mu'tasim (AD 796 – 842) in AD 836. It was located on the east bank of the river Tigris and it covered about 57 km^2, stretching over 50 km from end to end (Figure 5.4) (Milwright 2010, 81). The move from Baghdad to Samarra in AD 836 was due to political reasons. Al-Mu'tasim had newly built an army of mercenaries which was mainly composed of Turks from central Asia, many of whom were former slaves, and replaced the Arab and Khurasanian army which had helped to secure the ruling power for the 'Abbasids (Bennison 2009, 36; Wickham 2010, 324). The employment of the Turks had angered the old aristocrats in Baghdad and this is one of the reason al-Mu'tasim moved to Samarra with his army, so that the caliph could ensure their continued loyalty to himself by isolating the Turks from the elite of Baghdad (Bennison 2009, 38; Kennedy 2004, 163; Wickham 2010, 330-331).

Excavations in Samarra show that there was a Sassanian presence in Samarra and some small towns, a canal (Qatul al-Kisrawi, connecting to the Tigris river), palaces and hunting reserves were built in the area (Milwright 2010, 81).

In AD 836, Samarra was founded as the 'Abbasid capital and was designed to rival Baghdad. In the beginning, Samarra was composed of a caliphal city, Surra Man Ra'a with the Caliphal Palace Dar al-Khilafa and an avenue leading south past the markets and a congregational mosque. Also, military settlements (usually composed of a palace, houses, baths and a market) were built to house the Turks and the Central Asian Iranian mercenaries. Al-Karkh (Area F) and the Maghariba were built to house the Turks; al-

Matra was built to house the Central Asian Iranian mercenaries (Northledge 2005, 98, 185, 247).

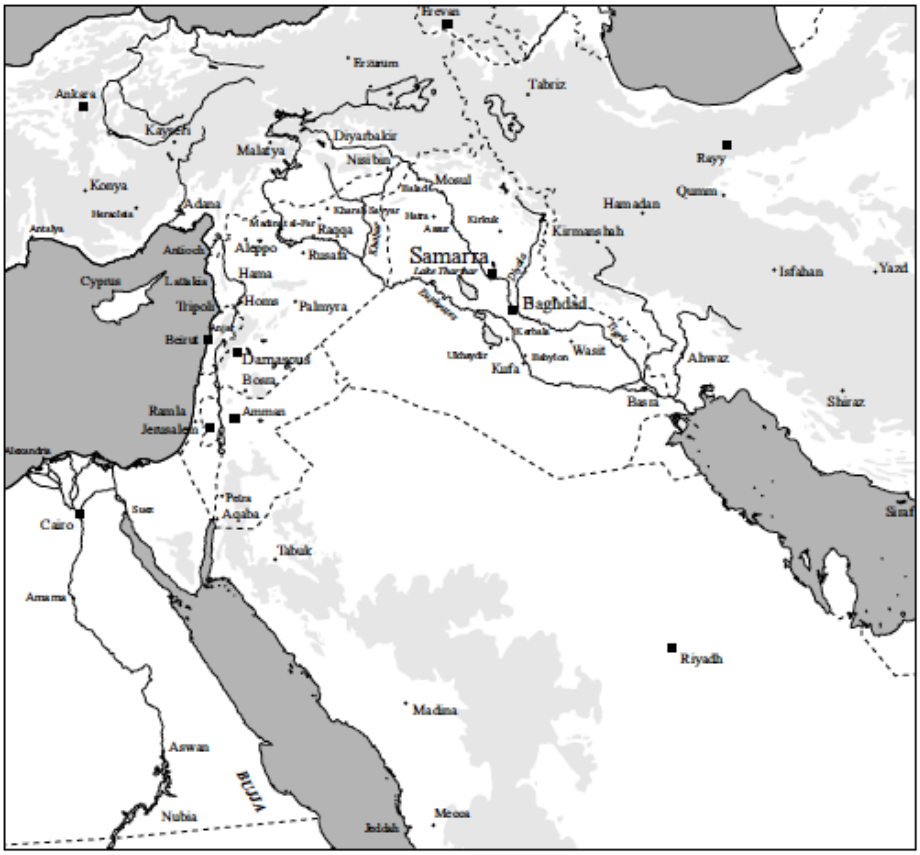


Figure 5.4. A plan showing the location of Samarra in the Middle East (Northledge 2005, 96, Fig. 41).

On the western bank of Samarra, al-Mu'tasim had constructed an industrial zone for Samarra. The 9th century AD geographer and historian al-Ya'qubi mentioned that al-Mu'tasim had 'brought… from al-Basra people who make glass, pottery, and mats…and from the other countries people of every skill and manufacture, and they were settled with their families in these places, and given allotments, and he established there markets for the craftsmen in the city' (Northledge 2005, 236). However, the majority of the evidence for glassmaking and glassworking were found in al-Qadisiyya (Area N), only pottery of Samarra was found to have been produced on the western bank of Samarra.



Figure 5.5. The plan of al-Qadisiyya in Samarra (site N1) where glassworks were found (Northledge 2005, 83, Fig. 33).

A large amount of glass waste and glass vessels were discovered in site N1, which was acted as a glass Tell (Figure 5.5) (Northledge 2005, 82-83). Brigadier General R. Pope Hennessy found seven pieces of furnace glass (C.396-1919; C.396A-1919; C.396B-1919; C.396C-1919; C.396E-1919; C.396F-1919) from an ancient kiln and they were given to the Victoria and Albert Museum as a gift. The museum curator B. Rackham wrote in 1919 that these fragments were evidence of an Islamic glass kiln in Samarra. It is possible that pottery and glass production operated in different zones: pottery was produced on the western bank of Samarra and glass production was carried out in al-Qadisiyya. This is similar to al-Raqqa where pottery and glass production were separated and located in different tells (Tell Aswad was for pottery production, Tell Zujaj and Tell Abu Ali were for glassmaking and glassworking) (Henderson 2013, 273). In terms of the glassmakers and glassworkers, it is possible that they were a mix of local (who already inhabited in al-Qadisiyya) and al-Basra glassmakers.

Under the caliph al-Mutawakkil, Samarra was expanded and the size of the city had doubled in this period. The central area of Samarra, Surra Man Ra'a was expanded and it extended south to include al-Matira. A new congregational mosque and new avenues were built to the east of Surra Man Ra'a (Northledge 2005, 100). Military settlement at al-Karkh was also expanded under al-Mutawakkil to include al-Dur (Area U), which was designed to accommodate an increasing number of Turkish mercenaries in Samarra. At the same time, the military settlement and palace Balkuwara (Area R) was built to the southeast of Samarra to house Arab soldiers, which was designed to counterbalance

the influence of the Turks in the army (Northledge 2005, 180, 189-191). New palaces were also built in this period. Al-Istablat (al-'Arus) and al-Musharrahat (al-Shah) were built south and southeast of Samarra respectively and they were situated outside the centre of Samarra. They were probably hunting palaces (Northledge 2005, 200-207).

A new city, al-Mutawakkiliyya, was constructed north of Surra Man Ra'a in AD 859. The city was laid out between the Turkish military settlements of al-Karkh and a-Dur. It was intended to replace Surra Man Ra'a as the caliphal city in Samarra (Norhledge 2011). The city itself is isolated from the palace al-Ja'fari, which was constructed north of al-Mutawakkiliyya, by an enclosure wall. A congregational mosque called Abu Dulaf and a market were constructed at the eastern side of the city (Northledge 2005, 216).

The city and palaces built by al-Mutawakkil were abandoned after his death in AD 862 (Northledge 2005, 211, 239). After suffering several raids by brigands in the late 9th century AD, the city was depopulated and by about AD 895 the majority of the 'Abbasid city was abandoned and the capital was moved back to Baghdad (Northledge 2005, 241-242).

5.5 Zeyrek Camii (Pantokrator monastery) in Istanbul, Turkey:

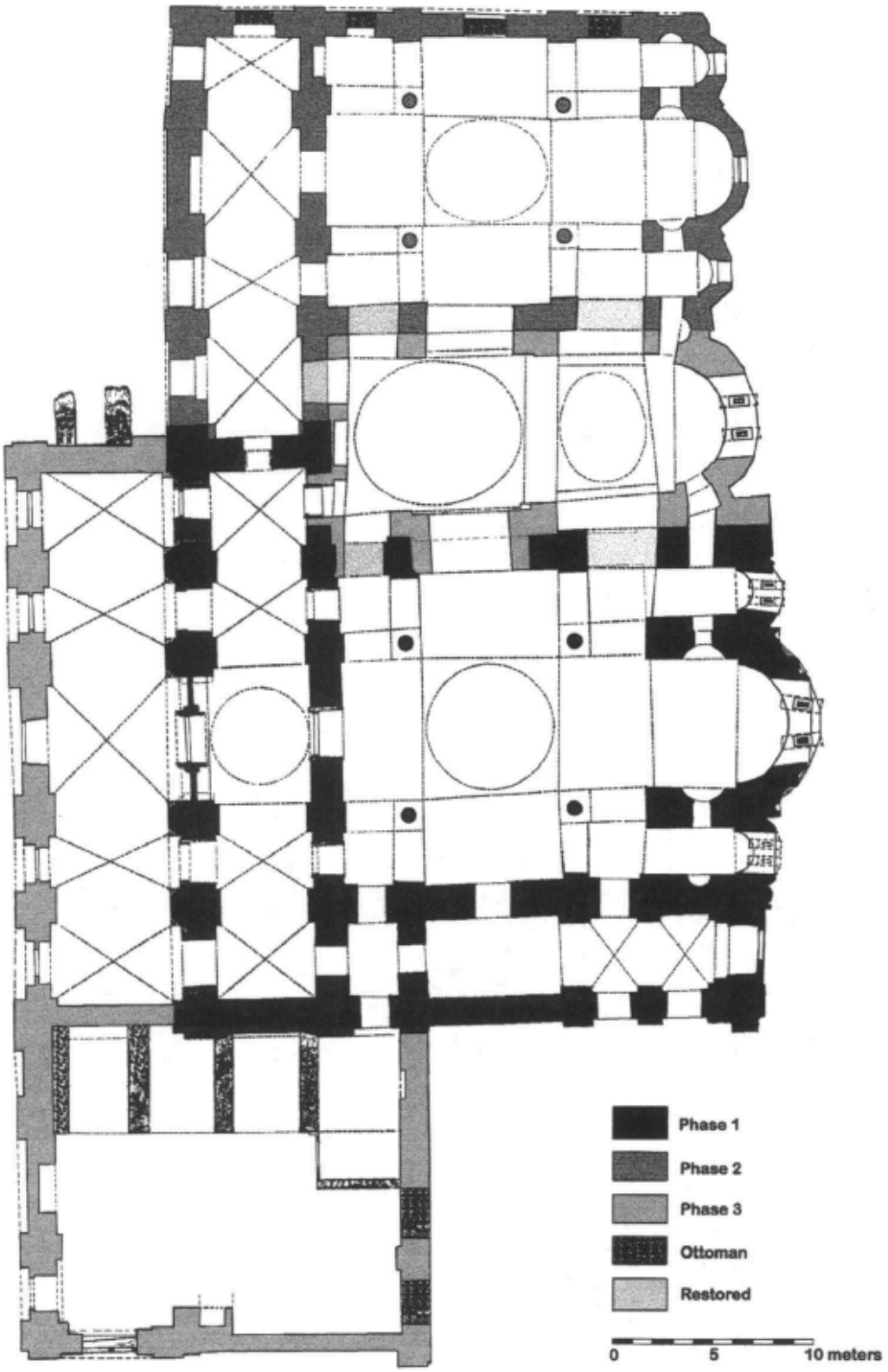


Figure 5.6. A plan of Zeyrek Camii showing the South Church, North Church and Middle Church built in different phases (Ousterhout *et al*. 2000, 267, Fig. 1).

Zeyrek Camii (the Pantokrator monastery) was built in AD 1118 – 1136 by the Byzantine Emperor John II Komnenos and the Empress Eirene. The complex consisted of three large interconnected churches and it was also an imperial mausoleum (Ousterhout 2001, 133; Ousterhout *et al.* 2000, 265). The building was built in three building phases (Figure 5.6) (Freely and Cakmak 2010, 211; Ousterhout 2001, 133; 2010, 345; Ousterhout *et al.* 2000, 265):

(1) The South Church was the first structure to be built and it was commissioned by Eirene (Figure 5.6). It served as a monastic church dedicated to Christ Pantokrator. It was the largest of the three structures and it was also the largest cross-in-square church of the Byzantine period. It has lateral aisles and it is measured 100 X 100 Byzantine feet and it is the same dimensions as the dome bay of Hagia Sophia.

(2) The North Church was the second structure to be built in the complex by John II Komnenos during the second phase (Figure 5.6). It was dedicated to the Virgin Eleousa and it was opened to the laity and served by a lay clergy. It is also a cross-in-square church. The South and North churches included accommodation for suffering women and people with eye diseases. Also, a house for the sick and elderly people and a leprosarium were included in the complex (Ahunbay and Ahunbay 2001, 117).

(3) John II Komnenos commissioned the building of the Middle Church and it was located in between the South and North churches (Figure 5.6). It is a twin-domed funerary chapel and it was served as an imperial mausoleum church, or *heroon*, for the Komnenos dynasty and it was dedicated to St. Michael. The name *heroon* means a hero's shrine, suggesting that those buried in here are heroes.

(4) The south courtyard and an exonarthex were built in the final phase.

The Pantokrator Church served as a major religious centre and an important icon in Constantinople in the 12th century AD. The *typikon* of the Pantokrator Church mentions that the Friday urban processions between Blachernae and the Chalkoprateia churches were redirected so that the Pantokrator Church could be brought into the imperial memorial services (Ousterhout 2010, 345). By AD 1136 the Pantokrator Church had developed into a five-domed complex (Figure 5.6), which was visually similar to the

five-domed church of the Holy Apostles, and it became part of an imperial ideology that bolstered the claim of the Komenos family and linked their success in this world with their salvation in the next world (Ousterhoust 2010, 345-346).

During the Latin rule of Constantinople (AD 1204 – 1261) the Pantikrator Church was occupied by the Roman Catholic clergy of the Venetians. In the Late Byzantine period it was turned into a church complex again and two of the last three of the Byzantine Emperors, Manuel II and John VIII, were buried in its mausoleum in AD 1425 and 1448 respectively (Freely and Cakmak 2010, 212, 214). After the conquest of Constantinople by the Turks, the church complex was turned into a mosque by Molla Mehmet Zeyrek and was renamed Zeyrek Camii (Freely and Cakmak 2010, 214; Ousterhout *et al.* 2000, 265).

Recently, the Pantokrator Church was restored in 1953, 1966 – 1967 and more recently in 1997 – 1998 and 2001 – 2005. The progress was summarised in Megaw (1963), Ahunbay and Ahunbay (2001), and Ousterhout *et al.* (2000) and (2009). In these restoration works, numerous small finds were discovered in the Pantokrator Church. The window glasses were described in detail by Megaw (1963) and some of the fragments were analysed by Brill (2005) and Henderson and Mango (1995) (Brill 2005, 221; Henderson and Mango 1995, 346; Megaw 1963, 349, 351-360, 365). Brick stamps of late antique period, mosaic tesserae, cornices and revetments, and capitals were found (Ousterhout *et al.* 2009, 250-252). It was found that on the edge of the pieces of the gold tesserae, the gold leaf is overlain by a very thin layer of glass that extended to the curved edge (Ousterhout *et al.* 2009, 251). Glass finds such as glass cake and chunks, crown glass, cast and painted window glass, a beaker and a lamp were also found and are dated to 11^{th} – 12^{th} century AD. Some of them were analysed in this study.

5.6 Tbilisi, Georgia:

The glass samples from Tbilisi came from two sites: (1) the medieval city wall that was recently revealed near the Liberty Square in the centre of the city (Figure 5.7); (2) glass materials were found in a pit near a grave under a church that is called Ormotsmotsameta (Forty Martyrs) which is located in the old part of Tbilisi and are

dated to the 10th – 14th centuries AD. At present, the excavations of these two sites are ongoing and no reports have been published yet. It is to be hoped that in the future we will know more about the archaeology of the sites where the glass fragments were found in order to investigate the relationship between the glass and the sites.



Figure 5.7. A photo of the Medieval City Wall in Tbilisi, Georgia (the picture is from Merab Dzneladze from the Georgian National Museum).

5.7 Pemba Island, Zanzibar:

It is not known where the five fragments of Islamic glass came from on Pemba Island. They were given by Major Francis B. Pearce, the then Governor of Zanzibar, as a gift to the Victoria and Albert Museum. The record states that they are of medieval date. Judging from their shapes and decorations, it is possible that these are Islamic-influenced glass.

At present, without any archaeological evidence of glass production, it is not known whether a glass industry existed on Pemba Island. Therefore, it is of interest to begin the research of glass in Africa of medieval date to establish the link between the African, Islamic or Byzantine glass industries, whether the three have any connections in terms

of glass technology and glass typology. Chemical and archaeological analyses are certainly the relevant approaches to do so.

5.8 Fustat, Egypt:

Fustat (Old Cairo) was established as the administrative capital of Egypt after the Arab Conquest in AD 641 – 642. The city was founded around the site of a siege-camp and grew quickly during the Umayyad period (Sheehan 2010, 79). Excavations have shown that in the early period the city was built with simple one or two storeys dwellings constructed of mud brick (Milwright 2010, 85).

After the 'Abbasid conquest in AD 750, a royal or administrative area (al-'Askar) was built north of the city and it was separated from the rest of Fustat. Another royal enclosure (al-Qata'I') was built north of al-'Askar in AD 868 when Ahmad ibn Tulun was governor of Egypt and became his capital when he rebelled against the 'Abbasid and established the Tulunid dynasty (Sheehan 2010, 80).

These two enclosures were gradually abandoned throughout the centuries and in AD 969 a third royal enclosure, al-Qahira, was founded northeast of the city by the Fatimids when they conquered the city. This area became the core of medieval Fustat and the richest and most populous city in the Middle East (Sheehan 2010, 80).

Fustat became desolated after a series of natural disasters during the reign of the Caliph al-Mustansir (AD 1036 – 1094) and was finally abandoned in AD 1072 and many of its buildings were robbed and reused elsewhere (Sheehan 2010, 82).

As we have discussed in Chapter 4, the archaeological excavations in Fustat where glass fragments were found was carried out by the American Research Centre in Egypt. Numerous fragments of Islamic glass were found and are dated to the 8^{th} – 12^{th} centuries AD (Pinder-Wilson and Scanlon 1973, 12-30; Pinder-Wilson and Scanlon 1987, 60-71; Scanlon and Pinder-Wilson 2001, 1-134). However, no remains of a glassworkshop was found. But the fragments brought to the Victoria and Albert Museum by G.D. Hornblower in 1921 did not come from the American excavations. Both fragments of

glass are a piece of raw glass and a frit. This could suggest a primary glass production centre existed in Fustat.

5.9 Summary:

This chapter provides an overview of the archaeological sites where the glass samples came from. These sites were chosen specifically to cover a wide region from the eastern Mediterranean to the south Caucasus and east Africa including Sria, Iraq, Egypt, Turey, Georgia, and Pemba Island. Al-Raqqa in northern Syria is a well-excavated site that has produced evidence of bot primary and secondary glass production dated to the late 8th – 12th centuries AD. Raw glass furnaces, glass vessels and glassworking debris were found in Tell Zujaj and Tell Abu Ali. Another primary and secondary glass production site is found in al-Qadisiyya (Area N) in Samarra, Iraq where raw glasses, glass vessels and glass wastes were found in archaeological excavations. Excavations in Fustat in Egypt also produced evidence of secondary glass production including numerous fragments of Islamic glass.

Other sites where glasses were selected for this study including al-Mina in modern day Turkey and it was a medieval port near Antioch; Zeyrek Camii (the Pantokrator monastery) built by the Byzantine Emperor John II Komnenos and the Empress Eirene in the early 12th century AD; the medieval city wall and a medieval church Ormotsmotsameta in Tbilisi in Georgia; and Oemba Island in Zanzibar.

The author hopes to study these glass samples to further our understanding of Byzantine, Islamic, east African and medieval Georgian glasses dated to the late 8th – 14th centuries AD using an archaeological and scientific approach. Some of the glass samples from sites such as al-Qadisiyya, al-Mina and Pemba Island are studied for the first time (they were discovered in the early 20th century). It is hoping that by studying these glasses, we are able to answer important questions regarding to the technology of glass production and social and economic aspects of glass in these regions during this period.

Chapter 6: Methodology

6.1 Introduction:

This chapter will look at the methodology used in this thesis to study the various glass samples from a range of archaeological sites and museum collections. First, we will look at the samples and the sampling techniques that were chosen to select materials in order to answer the series of research questions proposed in Chapter 1. The analytical technique that was chosen to analyse the glass samples is also discussed in detail and we will look at the analytical procedure performed to analyse the glass samples. And finally, we will discuss the glass samples that are diagnostic in more detail.

6.2 Sampling technique:

A total of 165 glass samples were selected for the electron microprobe analysis (EPMA-WDS): 113 samples come from al-Raqqa in northern Syria including 76 from the site of Tell Zujaj, 19 from Tell Abu Ali and 17 from Tell Fukhkhar; 9 samples come from Tbilisi in Georgia; 15 samples come from the Pantokrator Church (Zeyrek Camii) in Istanbul; 2 samples from Fustat; 5 samples from Pemba Island in Zanzibar; 6 samples from al-Qadisiyya in Samarra in Iraq; and 14 samples from al-Mina in southern Turkey.

A range of glass vessel forms were selected for analysis to see whether there is a relationship between glass vessel forms and chemical compositions. These include bowls, jugs, goblets, bottles, small bottles, beakers, flasks, vases, cups, lamps, dishes, bracelets, ring and window glasses. Decorations on glasses including scratch-decorated, mould blown, trailed/enamelled, lustre painted, tonged and cut were selected for this study. The majority of the samples from al-Raqqa are heavily weathered. The Georgian, Turkish and the Victoria and Albert Museum samples from al-Mina in Turkey, al-Qadisiyya in Samarra in Iraq, Fustat (Old Cairo) in Egypt and Island of Pemba in Zanzibar are less weathered and the surfaces of the glasses are visible. Many of these have parallels in the Byzantine and Islamic worlds during the late 8^{th} – 12^{th} centuries AD. This allows us to get a representative sample of glasses during this period and attempt to answer the important research questions concerning the study of Byzantine,

medieval east African and Islamic glasses. The Georgian samples are dated to the 10th – 14th centuries AD and the vessel forms appear to be different from the Byzantine and Islamic glasses. It is a great opportunity to study medieval glasses from southern Caucasus and to compare them with contemporary Byzantine and Islamic glasses. A description of the samples is presented in Table 6.1. A more detailed description of the samples together with the occurrence of similar vessels and their distribution patterns are discussed in Sections 6.6.

Raw glasses and a frit from al-Raqqa, Samarra and Fustat were selected specifically to look at what raw materials were used specifically to produce these glasses and the specific chemical composition of a glass production centre. This is because raw glasses represent the first stage of glass production when, in most cases, only raw materials were mixed together and no additives were added to colour and/or opacify the glasses. They represent the chemical composition of a glass production centre and provide a benchmark against contemporary raw glasses and vessel glasses found in other regions, which provide provenance information (Henderson 2013, 242-243).

However, there is evidence that glasses were recycled and/or mixed extensively during the late 8th – 12th centuries AD. Evidence of recycling and mixing can be spotted in bi-plots using chemical elements associated with silica- and calcium-rich raw materials and glass. A mixing line is formed showing the maximum and minimum values of different compositions of glass. The composition of glass that was resulted from recycling and mixing is usually presented in the middle of the mixing line (Henderson 2013, 340).

For instance, Henderson *et al*. (2004) and Henderson (2013) have suggested that some of the al-Raqqa Type 4 glasses were the result of varying proportions of raw glasses containing the highest MgO and lowest MgO compositions of glasses (Henderson *et al*. 2004, 457; Henderson 2013, 284). In the Byzantine world, old natron glasses were recycled and mixed with plant ash glasses imported from the Middle East in the 10th – 11th centuries AD. This type of glass is called mixed natron-plant ash glass. These were found in the mosaic glasses from the 11th century AD Monastery of Daphni in Greece and the 11th century AD Torcello Basilica in northern Italy (Arletti *et al*. 2010, 807-808). Therefore, it is interesting to see if there is any evidence of recycling and/or

mixing present in the glasses analysed in this study and to tell us something about the economy and technology of glass in this period.

Part of this thesis is designed to look at the relationship between chemical compositions, colours and their archaeological contexts. Therefore, a range of colours were selected. These include green, aqua, ‘black’, olive green, colourless and colourless with tints of blue, light blue and yellow-green. Rare colours such as red, yellow and turquoise are also included.

Sample Number	Sites	Find numbers	Contexts	Date (in AD)	Vessel Forms	Colour	Decorations
RAQ-01	TZ'94	B1 3A	325	Late 8th - 9th century	Bowl	Blue	Undecorated
RAQ-02	TZ'94	B1 11	108	Late 8th - 9th century	Window glass	Yellow-purple	Undecorated
RAQ-03	TZ'94	B1 54	46	Late 8th - 9th century	Window glass	Green	Undecorated
RAQ-04	TZ'94	B1 54	46	Late 8th - 9th century	Lustre-painted bottle	Aqua (base glass)/ brownish red (stain)	Lustre-painted
RAQ-05	TZ'94	B2 153	83	Late 8th - 9th century	Beaker/bowl	Colourless	Undecorated
RAQ-06	TZ'94	B2 153	83	Late 8th - 9th century	Bowl?	Blue	Undecorated
RAQ-07	TZ'94	B2 153	83	Late 8th - 9th century	Window glass	Red	Undecorated
RAQ-08	TZ'94	B2 174	304	Late 8th - 9th century	Bottle	Green	Undecorated

RAQ-09	TZ'94	B4 153	99	Late 8th - 9th century	Flask/jar	Yellow-green	Undecorated
RAQ-10	TZ'94	B19 467	333	Late 8th - 9th century	Bottle	Blue	Undecorated
RAQ-11	TZ'94	C 1	50	Late 8th - 9th century	Jar	Aqua	Undecorated
RAQ-12	TZ'94	C 2	69	Late 8th - 9th century	Small rectangular bottle	Colourless	Undecorated
RAQ-13	TZ'94	C 4 180	296	Late 8th - 9th century	Goblet	Aqua	Undecorated
RAQ-14	TZ'94	C 4 180	309	Late 8th - 9th century	Bottle	Aqua	Undecorated
RAQ-15	TZ'94	C 4 180	117	Late 8th - 9th century	Small bottle	Aqua	Undecorated
RAQ-16	TZ'94	C 4 206	275	Late 8th - 9th century	Pinced bowl	Colourless	Undecorated
RAQ-17	TZ'94	C 4 206	288	Late 8th - 9th century	Bowl	Blue	Undecorated
RAQ-18	TZ'94	D 3 352	138	Late 8th - 9th century	Small bottle	Colourless	Undecorated

RAQ-19	TZ'94	D 3 352	141	Late 8th - 9th century	Square flask	Light green	Undecorated
RAQ-20	TZ'94	174	337	Late 8th - 9th century	Bowl	Colourless	Undecorated
RAQ-21	TZ'94	Unknown	76	Late 8th - 9th century	Small bottle	Yellow-green	Undecorated
RAQ-22	TZ'94	Unknown	97	Late 8th - 9th century	Lamp	Colourless	Undecorated
RAQ-23	TZ'94	Unknown	97	Late 8th - 9th century	Bottle	Blue	Undecorated
RAQ-24	TZ'94	Unknown	329	Late 8th - 9th century	Jar	Blue	Undecorated
RAQ-25	TZ’94	Unknown	2	Late 8th - 9th century	Bottle?	Blue	Undecorated
RAQ-26	TZ'95	SFN-5046	500	Late 8th - 9th century	Bottle	Yellow-green	Undecorated
RAQ-27	TZ'95	SFN-5065	500	Late 8th - 9th century	Bottle	Light blue	Undecorated
RAQ-28	TZ'95	SFN-5110	513	Late 8th - 9th century	Bottle?	Green	Undecorated

RAQ-29	TZ'95	SFN-5149	501	Late 8th - 9th century	Goblet	Aqua	Undecorated
RAQ-30	TZ'95	SFN-5209	528	Late 8th - 9th century	Bottle	Aqua	Undecorated
RAQ-31	TZ'95	SFN-5255	556	Late 8th - 9th century	Bottle	Aqua	Undecorated
RAQ-32	TZ'95	SFN-5260	556	Late 8th - 9th century	Globular bottle	Yellow green	Undecorated
RAQ-33	TZ'95	SFN-5273	528	Late 8th - 9th century	Bottle?	Aqua	Undecorated
RAQ-34	TZ'95	SFN-5280	522	Late 8th - 9th century	Goblet	Aqua	Undecorated
RAQ-35	TZ'95	SFN-5299	554	Late 8th - 9th century	Jar	Colourless	Undecorated
RAQ-36	TZ'95	SFN-5346	556	Late 8th - 9th century	Bottle	Colourless	Undecorated
RAQ-37	TZ'95	SFN-5358	502	Late 8th - 9th century	Bottle	Colourless	Undecorated
RAQ-38	TZ'95	SFN-5400	576	Late 8th - 9th century	Goblet	Aqua	Undecorated

RAQ-39	TZ'95	SFN-5407	557	Late 8th - 9th century	Globular bottle	Green	Tonged
RAQ-40	TZ'95	SFN-5411	557	Late 8th - 9th century	Sprinkler?	Colourless	Vertical ribs
RAQ-41	TZ'95	SFN-5424	502	Late 8th - 9th century	Small bottle	Colourless	Undecorated
RAQ-42	TZ'95	SFN-5478	576	Late 8th - 9th century	Goblet	Blue	Undecorated
RAQ-43	TZ'95	SFN-5485	557	Late 8th - 9th century	Bottle	Colourless	Undecorated
RAQ-44	TZ'95	SFN-5492	576	Late 8th - 9th century	Bowl		Undecorated
RAQ-45	TZ'95	SFN-5511	557	Late 8th - 9th century	Bottle	Blue	Undecorated
RAQ-46	TZ'95	SFN-5511	557	Late 8th - 9th century	Bottle	Colourless	Undecorated
RAQ-47	TZ'95	SFN-5554	629	Late 8th - 9th century	Bottle	Green	Mould blown/tonged
RAQ-48	TZ'95	SFN-5568	562	Late 8th - 9th century	Bowl	Aqua	Undecorated

RAQ-49	TZ'95	SFN-5628	644	Late 8th - 9th century	Bottle/jar	Aqua	Undecorated
RAQ-50	TZ'95	SFN-5643	602	Late 8th - 9th century	Bowl?	Yellow-green	Mould Blown
RAQ-51	TZ'95	SFN-5667a	557	Late 8th - 9th century	Small bottle	Colourless	Undecorated
RAQ-52	TZ'95	SFN-5673	573	Late 8th - 9th century	Bottle	Blue	Undecorated
RAQ-53	TZ'95	SFN-5725	537	Late 8th - 9th century	Bottle	Aqua	Undecorated
RAQ-54	TZ'95	SFN-5747	675	Late 8th - 9th century	Small bottle	Colourless	Undecorated
RAQ-55	TZ'95	SFN-5754	568	Late 8th - 9th century	Physician's vessel	Colourless	Undecorated
RAQ-56	TZ'95	SFN-5828	675	Late 8th - 9th century	Bottle neck	Aqua	Undecorated
RAQ-57	TZ'95	SFN-5983	645	Late 8th - 9th century	Bottle neck	Blue	Undecorated
RAQ-58	TZ'95	SFN-5992	587	Late 8th - 9th century	Bottle	Olive green	Undecorated

RAQ-59	TZ'96	SFN-6181	840	Late 8th - 9th century	Bottle	Colourless	Undecorated
RAQ-60	TZ'96	SFN-6204	840	Late 8th - 9th century	Flask	Blue	Undecorated
RAQ-61	TZ'96	SFN-6208	840	Late 8th - 9th century	Beaker	Colourless	Undecorated
RAQ-62	TZ'96	SFN-6209	840	Late 8th - 9th century	Goblet	Aqua	Undecorated
RAQ-63	TZ'96	SFN-6362	840	Late 8th - 9th century	Bottle	Colourless	Undecorated
RAQ-64	TZ'96	SFN-6382	855	Late 8th - 9th century	Goblet	Aqua	Undecorated
RAQ-65	TZ'96	SFN-6435	855	Late 8th - 9th century	Vase	Aqua	Undecorated
RAQ-66	TZ'96	SFN-6437	855	Late 8th - 9th century	Goblet	Aqua	Undecorated
RAQ-67	TZ'96	SFN-6439	855	Late 8th - 9th century	Bottle	Aqua	Undecorated
RAQ-68	TZ'96	SFN-6441	855	Late 8th - 9th century	Goblet	Aqua	Undecorated

RAQ-69	TZ'96	SFN-6442	855	Late 8th - 9th century	Bowl	Aqua	Undecorated
RAQ-70	TZ'96	SFN-6443	855	Late 8th - 9th century	Bottle	Aqua	Undecorated
RAQ-71	TZ'96	SFN-6446	855	Late 8th - 9th century	Bottle	Aqua	Undecorated
RAQ-72	TZ'96	SFN-6535	855	Late 8th - 9th century	Goblet	Colourless	Undecorated
RAQ-73	TZ'96	SFN-6549	855	Late 8th - 9th century	Bottle	Aqua	Undecorated
RAQ-74	TZ'96	SFN-6596	857	Late 8th - 9th century	Physician's vessel	Blue	Undecorated
RAQ-75	TZ'96	SFN-6603	857	Late 8th - 9th century	Lamp	Blue	Undecorated
RAQ-76	TZ'96	SFN	750	Late 8th - 9th century	Furnace glass	Green	Undecorated
RAQ-77	TAA'96	SFN-2	50	Late 8th - 9th century	Goblet	Aqua	Undecorated
RAQ-78	TAA'96	SFN-22	50	Late 8th - 9th century	Goblet	Green	Undecorated

RAQ-79	TAA'96	SFN-40	1/4/5 (Mixed)	Late 8th - 9th century	Goblet	Aqua	Undecorated
RAQ-80	TAA'96	SFN-98	53	Late 8th - 9th century	Bowl/beaker	Colourless	Undecorated
RAQ-81	TAA'96	SFN-100	53	Late 8th - 9th century	Bowl	Colourless	Undecorated
RAQ-82	TAA'96	SFN-107	5	Late 8th - 9th century	Dish/bowl	Blue	Scratch-decorated
RAQ-83	TAA'96	SFN-118	5	Late 8th - 9th century	Bowl	Aqua	Undecorated
RAQ-84	TAA'96	SFN-119	5	Late 8th - 9th century	Bowl	Aqua	Undecorated
RAQ-85	TAA'96	SFN-126	5	Late 8th - 9th century	Goblet	Aqua	Undecorated
RAQ-86	TAA'96	SFN-131	5	Late 8th - 9th century	Goblet	Aqua	Undecorated
RAQ-87	TAA'96	SFN-132	5	Late 8th - 9th century	Goblet	Aqua	Undecorated
RAQ-88	TAA'96	SFN-154	2	Late 8th - 9th century	Beaker/bowl	Colourless	Tonged

RAQ-89	TAA'96	SFN-157	2	Late 8th - 9th century	Beaker/bowl	Colourless	Cut?
RAQ-90	TAA'96	SFN-158	2	Late 8th - 9th century	Beaker/bowl	Yellow-green	Tonged
RAQ-91	TAA'96	SFN-185	2	Late 8th - 9th century	Bottle	Colourless	Undecorated
RAQ-92	TAA'96	SFN-192	5	Late 8th - 9th century	Bowl	Aqua	Undecorated
RAQ-93	TAA'96	SFN-196	5	Late 8th - 9th century	Bowl	Aqua	Undecorated
RAQ-94	TAA'96	SFN-197	5	Late 8th - 9th century	Goblet	Aqua	Undecorated
RAQ-95	TAA'96	SFN-216	5	Late 8th - 9th century	Physician's vessel	Aqua	Undecorated
RAQ-96	TF'95	SFN-3	1F	11th century	Bracelet	Dark green	Undecorated
RAQ-97	TF'95	SFN-26	3F	11th century	Bracelet	Dark green	Undecorated
RAQ-98	TF'95	SFN-47	8	11th century	Bracelet	Dark green	Undecorated
RAQ-99	TF'95	SFN-48	8	11th century	Bracelet	Dark green	Undecorated
RAQ-100	TF'95	SFN-61	1F	11th century	Bracelet	Dark green	Undecorated
RAQ-101	TF'95	SFN-62	1F	11th century	Bracelet	Dark green	Undecorated
RAQ-102	TF'95	SFN-63	1F	11th century	Bracelet	Dark green	Undecorated

RAQ-103	TF'95	SFN-67	1C	11th century	Bracelet	Dark green	Undecorated
RAQ-104	TF'95	SFN-71	1F	11th century	Bracelet	Dark green	Undecorated
RAQ-105	TF'95	SFN-126	1F	11th century	Bracelet	Dark green	Undecorated
RAQ-106	TF'95	SFN-135	6H	11th century	Bracelet	Dark green	Undecorated
RAQ-107	TF'95	SFN-200	13	11th century	Bracelet	Dark green	Undecorated
RAQ-108	TF'95	SFN-309	59	11th century	Bracelet	Dark green	Undecorated
RAQ-109	TF'95	SFN-324	6H	11th century	Bracelet	Dark green	Undecorated
RAQ-110	TF'95	SFN-352	66	11th century	Bracelet	Dark green	Undecorated
RAQ-111	TF'95	SFN-652	120	11th century	Bracelet	Dark green	Undecorated
RAQ-112	TF'95	SFN-735	C 4	11th century	Bracelet	Dark green	Undecorated
RAQ-113	TF'96	SFN-	211	11th century	Furnace glass	Dark green	Undecorated
Geo-01	Tbilisi	No. 3	Pushkin Str. 1	10th - 13th centuries	Bracelet	Olive green	Undecorated
Geo-02	Tbilisi		Grage No. 5	12th - 13th centuries	Cup	Light green	Undecorated
Geo-03	Tbilisi	No. 8	Pushkin Str. 1	10th - 13th centuries	Bracelet	Olive green	Undecorated
Geo-04	Tbilisi	No. 12	Pushkin Str. 1	10th - 12th centuries	Bracelet	Dark green	Undecorated

Geo-05	Tbilisi	No. 13	Pushkin Str. 1	10^{th} - 12^{th} centuries	Bracelet	Dark green	Undecorated
Geo-06	Tbilisi	No. 693	Pit No. 85	12^{th} - 14^{th} centuries	Plate	Green	Undecorated
Geo-07	Tbilisi	No. 694	Pit No. 85	12^{th} - 14^{th} centuries		Green	Undecorated
Geo-08	Tbilisi		Pushkin Str. 1	10^{th} - 13^{th} centuries	Ring	Green	Undecorated
Geo-09	Tbilisi	N. 701	Pit No. 85	Medieval	Bracelet	Blue	Undecorated
ZC-01	Zeyrek Camii	1	Western part of the building	11^{th} - 12^{th} centuries	Chunk	Yellow	Undecorated
ZC-02	Zeyrek Camii	2	Western part of the building	11^{th} - 12^{th} centuries	Chunk	Blue	Undecorated
ZC-03	Zeyrek Camii	3	Western part of the building	11^{th} - 12^{th} centuries	Glass cake	Blue	Undecorated
ZC-04	Zeyrek Camii	5	Western part of the building	11^{th} - 12^{th} centuries	Cup	Green	Undecorated

ZC-05	Zeyrek Camii	6	Western part of the building	11^{th} - 12^{th} centuries	Crown glass	Green	Undecorated
ZC-06	Zeyrek Camii	9	Substructure	11^{th} - 12^{th} centuries	Lamp	Colourless	Undecorated
ZC-07	Zeyrek Camii	11	Substructure	11^{th} - 12^{th} centuries	Cast window glass	Blue	Undecorated
ZC-08	Zeyrek Camii	12	Substructure	11^{th} - 12^{th} centuries	Cast window glass	Colourless	Undecorated
ZC-09	Zeyrek Camii	14	Substructure	11^{th} - 12^{th} centuries	Cast, painted window glass	Lilac	Painted
ZC-10	Zeyrek Camii	17	Substructure	11^{th} - 12^{th} centuries	Cast, painted window glass	Purple	Painted
ZC-11	Zeyrek Camii	18	Substructure	11^{th} - 12^{th} centuries	Cast, painted window glass	Colourless	Painted
ZC-12	Zeyrek Camii	20	Substructure	11^{th} - 12^{th} centuries	Cast, painted window glass	Colourless	Painted

ZC-13	Zeyrek Camii	21	Substructure	11^{th} - 12^{th} centuries	Crown glass	Colourless	Undecorated
ZC-14	Zeyrek Camii	22	Substructure	11^{th} - 12^{th} centuries	Beaker	Colourless	Undecorated
ZC-15	Zeyrek Camii	23	Substructure	11^{th} - 12^{th} centuries	Rim	Colourless	Undecorated
VA-01	Fustat	C.1470-1921	Fustat excavation	Islamic period	Frit	Green	Undecorated
VA-02	Fustat	C.1471-1921	Fustat excavation	Islamic period	Furnace glass	Green	Undecorated
VA-03	Pemba Island	C.261-1916	Unknown	Medieval period	Base of a bottle	Emerald green	Scratch-decorated (Arabic inscription)
VA-04	Pemba Island	C.262-1916	Unknown	Medieval period	Bottle neck	Aqua	Mould Blown
VA-05	Pemba Island	C.263-1916	Unknown	Medieval period	Base of a flask neck	Emerald green	Mould Blown
VA-06	Pemba Island	C.264-1916	Unknown	Medieval period	Phial	Emerald green	Mould Blown

VA-07	Pemba Island	C.265-1916	Unknown	Medieval period	Base of a small flask	Turquoise	Mould Blown
VA-08	Al-Qadisiyya (Samarra)	C.396-1919	An Islamic glass kiln	$9^{th} – 10^{th}$ centuries	Tank furnace glass	Emerald green	Undecorated
VA-09	Al-Qadisiyya (Samarra)	C.396A-1919	An Islamic glass kiln	$9^{th} – 10^{th}$ centuries	Tank furnace glass	Emerald green	Undecorated
VA-10	Al-Qadisiyya (Samarra)	C.396B-1919	An Islamic glass kiln	$9^{th} – 10^{th}$ centuries	Tank furnace glass	Mid-green	Undecorated
VA-11	Al-Qadisiyya (Samarra)	C.396C-1919	An Islamic glass kiln	$9^{th} – 10^{th}$ centuries	Furnace glass	Aqua	Undecorated
VA-12	Al-Qadisiyya (Samarra)	C.396E-1919	An Islamic glass kiln	$9^{th} – 10^{th}$ centuries	Glass working refuse	Emerald green	Undecorated
VA-13	Al-Qadisiyya (Samarra)	C.396F-1919	An Islamic glass kiln	$9^{th} – 10^{th}$ centuries	Waster	Blue	Undecorated

VA-14	al-Mina	C.324B-1937	1936-1937 excavations	9th – 10th centuries	Pushed-in base of a bottle	Aqua	Undecorated
VA-15	al-Mina	C.324G-1937	1936-1937 excavations	9th – 10th centuries	Fragment of a flask	Blue	Indented
VA-16	al-Mina	C.325R-1937	1936-1937 excavations	9th – 10th centuries	Fragment of a bottle	Deep brown	Trailed/ enamelled/lustre ?
VA-17	al-Mina	C.325S, V, I-1937	1936-1937 excavations	9th – 10th centuries	Base of a bottle	Deep brown	Undecorated
VA-18	al-Mina	C.327B-1937	1936-1937 excavations	9th – 10th centuries	Base of a bowl	Aqua	Tonged
VA-19	al-Mina	C.327E-1937	1936-1937 excavations	9th – 10th centuries	Rim of a bowl	Aqua	Tonged
VA-20	al-Mina	C.327G-1937	1936-1937 excavations	9th – 10th centuries	Rim of a bowl	Colourless	Tonged (bird)
VA-21	al-Mina	C.327H-1937	1936-1937 excavations	9th – 10th centuries	Rim of a bowl	Aqua	Tonged (bird)
VA-22	al-Mina	C.327J-1937	1936-1937 excavations	9th – 10th centuries	Rim of a bowl	Aqua	Tonged (bird)

VA-23	al-Mina	C.327K-1937	1936-1937 excavations	9^{th} – 10^{th} centuries	Rim of a bowl	Aqua	Tonged (bird)
VA-24	al-Mina	C.327L-1937	1936-1937 excavations	9^{th} – 10^{th} centuries	Base of a bowl	Aqua	Tonged (bird)
VA-25	al-Mina	C.327M-1937	1936-1937 excavations	9^{th} – 10^{th} centuries	Fragment of a bowl/cup/ beaker?	Emerald green	Mould Blown
VA-26	al-Mina	C.327N-1937	1936-1937 excavations	9^{th} – 10^{th} centuries	Rim of a bowl	Aqua	Tonged
VA-27	al-Mina	C.328E-1937	1936-1937 excavations	9^{th} – 10^{th} centuries	Rim of a bowl	Deep brown	Scratch-decorated (shallow)
VA-28	al-Mina	C.329P-1937	1936-1937 excavations	9^{th} – 10^{th} centuries	Fragment of a shallow bowl	Aqua	Mould Blown

Table 6.1. A description of the glass samples analysed in this study. They are displayed according to sites, finds numbers, contexts/excavations, dates, types of vessels, colours and decorations.

6.3 Sample preparations:

Samples of approximately 0.5 cm were removed from each of the glass samples so that unweathered glass samples could be used for analysis. Weathered surfaces are undesirable for analysis because they are the result of alkalis leaching out of the glass (Freestone 2001). Each sample was then mounted in epoxy resin. Each epoxy resin block was ground using silicon carbide papers in the order of P600, P800, P1200 and P2500 to remove the damage result from sectioning and to decrease abrasive size for each stage. Subsequently each block was polished using 6 μm and 1 μm diamond pastes on polishing cloth to remove the damage caused by grinding. 0.25 μm diamond paste was then used to remove the remaining damage that could not be removed in previous stages. Finally, each block was carbon coated to prevent surface charging and distortion of the electron beam during analysis (Henderson 1988, 78; Henderson *et al.* 2004, 451).

6.4 Electron microprobe analysis:

Electron microprobe analysis has been proven useful and is widely used in the analysis of ancient glasses. It combines the back-scattered electrons images, secondary electrons images, elemental mapping and quantitative analysis, which produce a very powerful method of chemical analysis (Ionescu and Hoeck 2016, 288; Jose-Yacaman and Ascencio 2000, 420; Pollard *et al.* 2007, 93, 109). I present here is a summary of the technique as it has been extensively covered in other publications such as Reed (1997) and Goodhew *et al.* (2001).

6.4.1 Beam of electrons:

The electron gun in the microprobe will generate a primary beam of electrons (with a kinetic energy of 10 – 30 keV) that will be fired onto the sample surface. The beam of electrons can be focused electrostatically and/or magnetically to a few microns across the sample. However, an electromagnetic len is more commonly used nowadays (Goodhew *et al.* 2001, 27; Henderson 2000, 17; Pollard *et al.* 2007, 109; Reed 1997, 3). It is designed to provide a magnetic field almost parallel to the direction of travel of the electrons (Goodhew *et al.* 2001, 27).

In the study of glass, the beam of electrons has to be defocused to at least 80 microns (Henderson 2000, 17). The reason for doing so is because the kinetic energy of the beam, which is converted into heat, would cause the temperature of the sample volume to rise and this results the migration of sodium and other volatile elements from the point of impact of the electron beam (Henderson 1988, 78). It was observed there is minimal loss of sodium if the beam is defocused to 80 μm and if the count time is reduced to 10s on the sodium peak (Henderson 1988, 79).

6.4.2 Interaction between the electron beam and the sample:

When an electron beam hits a sample (usually less than or equal to 5 μm), a number of things occur as a result of the interaction between the incident electron beam and the inner shell electrons of the atom of a sample:

(1) secondary electrons are produced. They are electrons that escape from the sample with energies below about 50 eV. Their low energy suggests they come from the top few atomic layers and are very sensitive to surface topography. Their intensity across the sample surface reflects the topography of the sample and is used for imaging signal in electron microprobe.

(2) backscattered electrons are of higher energy and they come from deeper layers of the sample than secondary electrons. They are used for imaging, diffraction and to provide useful chemical information. We can use backscattered electron images to detect contrast between areas with different chemical compositions. Heavy elements (high atomic number) appear brighter than light elements (low atomic number). For instance, in ceramic analysis tiny grains of Fe oxides appear brighter than Ca oxides (Ionescu and Hoeck 2016, 296). We can combine qualitative images with positioned quantitative point analyses to identify the chemical composition and element distribution of the sample.

(3) characteristic X-rays or a characteristic (Auger) electron are given off and are characteristic of the chemical elements in the sample. These have specific energies for each element. They form the basis of analysis in the electron microprobe (Freestone

1982, 99; Goodhew *et al.* 2001, 34-35; Henderson 2000, 17; Ionescu *et al*. 2011, 468; Jose-Yacaman and Ascencio 2000, 410; Pollard *et al.* 2007, 109-110, Figure 5.6).

The wavelength and intensity of the lines in the X-ray spectrum from the elements allow the microprobe to perform qualitative and quantitative analyses on a sample. Qualitative analyses allow us to identify the elements present in a sample. On the other hand, quantitative analysis shows the concentration of the elements in a sample by analysing the intensities of the X-ray lines from a sample and compared with those from standards of known composition (Reed 1997, 3).

6.4.3 Wavelength-dispersive X-ray detector and energy dispersive detector:

The characteristic X-rays from the sample can be detected using one or more wavelength-dispersive X-ray detectors (WDS) and/or an energy dispersive detector (EDS) (Pollard *et al.* 2007, 111). The principle of WDS is that the X-rays coming from the sample are filtered. Only X-rays with characteristic wavelength of the elements of interest are allowed to fall on the detector (a proportional counter). To use WDS requires prior knowledge as to which elements are to be included before the analysis. Each WDS contains a crystal of known lattice spacing *d*. Several crystals with different *d* values are used to analyse the whole spectrum of characteristic wavelengths from the sample. This is because one crystal with a certain *d* value can detect only a limited range of characteristic wavelengths (Goodhew *et al.* 2001, 181; Ionescu and Hoeck 2016, 292; Jose-Yacaman and Ascencio 2000, 410; Reed 1997, 143). The most common crystals used are TAP (thallium acid phthalate), PET (pentaerythritol), LIF (lithium fluoride), ADP (ammonium dihydrogen phosphate), muscovite, quartz and LAP (potassium acid phthalate (Ionescu and Hoeck 2016, 292).

There are few advantages using WDS for chemical analysis:

(1) It is more precise and capable of detecting lower concentrations of elements than EDS. It can detect lower concentrations of elements than 0.01%. However, the detection limit depends on count time, excitation efficiency and background intensity. Henderson (1988) noted the detection limits of certain elements in mixed-alkali glasses using WDS: Na_2O is 0.076%, K_2O is 0.025%, CaO is 0.017%, Fe_2O_3 is 0.064%, CuO

is 0.12% and PbO is 0.02% (Henderson 1988, 80). Chemical analysis of glass has shown that WDS is more efficient in detecting transition metal than EDS, especially cobalt and iron for glass.

(2) It can collect data from a single element in a very short counting time due to the high counting rate (50,000 cps) of the X-ray detector in the crystal spectrometer.

(3) The peak-to-background ratio of each line is much higher using an X-ray detector than using solid detector, which allows WDS to measure elements in low concentration more precisely (Goodhew *et al.* 2001, 183; Henderson 1988, 80; Ionescu and Hoeck 2016, 292; Jose-Yacaman and Ascencio 2000, 412; Pollard *et al.* 2007, 111; Reed 1997, 185).

However, there are a few limitations to this technique:

(1) It takes longer to detect the elements and it takes longer to scan all the required wavelengths of X-rays.

(2) It will need at least two detectors to reduce the analysis time (Goodhew *et al.* 2001, 183; Jose-Yacaman and Ascencio 2000, 410).

EDS is different from WDS. In principle, the EDS detector consists of a small piece of semiconducting silicon or germanium (a solid state device) that is angled in line of the sample. This helps to collect as many X-rays as possible from the sample (Goodhew *et al.* 2001, 175). Also, EDS considers the secondary X-ray emitted by the exited atom as an X-ray photon whose energy is characteristic of the atom (Pollard *et al.* 2007, 102). It can perform qualitative analysis which identifies the elements present in the sample quickly (Jose-Yacaman and Ascencio 2000, 410; Reed 1997, 16).

The advantages of using EDS are that:

(1) It can measure all elements simultaneously in less than 100s and the software, which controls the EDS system, is able to identify peaks and to quantify them, and it includes calibration programs that perform absorption corrections.

(2) We do not have to decide which elements to be include since all elements are simultaneously measured (Pollard *et al.* 2007, 103-104; Reed 1997, 162).

However, there are a few disadvantages using EDS:

(1) It is not possible to detect elements lighter than sodium is with a standard detector.

(2) It has inferior peak resolution and overlap between adjacent peaks, for elements such as cobalt and iron.

(3) It has a limited total count rate and the data will be less precise than those from WDS (Goodhew *et al.* 2001, 180; Pollard *et al.* 2007, 104; Reed 1997, 163; Verita *et al.* 1994, 242).

6.4.4 Advantages and disadvantages of electron microprobe:

The above discussion shows that the electron microprobe has great advantages in the analysis of ancient glasses. The technique requires only a very small sample and can provide us with accurate data in the composition of a given material. WDS and EDS can also be combined to complement each other. Reed (1997) has suggested that EDS data can be used to analyse major elements and WDS data for minor and some trace elements (Reed 1997, 185). Another strength of the electron microprobe is its ability to combine quantitative analyses with backscattered electron images, which provides us with information on the chemical composition and element distribution of a sample (Ionescu and Hoeck 2016, 294-295). Many elements such as Na, Mg, Al, Cl, K, Ca, Mn, Fe and Cu, which are commonly encountered in the study of glass to provide information on the raw materials used and to determine compositional groups, can be detected and are accurately presented using electron microprobe analysis (Verita *et al.* 1994, 249).

However, its main disadvantage is that it requires a homogenous sample in order to determine more accurately the composition of an object. This is due to the size and shape of the sample used in the electron microprobe analysis (Jose-Yacaman and Ascencio 2000, 420; Pollard *et al.* 2007, 112). As we have mentioned before (6.4.1), in

the analysis of glass we have to be aware that alkali elements are subject to migration (Henderson 1988, 79). Therefore, measures must be taken to prevent the loss of alkali using this technique. Another limitation of this technique is that prolonged exposure to the electron beam can cause damage to sensitive materials such as glass because it can induce opacity in some glasses (Pollard *et al*. 2007, 112-113). Despite its disadvantages, this analysis is suitable for the analysis of ancient glasses to provide us with detailed information on the composition of a given sample. The accuracy and precision of the technique and its ability to provide detailed information on a glass sample are the reasons why this technique was chosen for this study.

6.5 Analytical procedure:

For the purpose of this project, 165 fragments of glass were selected for the electron-probe micro-analysis. The polished samples were analysed by EPMA-WDS using a Cameca SX100 electron microprobe in the School of Environment, Earth and Ecosystem Sciences of the Open University. The system is equipped with five wavelength-dispersive X-ray spectrometers with LTAP, PET, TAP, LPET and LLIF crystals, a single energy-dispersive X-ray spectrometer, secondary and backscattered detectors. Quantitative compositional analyses were carried out using the following analytical set-up: 20kV accelerating voltage, a 20nA beam current and a 25µm defocussed beam. The counting times were between 10 - 40 seconds on the peak (some elements generate more counts than others) and 15 seconds on the background either side of the peak. A defocused beam is used to reduce the effect of the migration of alkalis within the samples (Henderson 1988, 78-79).

The EMPA-WDS was calibrated against a combination of standard reference materials, including mineral (Barite, Bustamite, Cobaltite, Crocoite, Hematite, Stibnite, Willemite), pure metal (Cu, Ag, V, Ni) and synthetic standards (Cr_2O_3, KCl, LiF). The composition of 26 elements was sought and was expressed as weight percentages. Five areas of interest (at x1000) were analysed in each sample and the mean was calculated. So as to check the accuracy and precision of the EPMA-WDS system and to monitor any drift in the instrument (Meek *et al*. 2012, 790), repeat analyses of a secondary standard, Corning B, were included during the analytical run. The results are presented in Table 6.2.

	P_2O_5	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	MnO	CuO	ZnO	PbO	Na_2O	K_2O
Known	0.82	61.55	0.089	4.36	0.34	1.03	8.56	0.25	2.66	0.19	0.61	17.0	1.00
Measured (n=4)	0.77	61.44	0.11	4.21	0.35	1.03	8.37	0.24	2.94	0.20	0.45	17.47	1.01
St. dev.	0.09	1.44	0.03	0.02	0.02	0.07	0.08	0.04	0.03	0.04	0.05	0.15	0.04
Error (%)	6.10	0.18	23.60	3.44	2.94	0	2.22	4	10.5	5.26	26.23	2.76	1

Table 6.2. The results of the analysis of the Corning Glass Standard B (wt.%). The known composition for the Corning Glass Standard B comes from Brill (1999b, 544).

6.6 Description of the samples: Islamic glass in the late 8th – 12th centuries AD:

Islamic glass vessels of the 6th – 9th centuries AD were described by Carboni (2001) as 'proto-Islamic', which means many of its vessel forms and decorative techniques are essentially pre-Islamic but they continued to be used throughout the early Islamic period and gradually evolved into true Islamic forms (Carboni 2001, 15). These 'proto-Islamic' glasses were influenced by two traditions: (1) the Romans in Syria and Israel and (2) the Sassanians in Iraq and Iran (Carboni 2001, 15).

In terms of vessel forms, glassworkers continued to produce vessels such as vases, goblets, bottles, bowls and lamps, similar to its Roman/Byzantine predecessors before the 8th century AD (Carboni 2001, 16; Pollak 2003, 165). They served as tablewares and utilitarian purposes. Some of them may be used for special purposes unknown to us (Kroger 1995, 32).

Under the 'Abbasid and Fatimid rules, glass vessel forms underwent significant changes, along with their chemical compositions (which will be discussed in chapters 8 and 9). It is possible that artisans were brought from different places to the 'Abbasid court to develop glass vessels that are characteristically Islamic (Kroger 1995, 35). As far as we know, various glassworking production zones, such as Iraq, Iran and Egypt, flourished in producing their own decorative styles. It is still uncertain whether there was any exchange of glassworking techniques between production centres, such as Iran and Egypt, in the production of glass vessels (Kroger 1995, 35).

Old vessel forms from the Umayyad period continued to be used, but they began to disappear or become less dominant throughout the 'Abbasid period (Pollak 2003, 167). New forms began to appear and were found in the 'Abbasid contexts in various excavations in the Middle East. Here, we shall look at the typology of selected types of glass vessels dated to the Umayyad, 'Abbasid and Fatimid periods (7th – 12th centuries AD).

6.6.1 Goblets/wine glasses:

Goblets were a very common drinking glass vessel in the East before the Arab Conquest in the 7th century AD. This type of vessel continued to be produced and used throughout the Umayyad period but it went out of fashion during the 'Abbasid and Fatimid periods (Jackson-Tal 2012, 60). Different types of goblets can be distinguished base on their feet and stems (Burdajewicz 2011, 26). Unfortunately, the feet and stems of the goblets sampled in this study did not survive.

The goblet bowl is usually hemispherical, cylindrical or bell-shaped. The disc bases of the goblets RAQ-64, 72 and 77 from al-Raqqa show that these goblets have a hemispherical body. And RAQ-86 and 87 have a cylindrical shape. Another characteristic of these goblets is that they have either a tubular or knobbed stem which varies from large to small. RAQ-13 is an example of a goblet with a small stem. Examples of this is found in Horbat Biz'A in Israel where small, short cylindrical foot and small ring bases of wineglasses/goblets were found (Gorin-Rosen 2012, 59). The small stemmed goblet is one of the most common wineglass types in the Byzantine period and continued into the Umayyad period. It has a wide distribution pattern including Israel, Syria, Lebanon and Jordan (Gorin-Rosen 2012, 59).

Other examples of goblets are found in Hammat Gader, Hippos, Bet Shean, Bursa, Caesarea, Tiberias, Pella, Jerash, Ramla, and Khirbat el-Thahiriya in Israel and Jordan, and Fustat in Egypt (Burdajewicz 2011, 26; Cohen 1997, 405-407; Gorin-Rosen 2010, 221; Hadad 2005, 28; Jackson-Tal 2012, 60-61; Lester 2004, 173-174; Pollak 2003, 165; Scanlon and Pinder-Wilson 2001, 55; Walmsley *et al.* 1993, 222).

6.6.2 Bottles:

Byzantine period bottles continued to be used in the Islamic East during the Umayyad period. For instance, RAQ-70 is a bottle with a cylindrical neck and splayed rim. This type of bottle originated in the Byzantine period and continued into the Umayyad period (Lester 2004, 177).

At the same time, new types of bottles with Islamic characteristics began to appear during the Umayyad period. For instance, RAQ-31 is the base of a cylindrical bottle that is characterised by an upright, rounded rim, thick walls, cylindrical body and a flat, thickened base (Jackson-Tal 2012, 61). Similar parallels are found in Khirbat el-Thahirita (Hadad 2005, 40; Jackson-Tal 2012, 62).

RAQ-67, 71 and 73 are concave bases of small/medium bottles with thicker walls. These bottles usually with folded-in rims and a short neck and a globular or squat body (Gorin-Rosen 2010, 223). They are different from bottles found in the Byzantine period, which are larger and with squared-shapes. Some of them are decorated with wavy trailed decoration, which was a continuation of the Byzantine tradition.

The small and medium bottles in this study are thought to be originated from Syria, Israel and Egypt. These bottles are popular during the Umayyad period and continued into the first half of the 9th century AD. Similar parallels are found in Tiberias dated to the Umayyad period (Lester 2004, 182). Variants of this type of bottle are found in Hammat Gader, Bet Shean, Caesarea, Ramla and Khirbat el-Thahiriya in Israel, Seleucia in Iraq and Fustat in Egypt (Cohen 1997, 427-428; Gorin-Rosen 2010, 223-225; Hadad 2005, 23-25; Jackson-Tal 2012, 61; Scanlon and Pinder-Wilson 2001, 35; Pollak 2003, 165; Ponzi 1970, 72-74).

Globular and rounded bottles were also common in the 8th – 9th centuries AD. RAQ-63 has an everted rim with a straight neck. It is possible that it has a globular body and is dated to the late 8th – 9th centuries AD. RAQ-08, 26 and 28 are concave bases of bottles and RAQ-58 and 95 have convex bases. All of which appear to have a rounded shape. Their exact shapes cannot be reconstructed. But similar parallels are found in Qal'at Sem'an in Syria (Dussart 2003, 178). RAQ-10, 25, 36 and 43 are the body fragments of rounded bottles. Their exact shapes cannot be reconstructed.

RAQ-27 and 30 is a bottle neck with folded-in rims that are flattened. This type of bottle has a bulbous body. Similar parallels are found in Bet Shean, Tiberias, Humayma and Ramla in Israel, Fustat in Egypt and Qal'at Sem'an in Syria (Dussart 2003, 176; Hadad 2005, 40, No. 750-755; Jackson-Tal 2008, 173; Jones 2013, 538; Lester 2004, 182, No. 73-85; Scanlon and Pinder-Wilson 2001, 33). It has been suggested that this

type of bottle was common in Syria and Egypt during the 8th – 9th centuries AD (Lester 2004, 185).

RAQ-37 has a cylindrical neck and a curving round wall. The rim is missing; therefore, it is not possible to assign it to a specific type of bottle. But judging from the shape of the wall it is possible that this is a rounded bottle. Similar finds are found in Ramla in Israel and are dated to the 'Abbasid period (Jackson-Tal 2008, 174, No. 4; Gorin-Rosen 2010, 234, No. 11).

RAQ-57 is a bottle neck with a splayed rim and a ring was applied on the base of the bottle neck. This type of bottle is characterised by a pear-shaped or globular bodies (Lester 2004, 180). This type of vessel appeared during the Umayyad period and was common in Syria, Israel and Egypt. Two examples of these are found on two cage flasks that are originated from Syria (Carboni 2001, 24-25, Cat. 4a and 4b). It was common in the 'Abbasid-Fatimid period and continued to be used in the 12th century AD (Lester 2004, 182). Examples of this are found in Tiberias, Bet Shean, Ramla in Israel and Qal' at Sem'an in Syria (Dussart 2003, 173; Gorin-Rosen 2010, 234; Hadad 2005, 41; Jackson-Tal 2008, 179; Lester 2004, 180-182).

6.6.3 Bowls:

Bowls in this study are dated to the early Islamic period. They first appeared in the Umayyad period and are significantly different from the Byzantine bowls in shape. Roman and Byzantine bowls generally have flaring or upright outfolded rims, slanting walls or S-shaped profiles, and tubular ring bases (Gorin-Rosen 2010, 215). RAQ-69 is a bowl with flat base and in a spherical shape. This is a typical bowl of the early Islamic period.

RAQ-80, 83, 84, 92 and 93 are bowls with thickened, curving-in rims that are very common in the Umayyad, 'Abbasid and Fatimid periods. Similar parallels are found at Caesarea, Ramla, Khirbat el-Thahiriya, Bet She'an, and Humayma in Israel. They are sometimes decorated with horizontal trail and lustre painted (Gorin-Rosen 2010, 215; Hadad 2005, 21; Jackson-Tal 2008, 166; 2012, 60; Jones 2013, 535; Lester 2004, 168; Pollak 2003, 167).

During the 9th – 11th centuries AD, new types of bowl appeared. For instance, RAQ-06, 17, 20, 44 are body fragments of bowls and RAQ-20 and 50 are the bases of bowls which are flat and rounded. Based on the shapes of the body fragments and the bases, it appears that they have straight walls. The rims of these bowls are missing and it is not possible to determine the exact shapes of these bowls. Bowls with straight walls and flat bases are very common during the 9th – 11th centuries AD. Parallels for these are found in Ramla, Bet Shean, and Caesarea in Israel (Hadad 2005, 35; Jackson-Tal 2008, 167; Pollak 2003, 167).

6.6.4 Small bottles:

Small bottles with cylindrical body and rectangular body appeared in small quantity during the Umayyad period. The usual colour of this type of vessel is colourless, light or dark bluish green, yellowish green or light yellow (Hadad 2005, 39). The earliest examples were found in Bet She'an in Israel and are dated to AD 738 – 749 (Lester 2004, 191). They became more widespread during the 'Abbasid period (Gorin-Rosen 2010, 231; Hadad 2005, 39). Two examples (RAQ-12 and 19) are found in al-Raqqa in Syria. It has a funnel-shaped neck and round rim and thick base (Lester 2004, 188). The colour of these vessels are colourless and light green respectively.

Similar parallels are found in Bet Shean, Ramla, Tiberias and Caesarea in Israel, Fustat in Egypt, Nishapur (9th – 10th centuries AD) and 'Abbasid Bijan Island in Iran (Gorin-Rosen 2010, 229; Hadad 2005, 39; Kroger 1995, 63-70, Cat. 60-85, 77, Cat. 98-99; Lester 2004, 188-191; Pollak 2003, 167; Reiche 1996, 196; Scanlon and Pinder-Wilson 2001, 41-42).

Other variants such as bottles with cylindrical body and rounded base and bottles with flattened body were found in Nishapur and Fustat respectively and are dated to the 8th – 10th centuries AD (Kroger 1995, 78-79, Cat. 100-103; Scanlon and Pinder-Wilson 2001, 41, 44-45).

Small bottles with a globular body were also common in the Umayyad, 'Abbasid and Fatimid periods. Some have a short-ridged neck which is very common in the early Islamic period. RAQ-15, 18, 21, 41, 43, 51, 54 and 55 from al-Raqqa are small bottles

with a rounded shape. Parallels of these can be found in excavations such as Fustat in Egypt, Caesarea, Bet Shean, Tiberias (early ‘Abbasid context) and Ramla in Israel, and Nishapur in Iran (Gorin-Rosen 2010, 233-235; Pollak 2003, 167-168; Scanlon and Pinder-Wilson 2001, 47-49). These small bottles are thought to have held liquids such as perfume, cosmetic oil or medicine (Gorin-Rosen 2010, 229).

6.6.5 Islamic glass decoration:

In terms of glass decoration, they are diverse, complicated and elaborate. These decorations derived from their Roman and Sassanian predecessors and were adapted by the Muslims since the Umayyad period (Carboni 2001, 15). Art-historical and typological studies on Islamic glasses suggest various glass production centres in the Islamic East specialised in the production of various decorations on glass. These include Iraq, Iran, Egypt and Syria. As we shall see, archaeologists cannot always determine which decorative techniques derive from which regions. This is why chemical analysis of Islamic glass can offer a different approach to determine which techniques originated from where by studying the relationship between glass compositions and vessel forms.

6.6.6 Mould-blown decoration:

This decorative technique can be traced back to the Roman period. It was invented after the discovery of glass blowing in around the mid-1st century BC. Glass is blown into a patterned mould to create decoration. This technique continued to be used by both the Romans and the Sassanians (Kroger 1995, 85; Whitehouse 2002c, 81).

Two small metal dip moulds for producing glass vessels have been found. One is in the form of a cup with eight pairs of vertical stripes and each is separated by scrolling half-palmettes; another is in the form of a conical beaker with lozenge-shaped bosses in prominent relief, and thirteen horizontal rows of bosses extend from the top to bottom. A concentric circle of seven bosses is found on the base surrounded by a ring of thirteen bosses. An inscription with two lines of Arabic written in Neshki was scratched on the upper part of the exterior and they are now in The David Collection and The Corning Museum of Glass. They probably originated from western Asia, Egypt, Syria or Iraq

and are dated to the 9th – 10th centuries and 10th - 13th centuries AD respectively (von Folsach and Whitehouse 1993, 150-152, Fig. 3, 6; Whitehouse 2001b, 84-85, Cat. 10-11).

Excavations at Nishapur and Ghubayra in Iran have produced evidence that glass with mould-blown patterns were produced with two-part moulds (Carboni 2001, 197-198; Kroger 1995, 85). This is more common and when it was used it would leave distinctive seams on the sides and bottom of the object. On the other hand, the use of a single mould would not leave any seams on the final products (Baker 2000, 201; von Folsach and Whitehouse 1993, 150). The 11th century AD Serci Limani shipwreck produced numerous fragments of mould-blown glass that were made with single moulds as they have no seam marks on the vessels (Lledo 1997, 44). This decorative technique spread quickly in the Islamic lands, namely Iraq, Iran, Syria and Egypt, where excavations have revealed different types of mould-blown decorative motifs (Carboni 2001, 198). Mould-blown decorations are found in beakers, small-sized bottles, bowls, toilet flasks and jars, pear-shaped ewers and vases (Kroger 1995, 85; Pinder-Wilson and Scanlon 1987, 62-64; Scanlon and Pinder-Wilson 2001, 66-79; Whitehouse 2001b, 87-88, Cat. 13-14).

Several types of mould blown decorations were selected for this study:

(1) A flask (VA-05) from Pemba Island and a bowl/beaker (VA-25) from al-Mina are decorated with lozenge-shapes (at least 3 lozenges for the former and two for the latter). Each lozenge has a central sunken lozenge. The closest parallels of these are two miniature bottles from the Iranian or Central Asian region, both of which are decorated with rows of lozenges and are dated to the 11th – 12th centuries AD (Carboni 2001, 221, Cat. 58a and 58b). It has been suggested that lozenge patterns were produced in the Iranian or Central Asian regions rather than in the western Islamic region (Carboni 2001, 221).

(2) A phial (VA-06) and a flask (VA-07) from Pemba Island are fragments of miniature bottles decorated with vertical ribs. These ribs are relatively thick. Small bottles decorated with vertical ribs are found in Nishapur in Iran. This type of decoration was very common in Iraq and Iran from the Sassanian period onward (Kroger 1995, 85). A

fragment of a flask (VA-04) from Pemba Island is also decorated with vertical ridged ribs but they appear twisted. A similar parallel can be found in the al-Sabah collection where a small cylindrical bottle was decorated with similar pattern. It is thought to have originated from eastern Iran or Central Asia, particularly the area of Transoxiana (Carboni 2001, 207, Cat. 51b). At al-Raqqa, two fragments of glass are found to have mould-blown decorations. RAQ-40 is a bottle decorated with vertical ribs. A similar parallel is found in Samarra (Lamm 1928, 19, u. 37).

Lamm (1935) has published glass with vertical ribs patterns housed in the National Museum, Stockholm, which include a beaker, bottles, flasks, jugs and a pitcher dated to the 6th - 14th centuries AD. They were found in Rayy, Saveh and other unspecified locations in Iran (Lamm 1935, 10, Plate 18-20).

But mould-blown vertical ribs in these glasses could also have originated from the Levantine region and Egypt. They are commonly found on vessels such as cylindrical bowls, jars, flasks and bottles. They are found in Khirbat el-Thahiriya, Ramla, Caesarea, Tiberias and Bet Shean in Israel, Ghubayra in Iran and Fustat in Egypt (Baker 2000, 200-201; Gorin-Rosen 2010, 246; Hadad 2005, 27; Jackson-Tal 2012, 65; Pinder-Wilson and Scanlon 1987, 63; Scanlon and Pinder-Wilson 2001, 70-73). This decoration was very common in Syria, Egypt, the Israeli coast from the late Roman period (Carboni 2001, 218-219, Cat. 56; 242, Cat. 3.291a-c; Kroger 1995, 85; Pollak 2005, 171; Scanlon and Pinder-Wilson 2001, 70; Whitehouse 2001b, 82).

(3) A shallow bowl (VA-28) from al-Mina is decorated with sunken dots with patterns of tear-drops and circles. It is reported by Lane (1937, 67, Fig. 11 E) and similar pieces were found in Samarra (Lamm 1928, 43-44, No. 158-163). Similar motifs are very common in the Islamic East during the 8^{th} – 11^{th} centuries AD. For instance, they are found in Qal'at Sem'an in Syria, Bet Shean, Caesarea and Tiberias in Israel and the Serce Limani shipwreck (Dussart 2003, 177; Hadad 2005, 36; Lester 2004, 202; Lledo 1997, 45-54; Pollak 2003, 166). A bottle (RAQ-47) from al-Raqqa is decorated with a concentric circle.

6.6.7 Cut decoration:

Cut decoration is another popular decoration on Islamic glass vessels during the late 8th – 12th centuries AD. It originated in the Roman period and was practised extensively by the Romans until the 4th or 5th century AD but continued in Iraq and Iran under the rule of the Sassanids. It was used during the Islamic period until the 11th century AD (Carboni 2001, 71; Whitehouse 2001c, 155). In terms of its origin, Iraq and Iran are thought to be the regions that were famous for the production of cut decorations (Pinder-Wilson 1995, 115). The majority of the cut decorations are the result of wheel-engraving (Carboni 2001, 71). This technique belongs to the cold-work decoration and was carried out with a rotary, abrasive-fed tool and was applied to the glass after it had been free-blown or old-blown (Kroger 1995, 120). The tool was used to engrave patterns into the glass surface or to grind down or cut away part of the glass surface to create different motifs and decorations (Kroger 1995, 120). There are different types of cut decoration: (1) diamond-scratched decoration; (2) linear cut or U-shaped, intermediate and slant cutting (incised cut), (3) molar flasks, (4) facet cut and (5) relief cut decorations (Carboni 2001, 71; Kroger 1995, 120; Pollak 2005, 172; Scanlon and Pinder-Wilson 2001, 82-106). Here, we will only consider diamond-scratched decoration and linear-style decoration.

6.6.8 Diamond-scratched decoration:

Diamond-scratched decoration is created using a sharp tool with minerals such as corundum and topaz that have hardness greater than seven on the Mohs's scale, hard stones and diamonds in later centuries (Kroger 2005, 140; Whitehouse 2001c, 156). The incisions are very thin and they barely scrapped away the surface of the glass. This decoration is similar to the sgraffito technique that was used on pottery (Carboni 2001, 72).

This technique already appeared in the Roman and Byzantine periods alongside with wheel-cut and engraved decoration. Scratched-decoration appeared in the Umayyad period with two bowls decorated with lozenges and triangles, dated to the 8th century AD, found in Bet Shean in Israel. Parallels can be found in Susa in Iran (Hadad 2005, 22-23). This technique was widely practiced in the 'Abbasid period.

They are usually produced on dark coloured glass (80% of which are on dark blue glasses, also green or yellow glasses) rather than colourless glass as the incisions would show up better on the former (Carboni 2001, 72, 76; Carboni 2007, 88; Kroger 2005, 142; Scanlon and Pinder-Wilson 2001, 82; Whitehouse 2010, 13). The motifs are usually in the forms of chevrons and naturalistic floral themes (Scanlon and Pinder-Wilson 2001, 82). But they also include simple linear and geometric patterns, complicated patterns include figures of birds and geometric motifs, and Arabic inscriptions (Carboni 2001, 72; Carboni 2007, 88). This decoration is found on circular plates, bottles, bowls, dishes, cylindrical beakers, ewers, flasks, goblets, high-walled bowls and pitchers (Carboni 2007, 88; Kroger 2005, 142-143; Hadad 2005, 37; Whitehouse 2010, 13).

RAQ-82 from al-Raqqa and VA-27 from al-Mina are scratch decorated. RAQ-82 is a dish/bowl with complex scratched decorations. It consists of hatched triangles surrounding a braided motif. A rosette is at the centre of the dish/bowl. The colour of this dish/bowl is cobalt blue. Similar motifs are found in Nishapur in Iran, a flask in the Corning Museum and the Al-Sabah flask in Kuwait (Kroger 2005, 144). The possible origins of this decorative technique include Syria, Iran and Iraq (Kroger 2005, 144).

A bowl (VA-27) from al-Mina is decorated with a hatched triangle near the rim and has two vertical lines next to it. A semicircle filled with lines is found near the end of the fragment. This decoration has parallel from Bet Shean and Samarra and is dated to the ‘Abbasid and Fatimid periods (Hadad 2000, 64-65; 2005, 37; Lamm 1928, 82). The colour of this bowl is deep brown. This fragment was published by Lane (1937, 68, Fig. 12G). These decorations appear to have originated from Syria or Iraq and Iran (Carboni 2001, 113, Cat. 2.9a and 2.9b).

Inscriptions occur in several examples such as a goblet from western Asia or Egypt, and are dated to the 9th century AD. They can have a Kufic inscription on the body in between the continuous horizontal band of thirty-two isosceles triangles filled with transverse hatching and two parallel lines filled with hatching (Whitehouse 2001, 164-165, Cat. 71). Examples of geometric patterns and Kufic inscriptions are also found at Bet Shean and are dated to the ‘Abbasid and Fatimid periods (Hadad 2005, 37). A bottle

(VA-03) from Pemba Island is decorated with a band of Arabic inscriptions. The inscription appears at the base of the bottle.

Examples of scratched decorations are found in Fustat in Egypt, Qal'at Sem'an in Syria, Samarra in Iraq, Pella, Caesarea (Stratum VII), Bet Shean, Ghubayra and Ramla in Israel, but they are mostly from Syria, Iran and Iraq (Baker 2000, 198; Carboni 2001, 76-79, Cat. 17a-c; Dussart 2003, 177-178, Fig. 6.1 a 3-3a; Gorin-Rosen 2010, 245; Lane 1937, 67; O'Hea 1992, 259; Pollak 2003, 167; 2005, 172; Scanlon and Pinder-Wilson 2001, 82-83; Whitehouse 2001, 156).

The finds from Caesarea in Israel are thought to be imports as they were only found in small quantities (Pollak 2003, 167). Scratched decorated glass plates of the same dark blue colours, patterns and technique were traded extensively in the Islamic world and reached as far as China. The excavations at the Famen Temple in Shaanxi Province have yielded such glasses and have provided a date of AD 874 for the vessels, which is of the late Tang dynasty and shows that scratch-decorated glass was imported as a luxury item to the Far East and was used as grave goods (Carboni 2001, 80; Carboni 2007, 89). The *terminus ante quem* for these find suggests this glass group could have originated in the 9th century. Many of these finds were concentrated in the Syrian and Mesopotamian regions which could be where they were produced. It is possible that it was these regions that had produced the glasses found in China (Carboni 2007, 89).

Gorin-Rosen (2010) has noted that this technique was very widespread across the Islamic East in the 'Abbasid and Fatimid periods, in major cities and small settlements. Therefore, it is possible that one or more local workshops in Israel, Iraq, Iran, Syria and Egypt could have produced this ware (Gorin-Rosen 2010, 245; Kroger 2005, 146). Kroger (2005) suggests that Egypt was the main production centre of scratch-decorated glasses, and the Syro-Palestinian region the second important production centre of this ware (Kroger 2005, 147).

Scratched decoration was probably practised in Constantinople as well. Scribing with stick and needle is found on Byzantine enamelled window glass in the early 12th century AD (Megaw 1968, 13). Some Byzantine gilded glasses have scratched decorations on

them. However, the vessels are dated later than the Islamic glass, and it is not known if there is a relationship between the two.

6.6.9 Linear-style decoration:

A bowl/beaker (RAQ-89) from al-Raqqa is decorated with horizontal and vertical grooves. This type of cut decoration is similar to the linear style that is found in Nishapur and Samarra (Kroger 1995, 146-150; Lamm 1928, 68). It is characterised by cut lines of various depths and U-shaped in cross section. The motifs include vegetal forms and horizontal and vertical cuts are used to define the veins of leaves (Kroger 1995, 146). These decorations are found in small shallow bowls, cylindrical beakers and small bottles. It was noted that linear-style decoration was popular in the 9th century AD Samarra in Iraq (Kroger 1995, 120). It is likely that this style was originated from Iraq and Iran in the 9th century AD.

6.6.10 Tonged decoration:

Tonged decoration is produced by impressing after the glass was taken off the kiln and it was still malleable. A pair of tongs was used to impress the glass surface. The two ends of these tongs were circular or square and at least one side has a carved motif that was used to impress in relief on the glass (Carboni 2001, 261; Kroger 1995, 95; Lane 1937, 70). The motifs include simplified birds, leaves, straight lines and half circles, concentric circles with or without a central dot, concentric squares with blocks of dots, and V-shaped motifs (Carboni 2001, 263, Cat. 69a, 268-269, Cat.71a; Hadad 2005, 37; Kroger 1995, 95; Lane 1937, 70; Scanlon and Pinder-Wilson 2001, 82). They were usually found on open vessels such as bowls, cups and beakers. But they are also found on pitchers, jar and small bottles (Carboni 2001, 271, Cat. 72, 287, Cat. 3.55d-f; Gorin-Rosen 2010, 244; Hadad 2005, 37; Scanlon and Pinder-Wilson 2001, 80-82).

RAQ-39 and 88 are a globular bottle and a bowl/beaker decorated with circles. Similar decorations are found on a bowl (VA-26) from al-Mina. RAQ-90, VA-18 and 19 are beakers/bowls decorated with horizontal line of dashes. These decorative motifs are very common in the Islamic East during the ‘Abbasid period. They are found in Bet Shean, Caesarea, Khirbat el-Thahiriya, Ramla and Tiberias in Israel, Pella (‘Abbaisd

context) in Jordan, Fustat in Egypt, Samarra in Iraq and Nishapur in Iran (Gorin-Rosen 2010, 243; Hadad 2005, 37; Jackson-Tal 2008, 172, Fig. 6.113.4; 2012, 66, Fig.3. 41; Kroger 1995, 95; Lamm 1928, 45-48; Lester 2004, 204, Fig. 7.14. 178; O'Hea 2003, 134, Fig. 2; Pollak 2003, 168, Fig. 2, 30 and 33; Scanlon and Pinder-Wilson 2001, 80-81; Walmsley *et al*. 1993, 226, Fig. 25.11).

The tonged decorations of VA-20, 21, 22, 23 and 24, all of them are bowls from al-Mina, are unusual. They are decorated with stylised birds facing left or right. VA-20 and 24 show the full profile of the birds. It is possible that lines of dashes were also present in these bowls, as shown in VA-24. Lane (1937) has suggested that these bowls were locally made in northern Syria in the 9th and 10th centuries AD (Lane 1937, 68, 70). The closest parallels which have stylised birds are found on a fragment of a beaker from Fustat and a fragment of a bowl from the Mesopotamian region (Carboni 2001, 285, Cat. 3.54; Scanlon and Pinder-Wilson 2001, 80-81, Pl. 38i). But even these two examples are markedly different from the al-Mina examples. Therefore, it is not impossible that they were made locally in northern Syria.

In terms of the chronology, the earliest find of glass with tonged decoration is dated to the Umayyad period and is found in Stratum VIII Caesarea (Pollak 2003, 165, Fig. 1.15). It became more common in the 'Abbasid period. Large quantities of tonged decorated bowls and beakers were found in Bet Shean (a total of 41), others in Stratum VII Caesarea, Ramla (9th – 10th centuries AD) in Israel, beakers and bowls from Fustat (8th – 10th centuries AD) in Egypt and Nishapur (9th – 10th centuries AD) in Iran (Gorin-Rosen 2010, 244-245; Hadad 2005, 36-37; Kroger 1995, 96-99; Pollak 2003, 166; Scanlon and Pinder-Wilson 2001, 80-82).

No tonged decoration was apparently used after the 10th century AD (Kroger 1995, 96). It has been suggested that tonged decoration originated in Egypt in the 8th – 10th centuries AD and spread to Iraq and Iran during the 9th century AD. Regional production of specific motifs could exist throughout the 8th – 10th centuries AD, such as the amphora motif from al-Mina that was not found in Iran or Egypt (Carboni 2001, 261; Kroger 1995, 95; Lane 1937, 70; Scanlon and Pinder-Wilson 2001, 80).

6.6.11 Middle Byzantine glass (9^{th} – 12^{th} centuries AD):

Several types of glasses are found to be produced within the Byzantine Empire in the 9^{th} – 12^{th} centuries AD and can be divided between luxury goods and common goods. These include Blue Coil Ware, Red Streak Ware, stemmed, handled and goblet lamps, and gilded glasses. Their forms are significantly different from those of the Islamic East. Excavations in Amorium, Sardis and Istanbul in Turkey and Butrint in Albania have yielded glasses that are dated to the 9^{th} – 12^{th} centuries AD. The excavation at Amorium provides the most comprehensive study of middle Byzantine glass vessel forms. But in this study these types of wares will not be discussed because of the availability of materials for chemical analysis. Therefore, only the window glasses from the Byzantine Empire in the 9^{th} – 12^{th} centuries AD will be discussed.

6.6.12 Byzantine window glass:

Window glass was found to have been used and produced in the Byzantine Empire in the 9^{th} – 12^{th} centuries AD. In Sardis, 30 window glass fragments with the colours of pale blue and black-blue, deep and blackish purple, pale yellow, green and olive are found to be associated with Church E which is dated to the 13^{th} century AD (von Saldern 1980, 98, 101). In Amorium, some 550 fragments of window glass of olive, bluish green, light green, green, colourless, yellow and brown colours were found to be associated with the Large Building (a palace or official building) of the early Byzantine period in the 5^{th} – 7^{th} centuries AD (Gill 2002, 101). It continued to be produced in the middle Byzantine period as fragments of window glasses in the colours of bluish green, green, olive, colourless, yellow and brown are found in the 10^{th} – 11^{th} centuries AD contexts associated with domestic buildings in the Upper City and the Lower City Church (Gill 2002, 225-228).

In Istanbul, two groups of stained window glass were found in the Pantocrator Church (Zeyrek Camii) and in the Chora Church (Kariye Camii) (Henderson and Mango 1995, 346). The Zeyrek Camii glasses were found with H-shaped lead cames. Their colours are strong blue (24%), colourless (24%), amber-yellow (18%), emerald green (16%), purple-red (13%) and pink (5%) (Megaw 1963, 349). They were painted in opaque enamel paint on their interior surface and nine life-size human figures banded by

geometric motifs were painted (Henderson and Mango 1995, 346; Megaw 1963, 351-360).

In this study, the majority of the window glasses from Zeyrek Camii are cast and painted window glass (ZC-07, 08, 09, 10, 11, 12). Their colours include blue (n=1), lilac (n=1), purple (n=1) and colourless (n=3). Two fragments of crown glasses (ZC-05 and 13) are also studied in this study and their colours are green and colourless.

A small quantity of stained window glass associated with lead cames was found in Kariye Camii. They are in the colours of blue, purple-red, light and dark green, colourless, pink, red and amber-yellow (Megaw 1963, 365). Life-size human figures were also painted on these glasses. Megaw (1963) has suggested that these two groups of glasses came from two contemporary workshops (Megaw 1963, 365).

Who produced them and where these glasses were made are subjects of debate. Megaw (1963) has suggested that they were made in the Byzantine Empire, based on the use of colours (the blue glasses are darker than Western glasses, also only dark purple-red glasses were made in the East while ruby red was used in the 12th century AD western Europe), the presence of decorative motifs such as floral patterns in rotae which were typical for textiles in the Byzantine pictorial repertory, and the manufacturing technique of sheet glass (Dell'Acqua 2004, 71; Megaw 1963, 363). Megaw also suggested that these glasses are dated to AD 1124 – AD 1136 for the Zeyrek Camii fragments and AD 1120 for the Kariye Camii fragments, and the technique of the production of these window glasses can be attributed to the Byzantines because of the long Byzantine tradition of the glaziers' craft (Megaw 1963, 363).

Jean Lafond has disputed Megaw's claim that the glasses were made by the Byzantines and the glasses were dated to AD 1124 - 1136. Lafond claimed these glasses were made under German influence during the occupation of Constantinople in AD 1204 by the crusaders and when Zeyrek Camii was controlled by the Venetians (Henderson and Mango 1995, 346). These windows were not necessarily installed the same time as the foundations of the churches. The fact that we do not know if Kariye Camii was controlled by the crusaders suggests the window fragments could have been produced later and not by the Europeans (Henderson and Mango 1995, 348).

But recent analysis by Dell'Acqua (2004) suggests that the windows might have been produced by western master glaziers, who used fire-tempered grisaille and leading that were typical of western medieval stained glasses, but at the same time added motifs that were of Byzantine tradition to the window glass (Dell'Acqua 2004, 73-74). She has also suggested that the window glasses from Zayrek Camii and Karyie Camii were dated to the second half of the 12th century AD and the reign of the Byzantine Emperor Manuel I Komnenos (Dell'Acqua 2004, 73).

6.7 Summary:

The use of scientific techniques to analyse ancient glasses in the past decades has yielded promising results and findings concerning the technology, provenance, and economy of ancient glasses. Electron microprobe analysis (EPMA-WDS) was specifically chosen for this study. It is a powerful method of chemical analysis that provides us with information on the chemical composition and element distribution of a sample. Many major and minor elements, such as Na, Mg, Al, K, Ca, Mn and Fe, can be detected accurately using EPMA and provide us with information regarding glassmaking raw materials and glass compositional groups.

A range of glass vessel forms were selected for analysis to investigate whether there is a relationship between glass vessel forms and chemical compositions. Both undecorated and decorated vessels were selected. Raw glasses and a frit were also selected specifically to provide a benchmark against contemporary raw glasses and vessel glasses found in other regions and the chemical composition of a glass production centre.

With the right sampling and analytical techniques, combined with archaeological and typological analyses, we will be able to bridge the two disciplines together to answer important research questions of this study regarding Byzantine, Islamic, east African and Georgian glasses in the late 8th – 14th centuries AD.

Chapter 7: Results

7.1 Introduction:

All the glass groups identified in this study are given in Table 7.1. The full EPMA results are given in Appendix Tables 1-7. The mean and standard deviation of each group is given in Tables 7.2-7.8 (only glass samples with groups are shown, no means and standard deviations have been calculated for samples which are different but for which there are small numbers). They show that all but one of the samples are of the soda-lime-silica glasses (SiO_2: 57.59% - 74.48%; Na_2O: 11.22% - 18.88%; CaO: 3.23% - 11.79%). The chemical composition of RAQ-44 from al-Raqqa shows that it is not a glass sample. Therefore, it will not be discussed here. In this chapter, the author will attempt to identify the compositional groups of the glasses and to identify the raw materials used to produce these glass samples.

Sites	Natron Glass	Plant Ash Glass	Mixed Natron-Plant Ash Glass	High Alumina Glass
Al-Raqqa	Al-Raqqa Type 3, al-Raqqa Type 5	Al-Raqqa Type 1a and 1b, al-Raqqa Type 2, al-Raqqa Types 4a, 4b and 4c, al-Raqqa Type 6	None	None
Al-Mina	VA-19 and 27	Al-Mina Group 1, VA-15, VA-26	None	None
Fustat	None	VA-01 and VA-02	None	None
Pemba Island	None	VA-03 and 04, VA-05, VA-07	None	VA-06
Al-Qadisiyya, Samarra	None	VA-08, 09 and 12, VA-10 and 11, VA-13	None	None
Zeyrek Camii	None	Zeyrek Camii Group 1	Zeyrek Camii Group 2	None

Tbilisi	Geo-09	Geo-03 and 05, Geo-02, 06 and 07, Geo-01, Geo-04	None	Geo-08

Table 7.1. A summary table of all the glass groups found in this study.

In recent years, researchers have used scientific techniques to study natron and plant ash glasses to determine their chemical compositions, raw materials used to produce these glasses and their provenance. Major and minor elements are introduced in the glass batch by using primary raw materials such as mixing sands and the mineral natron to produce natron glasses; and mixing sands/quartz and plant ashes to produce plant ash glasses (Henderson 2013, 83). Therefore, it is possible to use certain major and minor elements to identify different chemical compositional groups, the geochemistry of the raw materials and the provenance of the glass groups.

For natron glasses, the primary raw materials used are natron, which is a relatively pure source of sodium carbonate, and it was mixed with beach sands, which are impure and provided the necessary SiO_2 for the glass. The lime source in natron glass was also provided by sands since natron does not contribute any calcium to the glass. And because beach sands are impure and contain various heavy minerals, characteristic elements such as Al_2O_3, Fe_2O_3 and TiO_2 are usually found in natron glasses. Therefore, we can use elements such as Al_2O_3, Fe_2O_3, TiO_2 and CaO to identify different glass compositional groups and the geological origins of the silica source (Henderson 2000, 27; 2013, 59-60, 309). Using this information, we can identify possible production zones for natron glasses.

On the other hand, it is a little complicated for plant ash glasses. As we can see from Chapter 3, plant ashes provide the necessary level of CaO to stabilise the glass as well as Na_2O and K_2O. Plant genera that are sodium rich are suitable for glassmaking. These include *Anabasis*, *Arthrocnemum*, *Halopeplis*, *Hammada* (*Haloxylon*), *Salicornia* and *Salsola* which belong to the halophytic plants of the Chenopodiaceae family. Soda-rich species have CaO values between 1.63% and 23.10% (Barkoudah and Henderson 2006, 297; Henderson 2013, 23; Rehren 2008, 2566; Tite *et al.* 2006, 1286-1287, Tables 1 and 2).

Various factors determine the chemical composition of plant ashes: (1) the geological backgrounds in which the plants grow, which determine the level of CaO in the plants; (2) the physiognomy of different plant species and genera, which determines the alkali levels in the plants; (3) the way plants are ashed; (4) the season in which the plants are harvested; (5) whether plant species were mixed before ashing (Barkoudah and Henderson 2006, 306-307, 317; Henderson 2013, 41, 310-312).

Despite these factors, it is still possible to use certain elements such as CaO, MgO, Na_2O and K_2O to determine different chemical compositions of plant ashes. Variations of these elements can also help us to determine glass compositional groups and possible production zones for plant ash glasses (Henderson *et al*. 2016, 138). Analyses of plants from different geographical regions and environments also help to provenance plant ash glasses (Barkoudah and Henderson 2006, 306-311; Henderson 2013, 313; Tite *et al.* 2006, 1286-1287, Tables 1 and 2). Similar to natron glasses, we can use Al_2O_3, Fe_2O_3 and TiO_2 to determine the silica sources used to produce plant ash glasses.

Using the elements K_2O and MgO, which usually derive from the alkali source, it is possible to distinguish the glass samples into mineral-based (low magnesia and potash) and plant ash-based (high magnesia and potash) glasses (Figure 7.1). The former usually has a concentration of K_2O and MgO less than 1.5%, which indicates a mineral source, natron, was the principle alkali flux used in the production of these glasses (Brill 2001, 28). They were produced and used extensively between 800 BC and AD 800 (Henderson 2002, 595).

Plant ash glasses have K_2O and MgO levels above 1.5%, which suggests a plant ash-based recipe was used to produce these glasses. They were produced since the 2nd millennium BC in the Mesopotamian region and throughout the Sassanian and Islamic periods (Brill 2001, 28; 2005, 67; Freestone 2006, 6, Table 2; Freestone *et al.* 2000, 69; Henderson 2002, 595; Lilyquist and Brill 1993, 41-42; Mirti *et al.* 2008, 430).

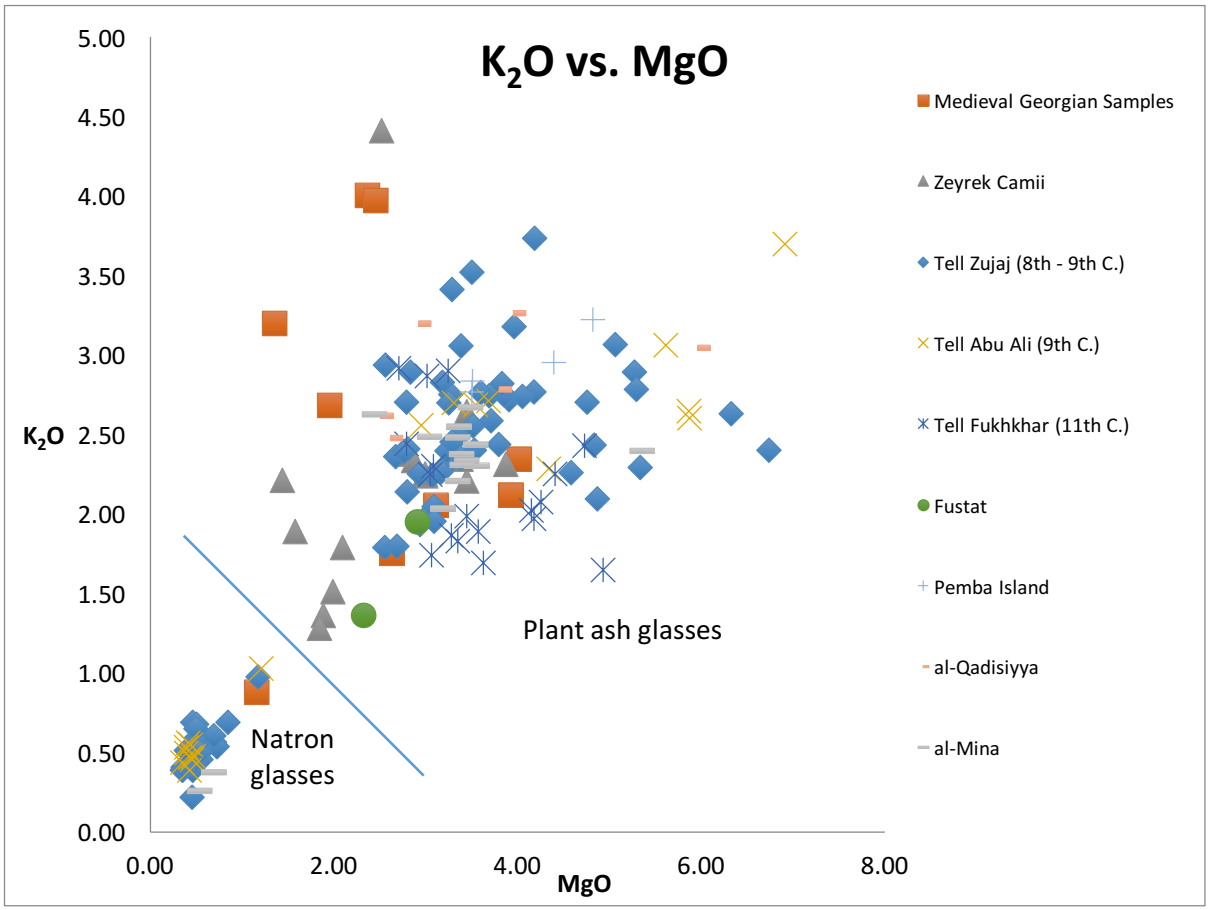


Figure 7.1: A bi-plot of K_2O versus MgO for all the analysed samples in this study. The samples are from al-Raqqa, al-Mina, al-Qadisiyya in Samarra, Fustat, Tbilisi, The Pemba Island and Zeyrek Camii in modern day Istanbul.

7.2 Natron glass:

The majority of natron glasses comes from the late 8^{th} – 9^{th} centuries AD strata of the glassworkshop at Tell Zujaj (n=25) and the 9^{th} century AD settlement at Tell Abu Ali (n=10) in al-Raqqa, Syria. Two samples from 9^{th} – 10^{th} century AD al-Mina (VA-19 and 27) in Syria and one sample dated to the 10^{th} – 13^{th} centuries AD from Tbilisi in Georgia (Geo-09) also belong to the natron-based glass type.

Elements	al-Raqqa Type 3 (wt%) (n=33)	al-Raqqa Type 5 (wt%) (n=2)	al-Mina (VA-19 and 27) (wt%)
SO_3	0.10 +/- 0.05	0.06 +/- 0.01	0.08 +/- 0.02
P_2O_5	0.10 +/- 0.04	0.08 +/- 0.03	0.14 +/- 0.05
V_2O_5	0.01 +/- 0.01	0.01 +/- 0.01	0.03 +/- 0.00
As_2O_5	0.14 +/- 0.11	0.14 +/- 0.12	0.11 +/- 0.10
Sb_2O_5	0.01 +/- 0.02	0.02 +/- 0.00	0.00
SiO_2	71.48 +/- 1.31	74.85 +/- 0.53	68.37 +/- 2.74
TiO_2	0.07 +/- 0.04	0.10 +/- 0.01	0.31 +/- 0.03
SnO_2	0.01 +/- 0.01	0.02 +/- 0.02	0.01 +/- 0.00
Al_2O_3	2.93 +/- 0.20	3.52 +/- 0.03	2.23 +/- 0.29
Cr_2O_3	0.01 +/- 0.01	0.01 +/- 0.01	0.02 +/- 0.01
Fe_2O_3	0.38 +/- 0.12	0.49 +/- 0.10	0.91 +/- 0.00
MgO	0.54 +/- 0.21	0.64 +/- 0.12	0.62 +/- 0.11
CaO	8.27 +/- 0.52	7.25 +/- 0.17	10.80 +/- 1.40
MnO	0.03 +/- 0.03	0.01 +/- 0.00	0.02 +/- 0.00
CoO	0.01 +/- 0.01	0.01 +/- 0.00	0.01+/- 0.01
CuO	0.02 +/- 0.02	0.00 +/- 0.00	0.00
ZnO	0.01 +/- 0.01	0.01 +/- 0.01	0.01 +/- 0.00
BaO	0.03 +/- 0.02	0.05 +/- 0.02	0.03 +/- 0.01
PbO	0.02 +/- 0.02	0.01 +/- 0.01	0.00
Na_2O	14.02 +/- 0.90	12.67 +/- 1.24	15.29 +/- 1.90
K_2O	0.53 +/- 0.16	0.50 +/- 0.06	0.32 +/- 0.08
Ag_2O	0.02 +/- 0.01	0.00 +/- 0.01	0.01 +/- 0.00
Cl	0.80 +/- 0.12	0.78 +/- 0.18	1.07 +/- 0.04

Table 7.1: Means and standard deviations of natron glass groups from al-Raqqa and al-Mina.

The levels of K_2O (0.22% - 1.03%) and MgO (0.35% - 1.18%) in these glasses are below 1.50%, which suggests that natron was the principle alkali source for these glasses. The compositions of the natron glasses from al-Raqqa, al-Mina and Tbilisi appear to be fairly homogenous, forming a tight cluster in terms of their K_2O, MgO,

Al_2O_3 and CaO levels (Figures 7.1 and 7.2). This suggests there was little variation in the raw material selection of silica and alkali sources, glass batch preparation and melting condition (Henderson *et al.* 2004, 454).

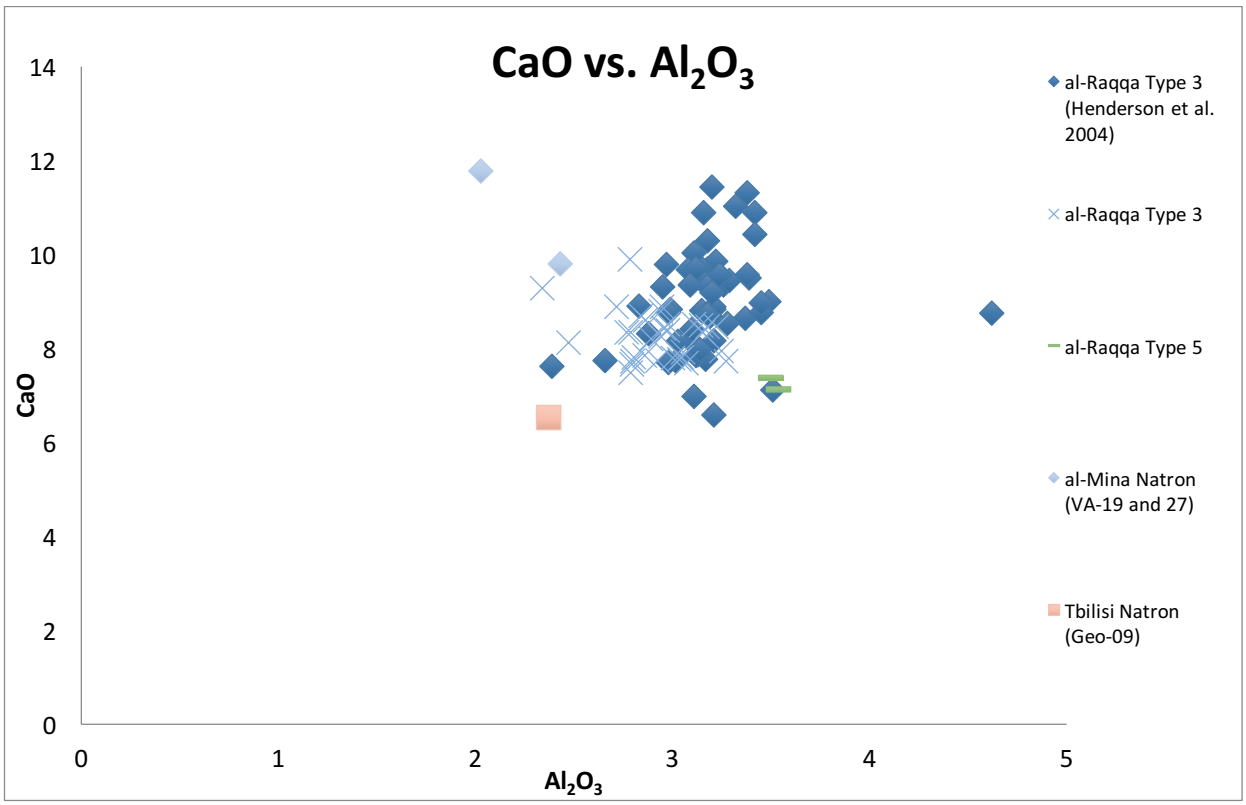


Figure 7.2: A bi-plot of CaO versus Al_2O_3 for natron glasses from 9th century AD Tell Zujaj and Tell Abu Ali in al-Raqqa, 9th – 10th century AD al-Mina and medieval Tbilisi. Data for al-Raqqa Type 3 glasses: Henderson *et al*. (2004).

However, based on their CaO and Al_2O_3, Fe_2O_3 and TiO_2 levels, which reflect the feldspar and carbonate fractions, and iron-bearing minerals present in sand, it is possible to distinguish three different groups of natron glasses in this study.

7.2.1 al-Raqqa Type 3:

Al-Raqqa Type 3 consists of glasses from Tell Zujaj and Tell Abu Ali. It has a relatively high concentration of Al_2O_3 (avg. 2.93%) and CaO (avg. 8.27%) (Figure 7.2, Table 7.1). The high concentrations of these elements suggest they were produced using a sand source which provides the necessary SiO_2 and CaO in the glasses (Henderson 2000, 84-85). It is possible that sands along the Israeli coast (e.g. the Belus River sand) with high

concentrations of feldspar (provides Al_2O_3) and shell fragments (provides CaO) were used (Freestone 2006, 10; Henderson 2013, 60).

As mentioned in Chapter 3, the sand along the Israel coast can provide an average of 2.98% of Al_2O_3 and 8% - 9% of CaO to the glasses, which corresponds to the values found in the al-Raqqa samples (Brill 1988, 266-267, 270; Freestone 2006, 10). Moreover, these glasses have low Fe_2O_3 (avg. 0.38%) and TiO_2 (avg. 0.07%). These are impurities from sand sources such as olivine, ilmenite and titanite (Henderson 2000, 27; 2013, 59-60). These values are consistent with glasses produced using sands from the Israeli coast, which provide an average of 0.33% of Fe_2O_3 and 0.04% of TiO_2 (Brill 1988, 266-267, 270; Nenna 2014, 180). The soda level in these glasses is relatively low (avg. 14.02%), which corresponds to natron glasses in the late antique/early medieval period (Freestone 2003, 111-112; 2005, 197; Henderson 2002, 597-598).

Figure 7.2 also shows that the majority of Type 3 glasses belong to Henderson *et al.* (2004)'s Type 3 natron glass from al-Raqqa. But many of these belong to the lower end member of the al-Raqqa natron glass. Figure 7.3 shows that the al-Raqqa glasses from al-Raqqa Type 3 have a higher concentration of TiO_2 than some of the samples of Henderson *et al.* (2004)'s Type 3, which has negligible levels of TiO_2 but have similar Al_2O_3 and Fe_2O_3 levels (Figure 7.4). These suggest two different glass batches were produced using sand sources with various levels of impurities from the Levantine coast.

The fact that the composition of the natron glasses from Tell Abu Ali are very similar to those from Tell Zujaj suggests the glassworkshops at Tell Zujaj and Tell Abu Ali were importing glass from a similar part of the Levant.

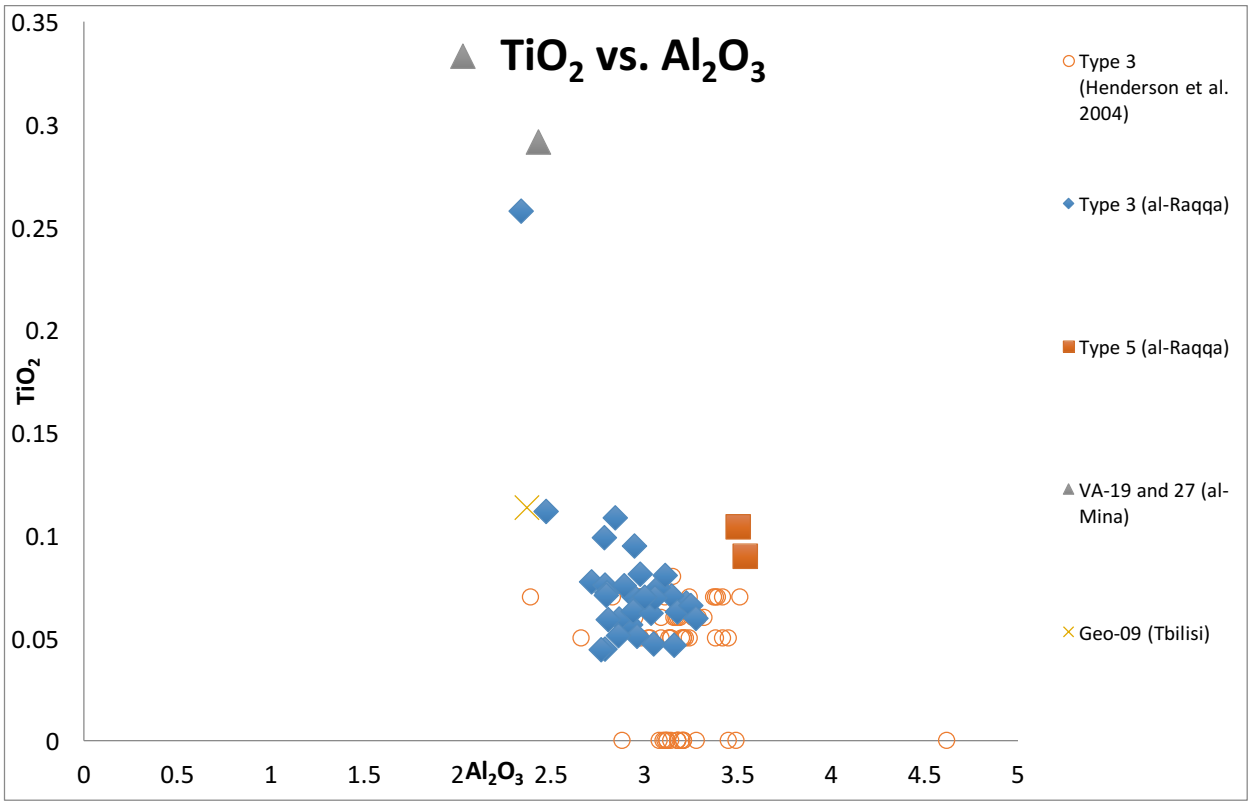


Figure 7.3: A bi-plot of TiO_2 versus Al_2O_3 for natron glasses from 9th century AD Tell Zujaj and Tell Abu Ali in al-Raqqa, 9th – 10th century AD al-Mina and medieval Tbilisi. Data for al-Raqqa Type 3 glasses: Henderson *et al*. (2004).

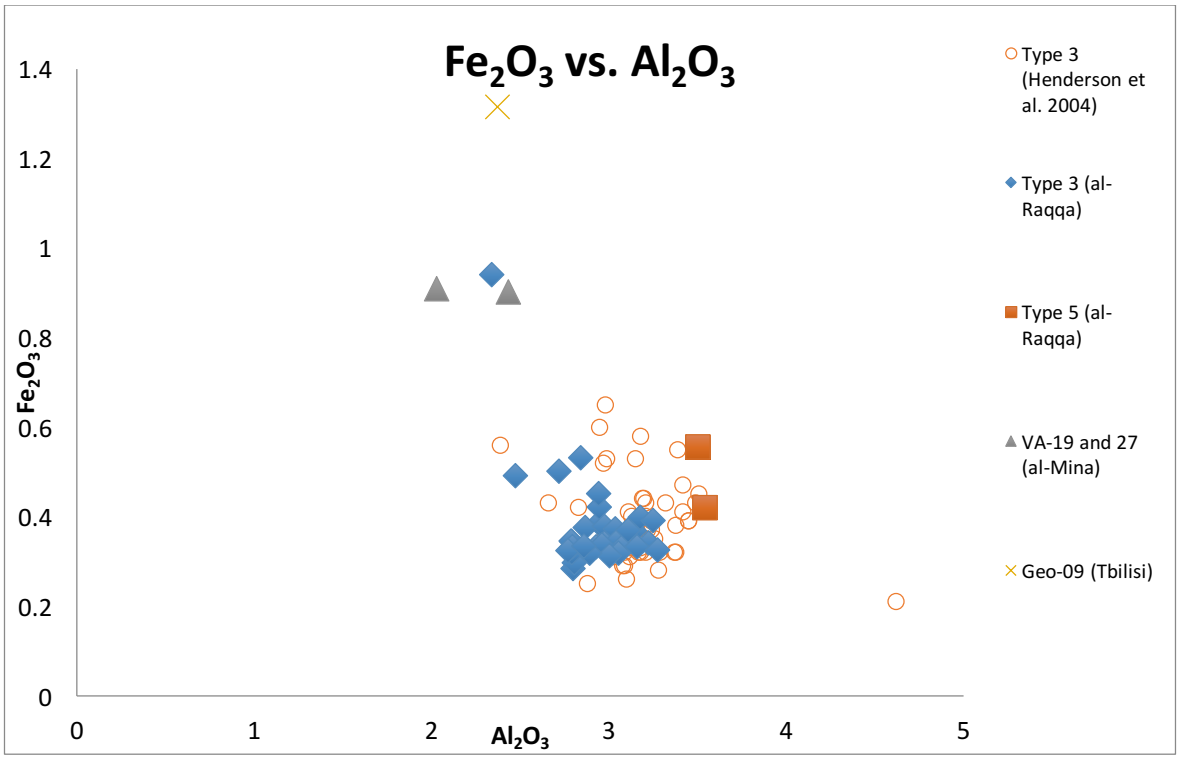


Figure 7.4: A bi-plot of Fe_2O_3 versus Al_2O_3 for natron glasses from 9th century AD Tell Zujaj and Tell Abu Ali in al-Raqqa, 9th – 10th century AD al-Mina and medieval Tbilisi. Data for al-Raqqa Type 3 glasses: Henderson *et al*. (2004).

7.2.2 al-Raqqa Type 5:

Al-Raqqa Type 5 (RAQ-04 and 14) is characterised by a higher concentration of SiO_2 (74.48% - 75.22%) than al-Raqqa Type 3 (Table 7.1). Moreover, its concentrations of CaO (7.13% - 7.38%) is slightly lower than Type 3 (Figure 7.2) and Na_2O (avg. 12.67%) are significantly lower than Type 3 (avg. 14.02%). This may reflect a different source of silica and a reduced amount of natron was used to produce Type 5 glasses.

7.2.3 al-Mina VA-19 and 27:

VA-19 and 27 (two rims of bowls) are natron glasses from al-Mina. They are significantly different from al-Raqqa Types 3 and 5. They have very high concentration of CaO (avg. 10.80%) and low concentration of Al_2O_3 (avg. 2.23%) (Figure 7.2, Table 7.1). Moreover, they have a very high concentration of Fe_2O_3 (0.90% - 0.91%) and TiO_2 (0.29% - 0.33%) when compared with the al-Raqqa natron glasses (Figures 7.3 and 7.4). These suggest a very different sand source was used to make the natron glass from al-Mina. Sand source with high concentrations of impurities such as Fe_2O_3 and TiO_2 and possibly limestone, not shell fragments, was used to produce these glasses.

7.2.4 Tbilisi Geo-09:

On the other hand, Geo-09 (a glass bracelet) from Tbilisi has a slightly lower level of CaO of 6.53% than the glasses from al-Raqqa and al-Mina (Figure 7.2). It has higher concentrations of Fe_2O_3 (1.32%), TiO_2 (0.11%) and MnO (0.44%) than the natron glasses from al-Raqqa and al-Mina (Figures 7.3 and 7.4). Fe_2O_3 and TiO_2 appear to have come from the silica source (Nenna 2014, 188-189). Nilotic sands in Egypt are found to have high concentrations of TiO_2 and Fe_2O_3 (Nenna 2014, 187). This may suggest Egyptian sand was used to produce this piece of glass. It is unlikely that MnO derived from the sands as analysis of Nilotic sand from Egypt shows that it has a low level of MnO (Nenna 2014, 187). MnO was likely to be added deliberately to the glass by glassworkers. Also, its Na_2O (17.75%), MgO (1.32%) and K_2O levels (0.88%) are significantly higher than those from al-Raqqa and al-Mina (Appendix Tables 1 and 2). It is also observed that SO_3 (0.66%) and P_2O_5 (0.21%) levels in this piece of glass are

significantly higher than al-Raqqa Types 3 and 5 (SO_3: 0.04% - 0.25%; P_2O_5: 0.02% - 0.20%) and al-Mina glasses (SO_3: 0.06% - 0.09%; P_2O_5: 0.11% - 0.17%) in this study.

7.2.5 Colourants for natron glass:

Figure 7.5 shows that 28 samples from al-Raqqa Type 3, 1 sample from al-Mina and all of the glasses from al-Raqqa Type 5 are coloured in aqua. This is due to the presence of iron as ferrous (Fe^{2+}) and ferric (Fe^{3+}) ions, and their concentrations of Fe_2O_3 are fairly low, ranging from 0.29% to 0.50%. It is likely that the iron in the glass was introduced as an impurity from the sands. It has been estimated that iron as a contaminant in glasses lies between 0.3% to 1.5% (Schreurs and Brill 1984, 199). In order to produce a clear and transparent glass the iron oxides in the raw materials must be less than 0.1% (Mysen and Richet 2005, 291).

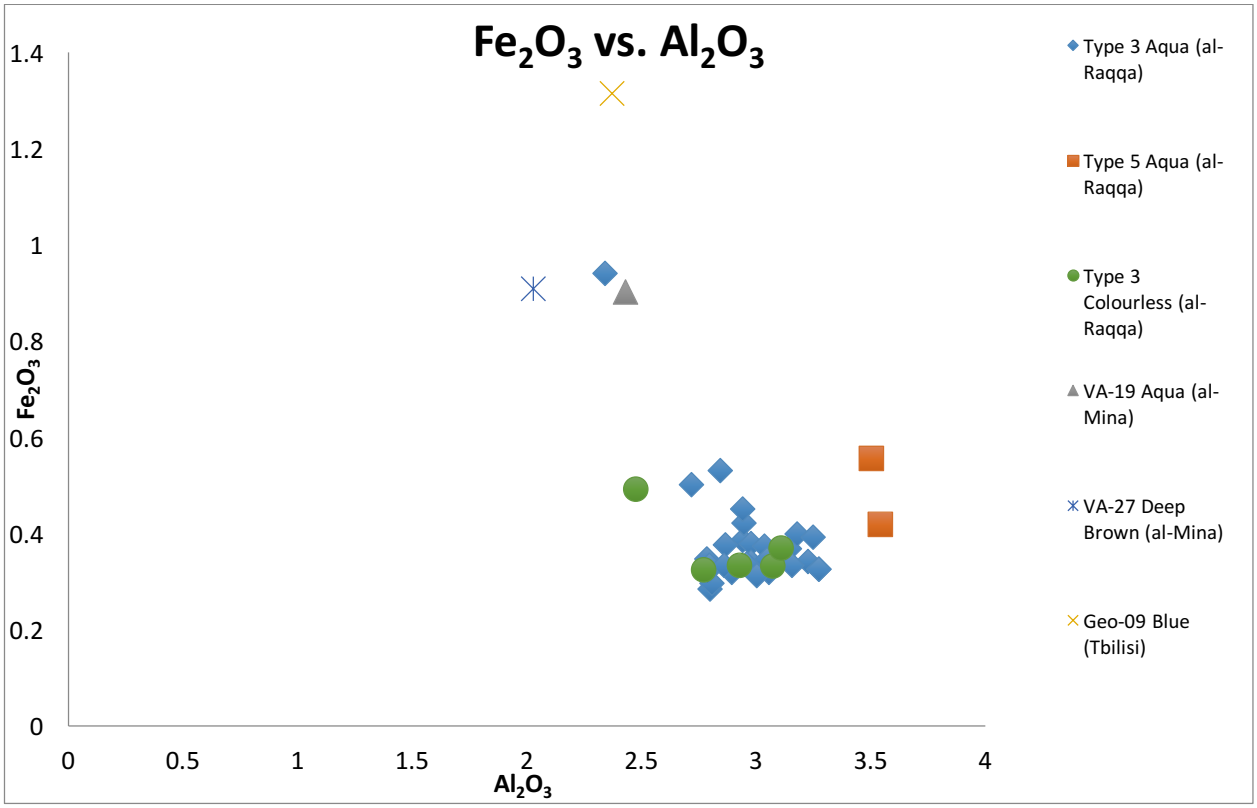


Figure 7.5: A bi-plot of Fe_2O_3 versus Al_2O_3 for natron glasses from 9th century AD Tell Zujaj and Tell Abu Ali in al-Raqqa, 9th – 10th century AD al-Mina and medieval Tbilisi. It is displayed according to compositional groups and coloration.

On the other hand, one piece of glass (RAQ-33) from al-Raqqa Type 3 and one sample (VA-19) from al-Mina have high concentrations of Fe_2O_3 (0.94% and 0.90%

respectively). It is possible that sands with a higher level of iron-bearing minerals were used and the aqua colour was produced in the furnace through the oxidising-reducing conditions (Henderson *et al*. 2004, 462).

The deep brown colour found in a glass samples from al-Mina (VA-27) is largely the result of a high concentration of Fe_2O_3 (0.91%) in the form of ferric ion (Fe^{3+}). Ferric ion will become a network former when the melting conditions are oxidised and using short melting times, thus it will impart darker green or brown colours (Pollard and Heron 2008, 164; Sanderson and Hutchings 1987, 105).

As regards the blue glass (Geo-09) from Tbilisi, the blue colour in this sample was the result of the high concentration of CoO (0.09%) in the glass (Henderson 2013, 69).

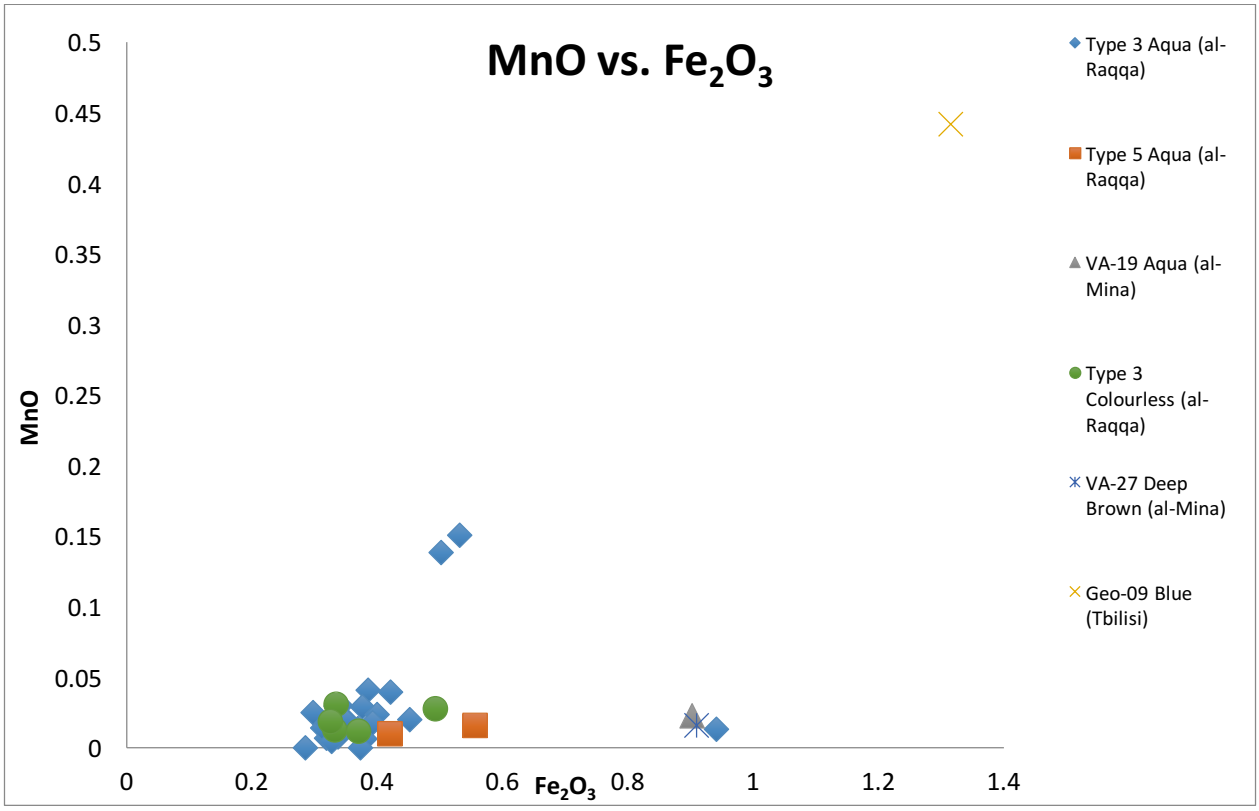


Figure 7.6: A bi-plot of MnO versus Fe_2O_3 for natron glasses from 9th century AD Tell Zujaj and Tell Abu Ali in al-Raqqa, 9th – 10th century AD al-Mina and medieval Tbilisi. It is displayed according to compositional groups and coloration.

Figure 7.6 shows that the majority of the natron glasses from al-Raqqa and al-Mina have very low concentrations of MnO (<0.2%). The same is true for the colourless glass

in al-Raqqa Type 3, which contain only 0.01% - 0.03%. Therefore, it is unlikely MnO was deliberately added to the glasses to counteract the effect of iron in the glasses.

7.3 Plant ash glass:

Fifty samples from Tell Zujaj, nine samples from Tell Abu Ali, eighteen samples from Tell Fukhkhar, seven samples from Tibilisi, fifteen samples from Zeyrek Camii, two samples from Fustat, five samples from Pemba Island, six samples from al-Qadisiyya and thirteen samples from al-Mina are identified as plant ash based glasses in this study (Figure 7.1). They have K_2O levels between 1.28% and 4.41% and an MgO level between 1.35% and 6.91% (Figure 7.1). Also, the levels of SO_3 and P_2O_5 in plant ash glasses are significantly higher than the levels found in natron glasses (Appendix Tables 1-7). This is because these two elements derive from plant ashes.

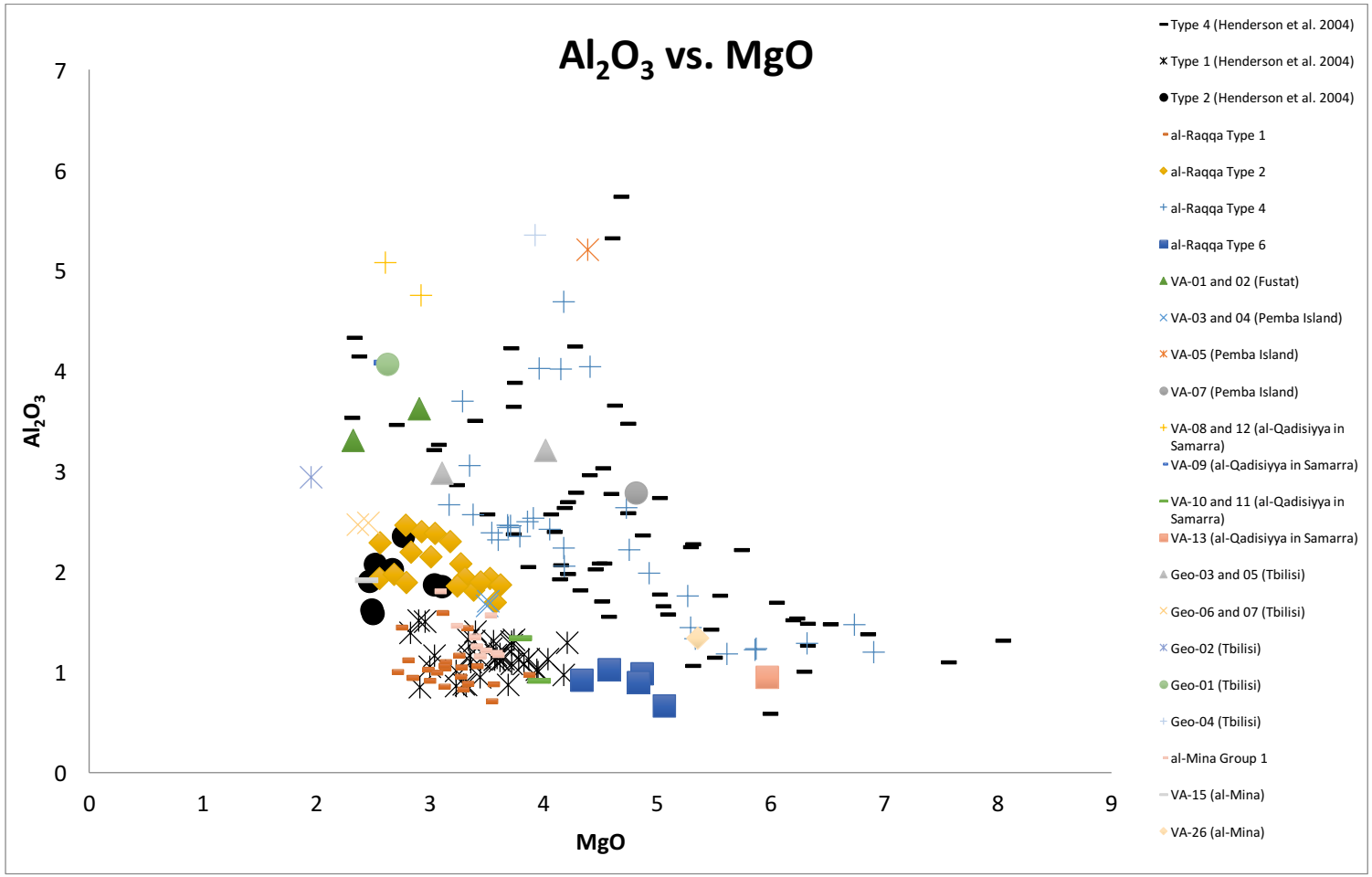


Figure 7.7: A bi-plot of Al_2O_3 versus MgO for plant ash glasses from 9th century Tell Zujaj and Tell Abu Ali in al-Raqqa, 9th – 10th centuries al-Mina, Islamic period Fustat, Islamic period Pemba Island, 9th – 10th centuries AD al-Qadisiyya in Samarra and 10th – 14th centuries Tbilisi. Data for al-Raqqa Types 1, 2 and 4 glasses: Henderson *et al.* (2004).

7.3.1 al-Raqqa:

Figure 7.7 shows that four different groups of plant ash glasses from al-Raqqa were found in this study based on their Al_2O_3 and MgO concentrations. Both elements come from the silica and alkali source respectively, which make them good indicators for plant ash glasses.

Elements	al-Raqqa Type 4a (wt%) (n=6)	al-Raqqa Type 4b (wt%) (n=13)	al-Raqqa Type 4c (wt%) (n=12)
SO_3	0.19 +/- 0.08	0.23 +/0.05	0.26 +/- 0.09
P_2O_5	0.45 +/- 0.04	0.31 +/- 0.08	0.22 +/- 0.24
V_2O_5	0.03 +/- 0.01	0.02 +/- 0.01	0.01 +/- 0.01
As_2O_5	0.23 +/-0.09	0.17 +/- 0.10	0.12 +/- 0.12
Sb_2O_5	0.01 +/- 0.01	0.01 +/- 0.01	0.01 +/- 0.01
SiO_2	62.65 +/- 3.28	64.49 +/- 1.56	66.42 +/- 1.93
TiO_2	0.27 +/- 0.03	0.16 +/- 0.02	0.10 +/- 0.03
SnO_2	0.01 +/- 0.01	0.01 +/- 0.01	0.02 +/- 0.02
Al_2O_3	3.92 +/- 0.53	2.43 +/- 0.17	1.56 +/- 0.43
Cr_2O_3	0.02 +/- 0.01	0.01 +/- 0.01	0.01 +/- 0.01
Fe_2O_3	1.95 +/- 0.36	1.04 +/- 0.25	0.75 +/- 0.45
MgO	3.89 +/- 0.46	3.84 +/- 0.39	5.54 +/- 0.92
CaO	7.70 +/- 1.21	7.55 +/- 1.03	5.33 +/- 0.92
MnO	0.16 +/- 0.12	1.13 +/- 0.73	0.94 +/- 0.52
CoO	0.01 +/- 0.01	0.02 +/- 0.03	0.03 +/- 0.04
CuO	0.03 +/- 0.02	0.05 +/- 0.05	0.05 +/- 0.06
ZnO	0.02 +/- 0.01	0.07 +/- 0.11	0.07 +/- 0.18
BaO	0.02 +/- 0.02	0.04 +/- 0.02	0.03 +/- 0.01
PbO	0.02 +/- 0.03	0.05 +/- 0.06	0.02 +/- 0.01
Na_2O	15.11 +/- 1.42	14.76 +/- 0.57	15.28 +/- 1.36
K_2O	2.44 +/- 0.68	2.69 +/- 0.36	2.67 +/- 0.48
Ag_2O	0.02 +/- 0.01	0.01 +/- 0.01	0.01 +/- 0.01
Cl	0.70 +/- 0.19	0.63 +/- 0.11	0.59 +/- 0.10

Table 7.2: Means and standard deviations of plant ash glass group Type 4 from al-Raqqa.

7.3.2 al-Raqqa Type 4:

Al-Raqqa Type 4 consists of 19 samples from the late 8^{th} - 9^{th} century AD Tell Zujaj, 6 samples from 9^{th} century AD Tell Abu Ali and 6 samples from 11^{th} century AD Tell Fukhkhar. Figure 7.7 shows that this group has a wide range of compositions in terms

of Al_2O_3 (1.18% - 4.69%) and MgO (3.17% - 6.91%). Such variation has been noted by Henderson and co-workers in their studies of plant ash glasses from al-Raqqa (Henderson 1995, 67-68; 1999, 232, Figure 7; 2000, 85; 2002, 599-600; 2013, 284-286; Henderson *et al.* 2004, 455-459). This wide range of composition has been interpreted as a result of experimentation with a new glass recipe and raw materials by glassmakers in Tell Zujaj in the late 8th – 9th centuries AD (Henderson 2013, 284).

With regard to the lime content in Type 4 as a whole, it is interesting to note that there is a positive correlation between CaO and Al_2O_3 (Figure 7.14), none of which is found in other glass groups apart from some glasses in al-Raqqa Type 2. It is thought a third major raw material, possibly feldspar rich in both Al_2O_3 and CaO was used to increase the lime content in the glass (Henderson 2013, 284).

Three subgroups are observed: the low MgO-high Al_2O_3 glasses (Type 4a), recycled/mixed glasses (Type 4b) and high MgO-low Al_2O_3 glasses (Type 4c) (Figure 7.8). This reflects the use of different genera of plant species and/or plants that grew in different geological bedrock, mixed with different silica sources with different levels of impurities. The group in the middle that forms a tight cluster is possibly the result of mixing between the two end members (Types 4a and 4c) (Henderson 2013, 284).

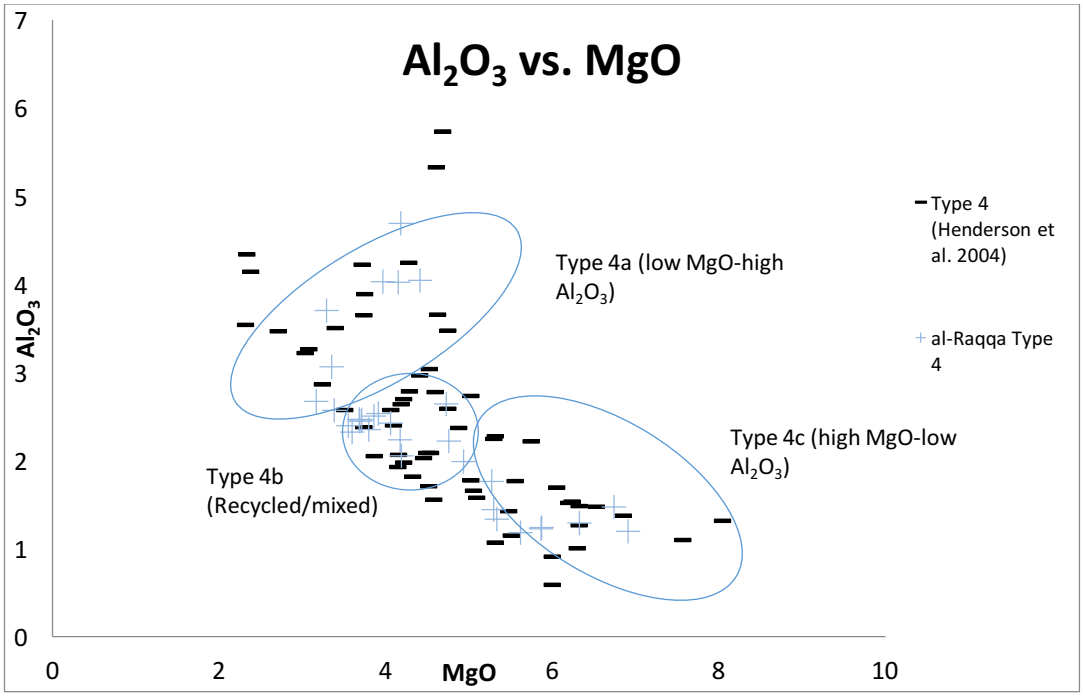


Figure 7.8: A bi-plot of Al_2O_3 versus MgO for al-Raqqa Type 4 glasses from 9th century Tell Zujaj and Tell Abu Ali in al-Raqqa. Data for al-Raqqa Type 4 glasses: Henderson *et al*. (2004).

7.3.3 al-Raqqa Type 4a (low MgO-high Al_2O_3 glass):

This glass type is characterised by low MgO (3.29% - 4.41%) and high Al_2O_3 (3.06% - 4.69%) contents (Figure 7.8). Glassmakers had mixed plant ashes of relatively high MgO with sands that contain high impurities. The latter is reflected in their high concentration of Fe_2O_3 (1.48% - 2.55%) and TiO_2 (0.24% - 0.34%). The positive correlation between Al_2O_3, Fe_2O_3 and TiO_2 suggests these elements were impurities from the silica source and they were not added deliberately to colour the glasses (Figures 7.9 and 7.10). In terms of the lime content, these glasses have a relatively high concentration of CaO between 6.40% and 9.63% (Figure 7.11).

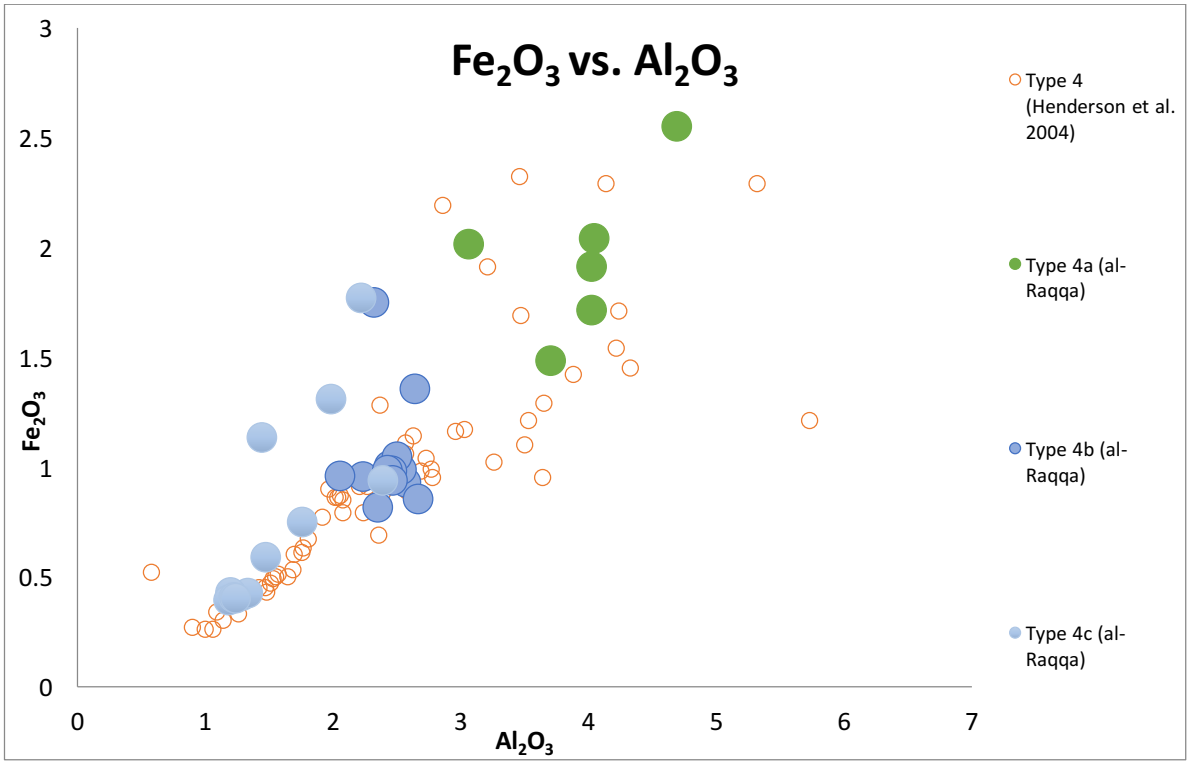


Figure 7.9: A bi-plot of Fe_2O_3 versus Al_2O_3 for al-Raqqa Types 4a, 4b and 4c glasses from 9th century Tell Zujaj and Tell Abu Ali in al-Raqqa. Data for al-Raqqa Type 4 glasses: Henderson *et al.* (2004).

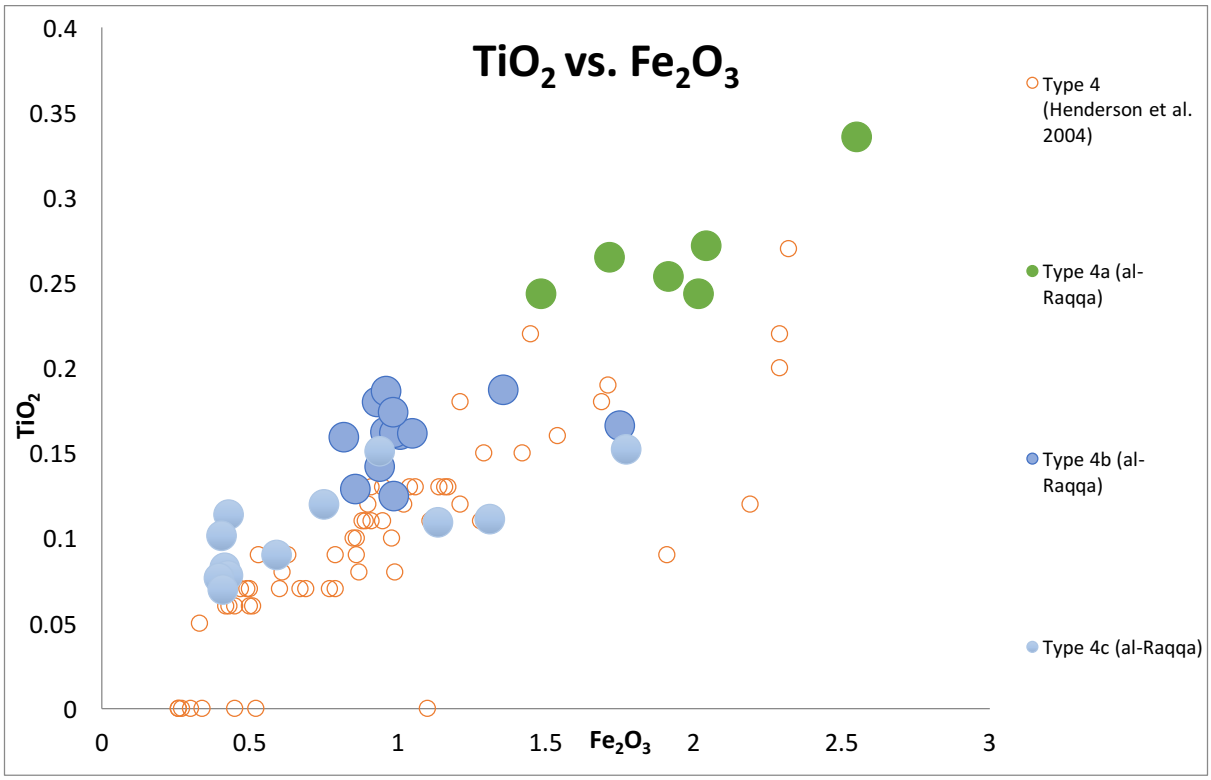


Figure 7.10: A bi-plot of TiO_2 versus Fe_2O_3 for al-Raqqa Types 4a, 4b and 4c glasses from 9th century Tell Zujaj and Tell Abu Ali in al-Raqqa. Data for al-Raqqa Type 4 glasses: Henderson *et al*. (2004).

There are some differences between the 9th century AD Tell Zujaj and the 11th century AD Tell Fukhkhar glasses in this end member: RAQ-28 and RAQ-58 from Tell Zujaj have lower concentrations of Na_2O (14.0% and 14.41% respectively) than RAQ-96, 102 and 109 from Tell Fukhkhar (15.71%, 16.40% and 16.86% respectively); and the Tell Zujaj glasses have higher concentrations of K_2O (3.18% and 3.41% respectively) than the Tell Fukhkhar glasses (1.97%, 2.02% and 2.25% respectively). This suggests there was a chronological difference in the use of different compositions of plant ashes to produce glass in al-Raqqa: glassmakers in the late 8th – 9th centuries AD used a type of plant ash with low Na_2O and high K_2O, whereas in the 11th century AD a type of plant ash with high Na_2O and low K_2O was used. Henderson *et al.* (2004) have noted that some of the late 8th - 9th and 11th century AD raw furnace glasses belong to Type 4a (Henderson 2013, 285, Figure 10.3; Henderson *et al.* 2004, 452, Figure 2).

7.3.4 al-Raqqa Type 4c (high MgO-low Al_2O_3 glass):

On the other hand, a separate plant ash of higher MgO content (5.03% - 6.91% of MgO in the glasses) was used to mix with a purer silica source of quartz or chert, which

provided lower levels of Al_2O_3 (1.20% - 2.20%), Fe_2O_3 (0.39% - 1.77%) and TiO_2 (0.07% - 0.15%) in Type 4c glasses (Figures 7.8-7.10). The majority of the glasses also have a lower concentration of CaO, between 4.45% and 5.68%, than Type 4a, except for RAQ-25 which has CaO of 7.21% (Figure 7.11). The low CaO would have caused the glasses to be chemically less stable but the high concentration of MgO in the glasses helped to stabilise the glasses (Henderson *et al.* 2004, 459).

No raw furnace glasses were found in the high MgO-low Al_2O_3 glasses in this study and Henderson *et al.* (2004)'s Type 4, which has been suggested that these low Al_2O_3 and high MgO glasses might have been imported from the Mesopotamian region (Henderson 2013, 291).

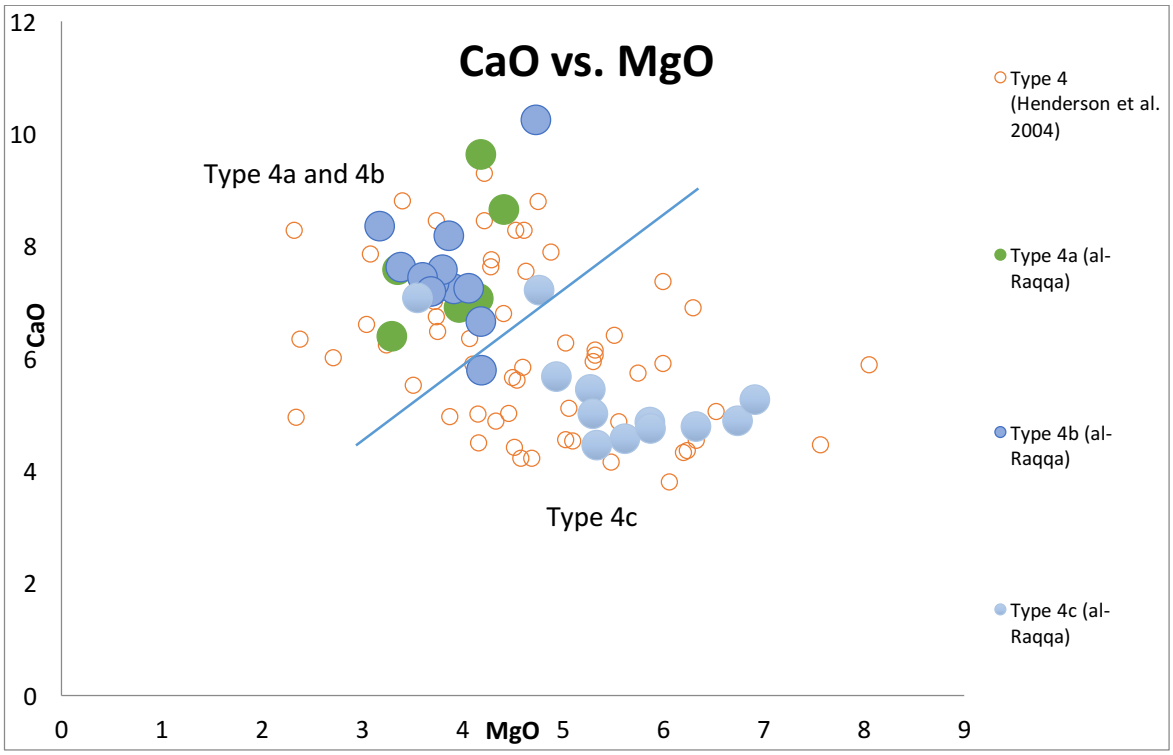


Figure 7.11: A bi-plot of CaO versus MgO for al-Raqqa Types 4a, 4b and 4c glasses from 9th century Tell Zujaj and Tell Abu Ali in al-Raqqa. Data for al-Raqqa Type 4 glasses: Henderson *et al.* (2004).

7.3.5 al-Raqqa Type 4b (recycling and mixing):

Type 4b shows evidence of recycling and mixing. They form a tight cluster in between the two end members in terms of their levels of MgO, Al_2O_3, Fe_2O_3 and TiO_2 (Figures

7.8 – 7.10). There is no significant correlation between Al_2O_3, Fe_2O_3 and TiO_2 in these glasses (Figures 7.9 - 7.10).

These glasses were probably the result of glassmakers mixing recycled or reused cullet from the two end members (Types 4a and 4c) with raw glasses. This helps to control the chemical compositions in the final glass melt and the working properties of the glass (Henderson 2000, 85; 2002, 599; 2013, 284; Henderson *et al.* 2004, 457-459).

7.3.6 Colourants in al-Raqqa Type 4:

The colours in glasses from al-Raqqa Type 4 are more diverse than the natron glasses Types 3 and 5 from al-Raqqa. Al-Raqqa Type 4a is dominated by different shades of green which include green (n=1), olive green (n=1) and dark green (n=4). Six glasses from al-Raqqa Type 4c also have various shades of green that include light green (n=1), green (n=3), yellow-green (n=1) and dark green (n=1). But this subgroup also has other colours which include aqua (n=1), blue (n=2) and two colourless glasses. On the other hand, Type 4b is dominated by yellow-green (n=4), blue (n=3) and aqua colours (n=4). Other colour such as green (n=1) is also found in this group.

Figure 7.12 shows that a correlation between Fe_2O_3 and Al_2O_3 in glasses from al-Raqqa Type 4. This shows that iron was not deliberately added to coloure the glasses and it was introduced to the glass as an impurity from the silica source (sands and quartz for Type 4a and 4c respectively). It is noted from Figure 7.12 that the majority of the yellow-green glasses have iron contents between 0.82% and 0.99%. Only one sample (RAQ-90) has a low iron content of 0.40%. And Figure 7.13 shows that all of the yellow-green glasses have relatively high concentrations of MnO (0.91% - 2.67%). It is possible that MnO was added to counter the green colour imparted by Fe_2O_3 in the glasses to produce a yellow-green colour (deliberately or accidentally).

All of the dark green glasses have high concentrations of Fe_2O_3 ranging from 1.31% to 2.55% and have a positive correlation between Al_2O_3 and Fe_2O_3 (Figure 7.12). It is unlikely that Fe_2O_3 was deliberately added to the glasses but it was derived from the silica source, which is probably sands. It is also noted that these dark green glasses have negligible MnO (0.04% - 0.38%) (Figure 7.13) and this is likely to be impurities from

the raw materials. It is possible that the dark green colour was deliberately produced in the furnace under the oxidising conditions. The same can be observed in the olive green glass sample (RAQ-58) which has a high content of Fe_2O_3 (1.48%) but a low concentration of MnO (0.36%) which is likely to be impurity from the raw materials (Figure 7.13).

Many of the aqua glasses in al-Raqqa Type 4 are fairly similar to the aqua natron glasses from al-Raqqa with a relatively low concentration of Fe_2O_3 (0.42% - 1.05%). However, it is shown in Figure 7.13 that the aqua glasses in Type 4 have high concentrations of MnO between 0.25% and 1.04%, which is not found in the al-Raqqa natron glasses (<0.2%). This shows that a different silica source with a higher concentration of Fe_2O_3 was used to produce Type 4 aqua glasses and glassmakers deliberately added MnO to counter the effect of iron on the glasses.

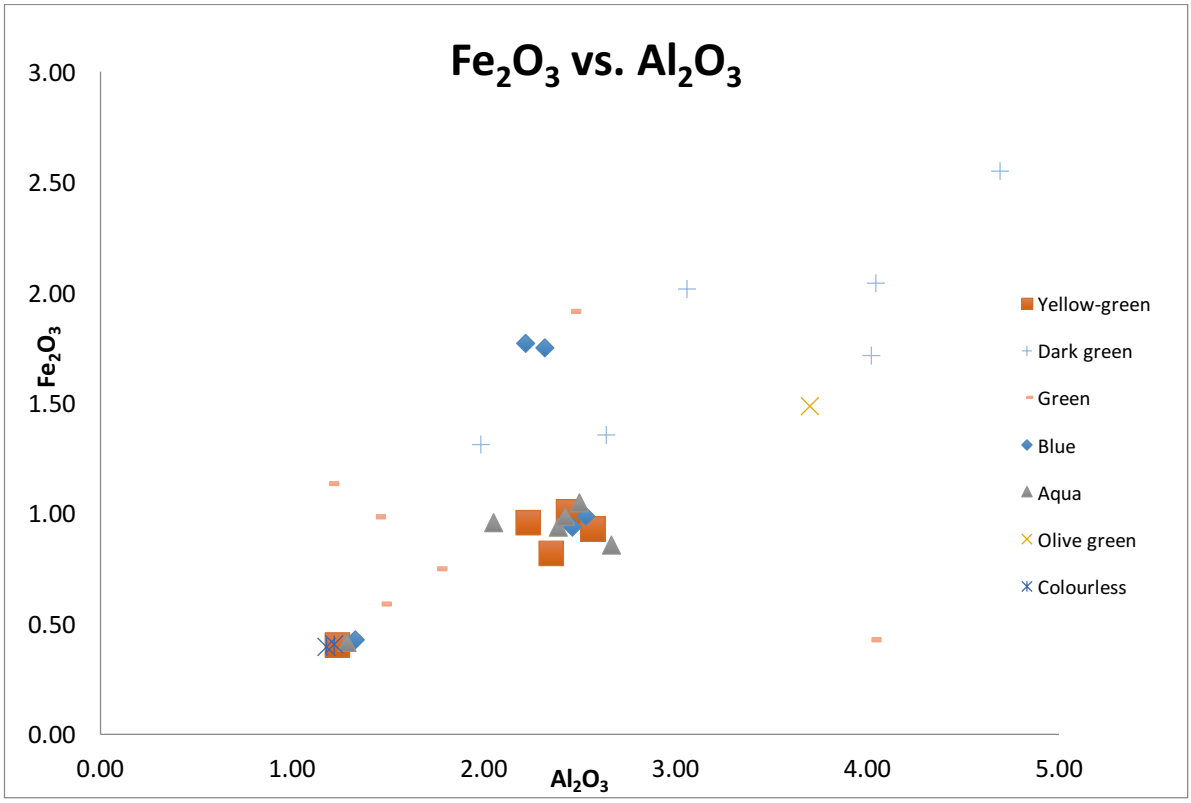


Figure 7.12: A bi-plot of Fe_2O_3 versus Al_2O_3 for al-Raqqa Type 4 glasses from 9th century Tell Zujaj and Tell Abu Ali in al-Raqqa. It is displayed according to colours.

As regards the blue glasses, two fragments (RAQ-25 and 57) have high concentrations of Fe_2O_3 (1.75% - 1.77%) (Figure 7.12). Moreover, these two fragments have elevated

levels of CoO (0.11% - 0.14%), ZnO (0.42% - 0.65%) and CuO (0.17% - 0.20%). It is possible that the blue colour in these two fragments was the result of the use of a cobalt-bearing ore (Henderson *et al*. 2004, 462). It has been noted that cobalt in the form of Co^{2+} and at a level as low as 0.02% can impart a deep blue colour (Biek and Bayley 1979, 8; Brill 2006, 134; Henderson 2013, 69). On the other hand, the remaining blue glasses in Type 4 have negligible CoO, CuO and ZnO and their blue colours were the result of the Fe_2O_3 in the form of ferrous ion and the glasses were melted under reducing conditions, which imparts a bluish colour (Brill 1988, 172; Henderson *et al*. 2004, 462; Weyl 1976, 106).

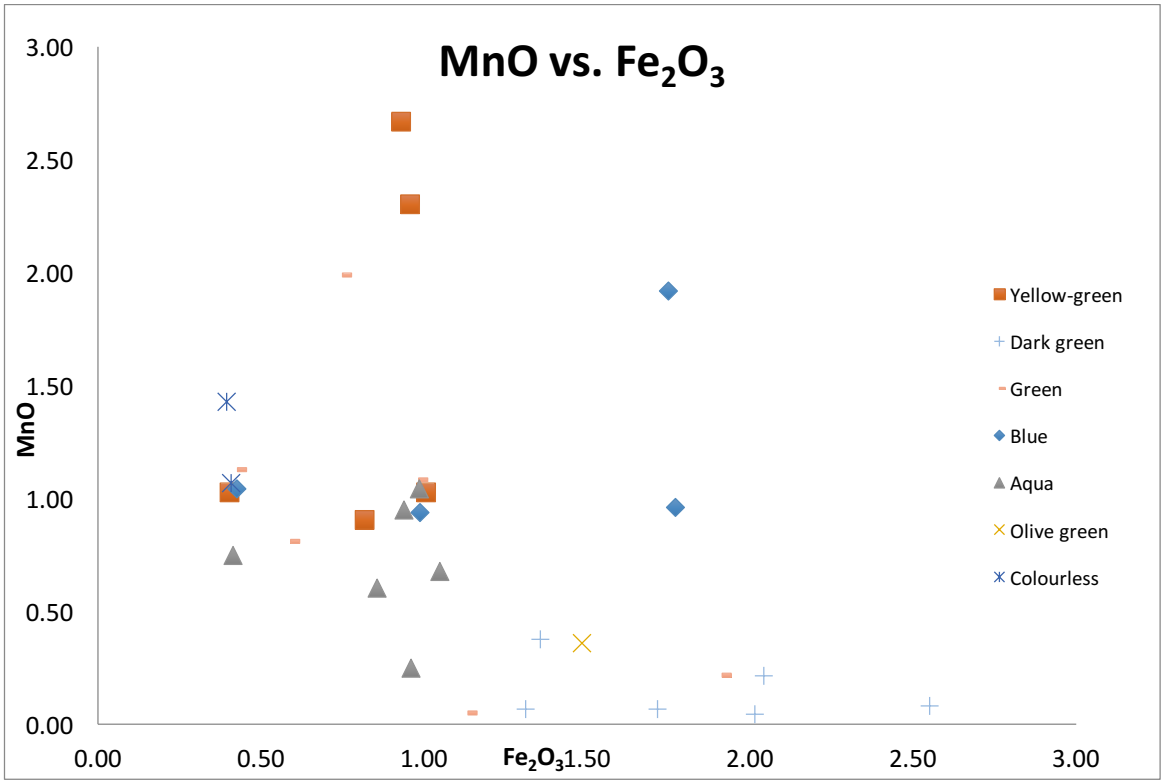


Figure 7.13: A bi-plot of MnO versus Fe_2O_3 for al-Raqqa Type 4 glasses from 9th century Tell Zujaj and Tell Abu Ali in al-Raqqa. It is displayed according to colours.

The two colourless glass samples (RAQ-88 and 89) from Type 4 have relatively low concentrations of Fe_2O_3 (0.39% - 0.41%). But Figure 7.13 shows that they have relatively high concentrations of MnO (1.07% - 1.43%) which was deliberately added to decolourise the glasses.

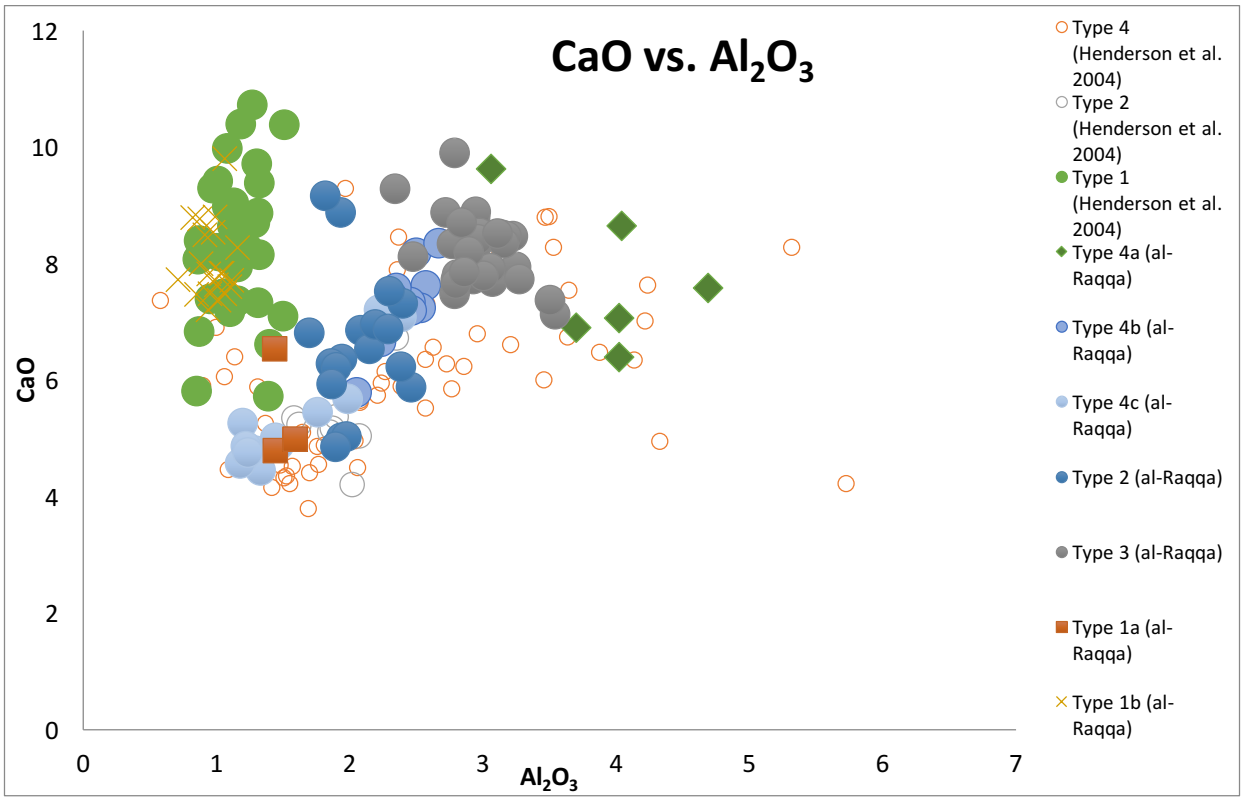


Figure 7.14: A bi-plot of CaO versus Al_2O_3 for al-Raqqa Types 1a, 1b, 2, 3, 4a, 4b and 4c glasses from 9th century Tell Zujaj and Tell Abu Ali in al-Raqqa. Data for al-Raqqa Types 1, 2 and 4 glasses: Henderson *et al*. (2004).

7.3.7 al-Raqqa Type 1:

Al-Raqqa Type 1 consists of 19 glasses from the late 8th - 9th centuries AD Tell Zujaj, 1 from 9th century AD Tell Abu Ali, and 5 from 11th century AD Tell Fukhkhar. The composition of this glass group is relatively homogenous. There is no wide range of compositional variation as found in Type 4 (Figure 7.7). The presence of raw glasses RAQ-76 and RAQ-113 from Tell Zujaj and Tell Fukhkhar suggest this glass composition was produced in al-Raqqa between the late 8th and 11th centuries AD.

This group is characterised by low Al_2O_3 (0.71% - 1.59%), Fe_2O_3 (0.32% - 2.47%) and TiO_2 (0.06% - 0.13%). Unlike al-Raqqa Type 4, a relatively pure silica source, such as quartz or chert, was probably used to provide the silica source (Figure 7.15) (Henderson 1999, 232; 2000, 84; Henderson *et al.* 2004, 454).

Elements	al-Raqqa Type 1a (wt%) (n=3)	al-Raqqa Type 1b (wt%) (n=19)
SO_3	0.20 +/- 0.04	0.16 +/- 0.05
P_2O_5	0.40 +/- 0.09	0.30 +/- 0.05
V_2O_5	0.01 +/- 0.00	0.01 +/- 0.01
As_2O_5	0.16 +/- 0.09	0.13 +/- 0.09
Sb_2O_5	0.02+/- 0.02	0.02 +/- 0.02
SiO_2	67.83 +/- 0.44	67.82 +/- 1.56
TiO_2	0.11 +/- 0.02	0.08 +/- 0.01
SnO_2	0.02 +/- 0.02	0.02 +/- 0.02
Al_2O_3	1.49 +/- 0.09	0.96 +/- 0.10
Cr_2O_3	0.01 +/- 0.01	0.01 +/- 0.01
Fe_2O_3	1.48 +/- 0.87	0.40 +/- 0.09
MgO	3.02 +/- 0.29	3.13 +/- 0.29
CaO	5.44 +/- 0.96	8.02 +/- 0.67
MnO	0.08 +/- 0.07	1.37 +/- 0.46
CoO	0.00	0.01 +/- 0.01
CuO	0.03 +/- 0.01	0.02 +/- 0.01
ZnO	0.01 +/- 0.01	0.01 +/- 0.01
BaO	0.03 +/- 0.03	0.03 +/- 0.02
PbO	0.02 +/- 0.01	0.02 +/- 0.01
Na_2O	16.56 +/- 1.24	13.65 +/- 1.23
K_2O	2.17 +/- 0.65	2.44 +/- 0.37
Ag_2O	0.01 +/- 0.01	0.01 +/- 0.01
Cl	0.89 +/- 0.11	0.85+/- 0.07

Table 7.3: Means and standard deviations of plant ash glass group Type 1 from al-Raqqa.

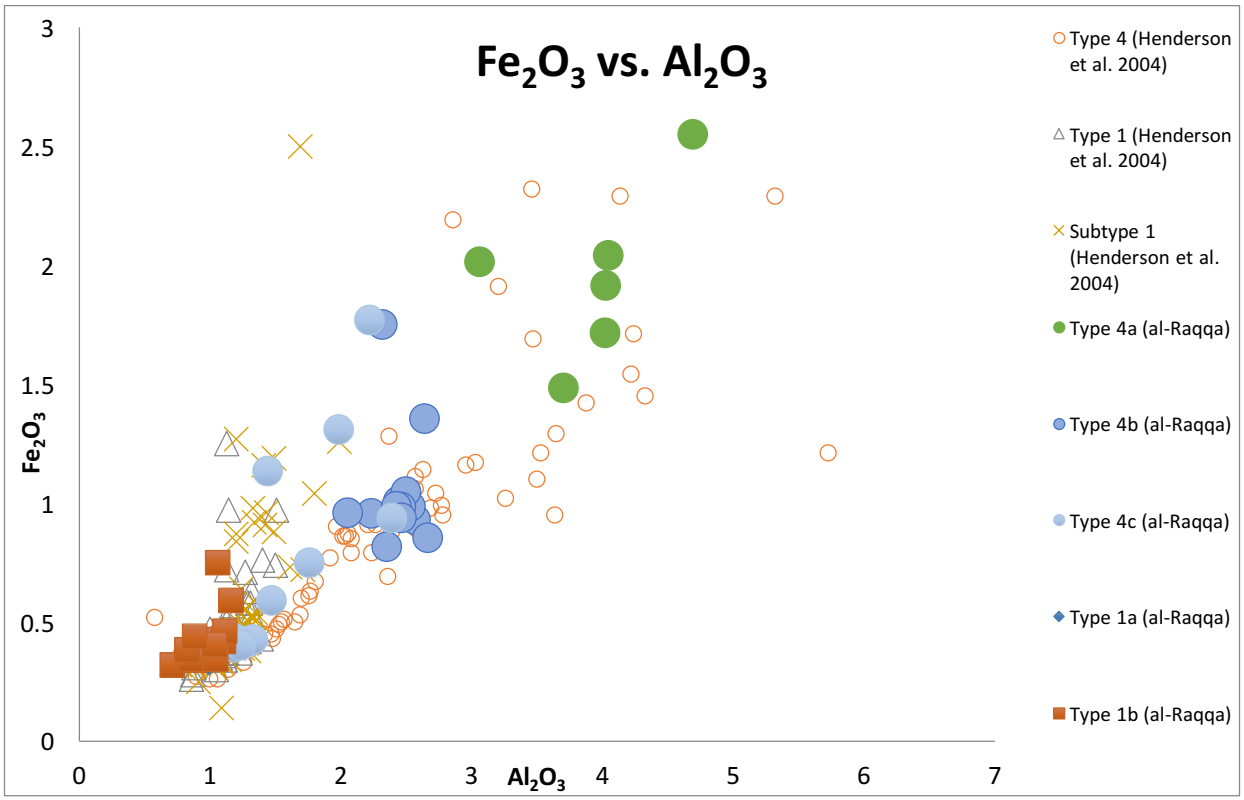


Figure 7.15: A bi-plot of CaO versus Al_2O_3 for al-Raqqa Types 1a, 1b, 4a, 4b and 4c glasses from 9th century Tell Zujaj and Tell Abu Ali in al-Raqqa. Data for al-Raqqa Types 1 and 4 and subtype 1 glasses: Henderson *et al*. (2004).

Plant ash was used as the alkali flux in the production of this glass group. It provided high concentrations of MgO (2.67% - 3.96%) and CaO (4.79% - 9.81%). Unlike Type 4, no correlation between Al_2O_3 and CaO was found in this glass group (Figure 7.14). It is unlikely that a separate alumina- and lime-rich source was added to the glass to increase its lime content. It is also noted that Type 1 has a lower level of Na_2O (11.37% - 17.80%) and MgO than Type 4 (Figures 7.16 and 7.17). These suggest plant ashes of different composition or even species (lower MgO and Na_2O, high CaO) were used for the production of Type 1. This glass recipe continued to be used in Syria, Israel and Lebanon for at least another 600 years (Henderson *et al.* 2004, 458). This group can be divided into two subgroups based on the concentrations of alumina, iron, soda and lime.

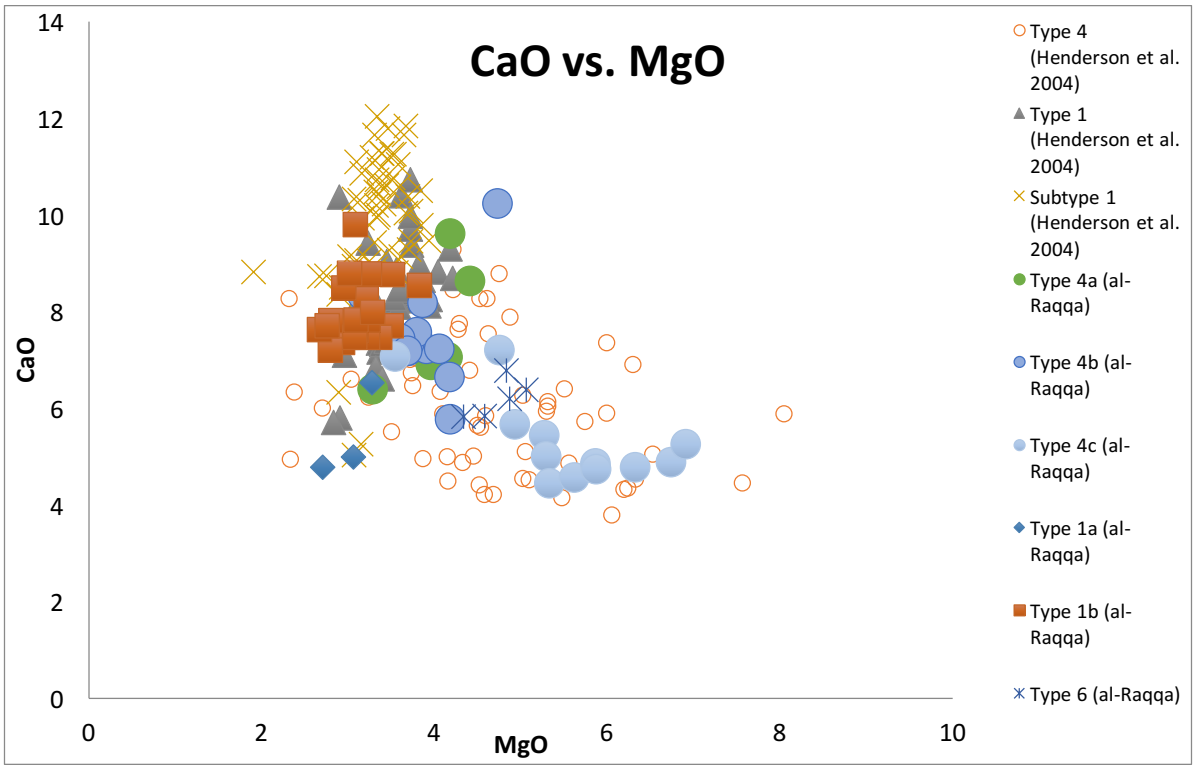


Figure 7.16: A bi-plot of CaO versus MgO for al-Raqqa Types 1a, 1b, 4a, 4b, 4c and 6 glasses from 9th century Tell Zujaj and Tell Abu Ali in al-Raqqa. Data for al-Raqqa Types 1 and 4 and subtype 1 glasses: Henderson *et al*. (2004).

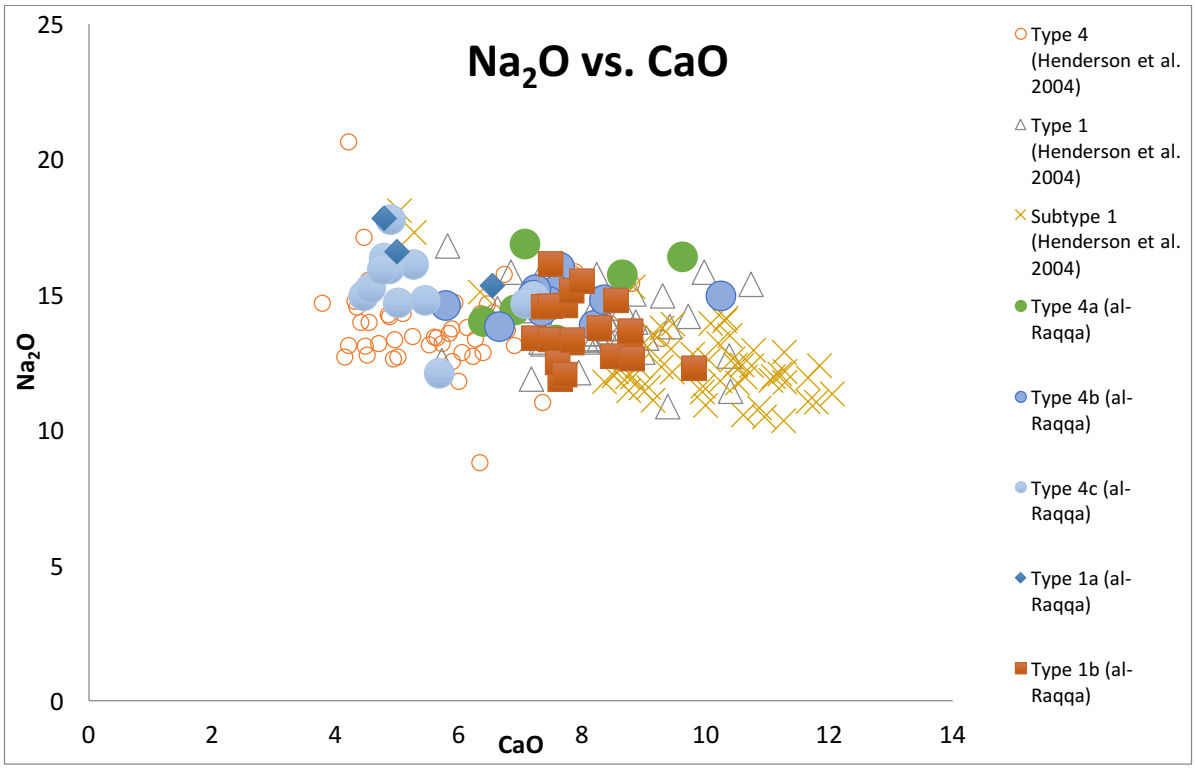


Figure 7.17: A bi-plot of CaO versus Na_2O for al-Raqqa Types 1a, 1b, 4a, 4b and 4c glasses from 9th century Tell Zujaj and Tell Abu Ali in al-Raqqa. Data for al-Raqqa Types 1 and 4 and subtype 1 glasses: Henderson *et al*. (2004).

7.3.8 al-Raqqa Type 1a:

Al-Raqqa Type 1a consists of three glasses from Tell Fukhkhar, RAQ-97, 98 and 99. They are characterised by a relatively high Al_2O_3 (1.44% - 1.59%), Fe_2O_3 (0.83% - 2.47%) and Na_2O (15.32% - 17.80%) content. There is no correlation between Al_2O_3 and Fe_2O_3 in Type 1a (Figure 7.15). It is likely that Fe_2O_3 was deliberately added to colour the glasses and produced a dark green colour. Their lime content is especially low, between 4.79% and 6.54% (Figure 7.16). Moreover, they have some of the highest concentrations of P_2O_5 in Type 1, between 0.32% and 0.50%.

7.3.9 al-Raqqa Type 1b:

Al-Raqqa Type 1b consists of twenty-three samples from the late 8^{th} - 9^{th} centuries AD Tell Zujaj and Tell Abu Ali, and two samples from 11^{th} century AD Tell Fukhkhar. When it is compared to al-Raqqa Types 4 and 1a, this group has very low Al_2O_3 (0.71% - 1.11%) and Fe_2O_3 (0.32% - 1.15%). This suggests a purer silica source was used to produce these glasses. This glass group is different from Type 1a in terms of Na_2O, K_2O and CaO levels. It has lower level of Na_2O (11.87% - 16.12%) but higher levels of CaO (7.21% - 9.81%) and K_2O (1.93% - 3.52%) (Figures 7.16 and 7.17, Table 7.3).

7.3.10 Colourants for al-Raqqa Type 1:

Al-Raqqa Type 1 is dominated by colourless glass and various shades of green (dark green, yellow-green and aqua) coloured glasses. All three glasses (RAQ-97, 98 and 99) from al-Raqqa Type 1a are coloured dark green. On the other hand, only two glasses (RAQ-111 and 113) from al-Raqqa Type 1b are dark green. Figure 7.18 shows that the dark green glasses from Type 1a have higher concentrations of Al_2O_3 (1.44% - 1.59%) and Fe_2O_3 (0.83% - 2.47%). There is no positive correlation between Al_2O_3 and Fe_2O_3 in these glasses. It is possible that iron was deliberately added to colour the glasses dark green in an oxidising furnace condition. It is also found that these dark green glasses have negligible MnO contents (0.02% - 0.16%) (Figure 7.19).

Curiously, the two dark green glasses from Type 1b have lower concentrations of Al_2O_3 (0.99% - 1.06%) and Fe_2O_3 (0.33% - 0.46%) than the ones in Type 1a (Figure 7.18). It

is unlikely that iron was deliberately added to the glass but was present as an impurity from the raw materials. On the contrary, MnO seems to be deliberately added to the dark green glasses from Type 1b to decolourise the glasses but it was unsuccessful in removing the green colour (Figure 7.19).

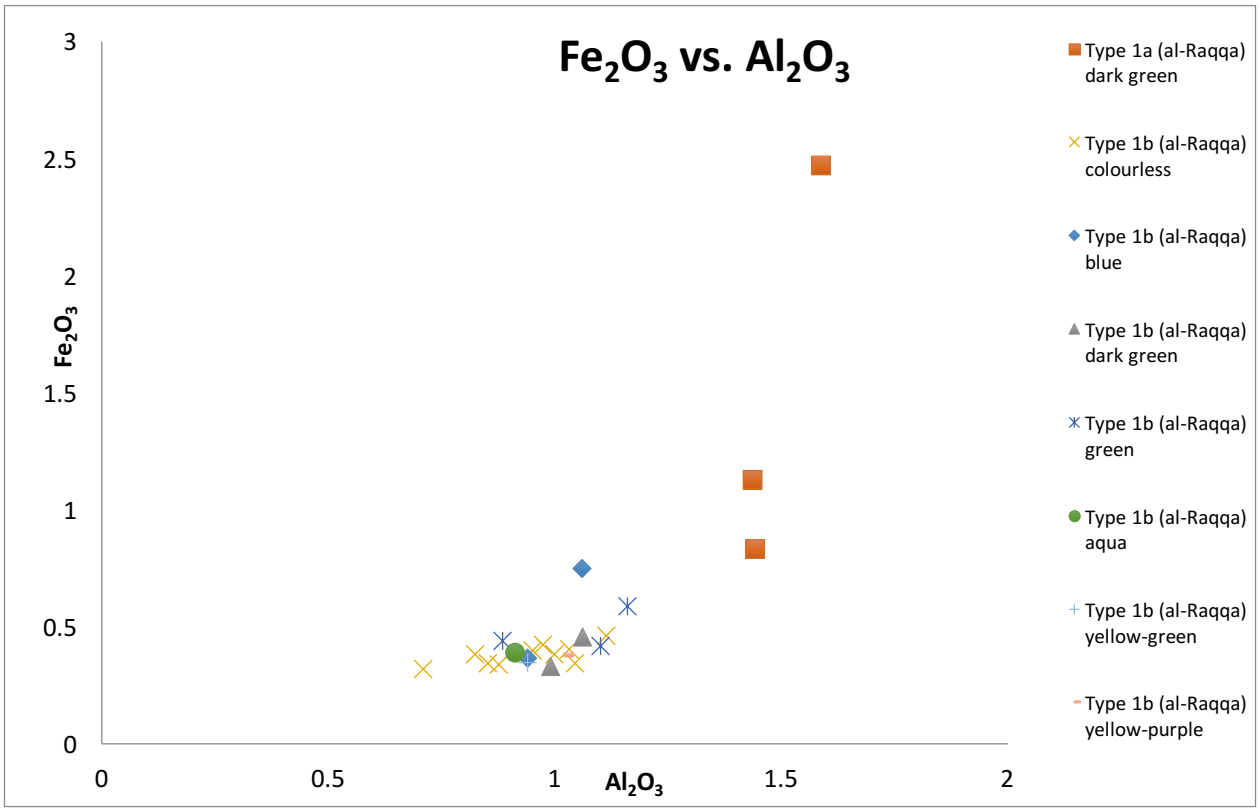


Figure 7.18: A bi-plot of Fe_2O_3 versus Al_2O_3 for al-Raqqa Type 1 glasses from 9th century Tell Zujaj and Tell Abu Ali in al-Raqqa. It is displayed according to compositional groups and colours.

The same can be said of the green (RAQ-39 and 76), yellow-green (RAQ-32) and aqua (RAQ-84) glasses from Type 1b. All of these glasses have relatively low concentrations of Al_2O_3 (0.88% - 1.10%) and Fe_2O_3 (0.35% - 0.42%) (Figure 7.18), which suggests iron was present as an impurity in the glasses. It is likely that the green and yellow-green glasses were melted in oxidising conditions in the furnace to produce the green colour while the aqua glass was melted in a furnace with reducing condition which impart a bluish green colour. All of these glasses have high concentrations of MnO (1.24% - 2.19%) (Figure 7.19), which suggests MnO was deliberately added to the glasses. Only two blue glasses (RAQ-06 and 24) are found in Type 1b. The blue colour is likely produced by the presence of ferrous ion in the glasses.

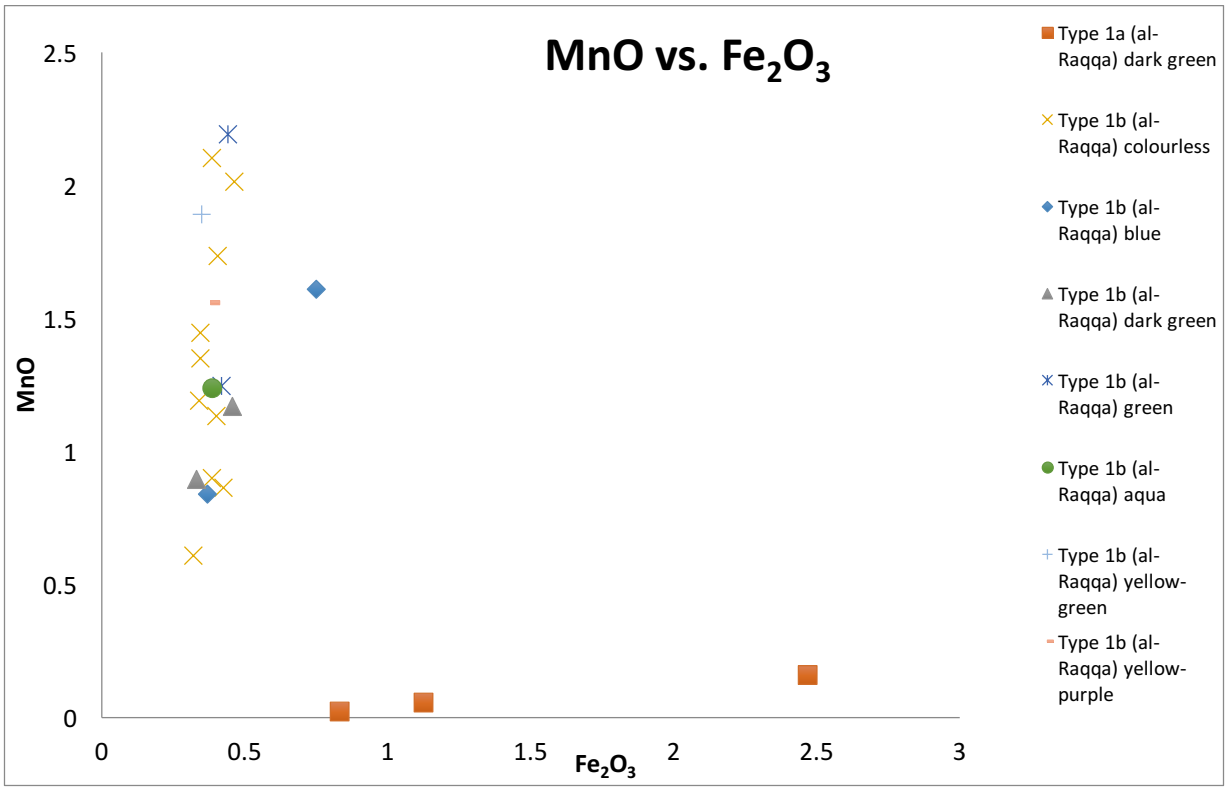


Figure 7.19: A bi-plot of MnO versus Fe_2O_3 for al-Raqqa Type 1 glasses from 9th century Tell Zujaj and Tell Abu Ali in al-Raqqa. It is displayed according to compositional groups and colours.

In terms of the colourless glasses (RAQ-05, 35, 36, 37, 41, 43, 46, 51, 58, 61) of Type 1b, they have low concentration of Fe_2O_3 (0.32% - 0.46%) and this is likely to be impurity from the raw materials (Figure 7.18). It is found that they have relatively high levels of MnO (0.61% - 2.10%) (Figure 7.19) which was deliberately added to decolourise the glasses. The average ratio of Fe_2O_3 and MnO in the colourless glasses is 0.38/1.34. The yellow-purple glass (RAQ-02) also has a low concentration of Fe_2O_3 (0.38%) and a relatively high level of MnO (1.56%). But it is likely that MnO was present as Mn^{3+} in the glass which imparts a purple colour (Bamford 1977, 50; Brill 1988, 276; Henderson 1985, 283). It is possible that minerals such as pyrolusite (MnO_2) were deliberately added to the glass to produce a purple colour (Brill 1988, 276; Henderson 2000, 34-35).

7.3.11 al-Raqqa Type 2:

This group contains 11 samples from Tell Zujaj, 1 sample from Tell Abu Ali and 6 samples from Tell Fukhkhar. Unlike al-Raqqa Type 4, it forms a tight cluster which suggests glassmakers were able to control the batch preparation and melting conditions.

Elements	al-Raqqa Type 2 (wt%) (n=18)
SO_3	0.19 +/- 0.11
P_2O_5	0.34 +/- 0.11
V_2O_5	0.02 +/- 0.01
As_2O_5	0.14 +/- 0.09
Sb_2O_5	0.01 +/- 0.01
SiO_2	66.34 +/- 2.25
TiO_2	0.15 +/- 0.04
SnO_2	0.01 +/- 0.01
Al_2O_3	2.06 +/- 0.23
Cr_2O_3	0.01 +/- 0.01
Fe_2O_3	1.56 +/- 0.95
MgO	3.10 +/- 0.35
CaO	6.60 +/- 1.16
MnO	1.20 +/- 1.12
CoO	0.03 +/- 0.05
CuO	0.11 +/- 0.20
ZnO	0.04 +/- 0.04
BaO	0.04 +/- 0.02
PbO	0.02 +/- 0.01
Na_2O	14.58 +/- 1.43
K_2O	2.40 +/- 0.46
Ag_2O	0.01 +/- 0.01
Cl	0.78 +/- 0.13

Table 7.4: Means and standard deviations of plant ash glass group Type 2 from al-Raqqa.

This group is characterised by variable CaO (4.86% - 9.16%), MgO (2.56% - 3.58%) and Al_2O_3 of (1.79% - 2.46%). The concentrations of Fe_2O_3 (0.37% - 3.45%) and TiO_2 (0.06% - 0.23%) are high. Their soda levels are higher than all al-Raqqa Type 1, between 11.67% and 17.77% but lower than al-Raqqa Type 4 (Figure 7.20). Its K_2O level is also lower than other plant ash glass groups from al-Raqqa, between 1.44% and 3.06% (Figure 7.20).

The most striking aspect of this group is its similarity to the recycled/mixed glasses in Type 4b. Both of which show no correlation between Al_2O_3 and Fe_2O_3 (Figure 7.21). The majority of Type 2 glasses has very similar concentrations of alkali (soda and potash), Al_2O_3, Fe_2O_3 and TiO_2 as Type 4b (Figures 7.20 and 7.21). Al-Raqqa Types 2 and 4 also display a positive correlation between CaO and Al_2O_3, which suggests feldspars were probably used to provide both CaO and Al_2O_3 in these glasses (Figure 7.22).

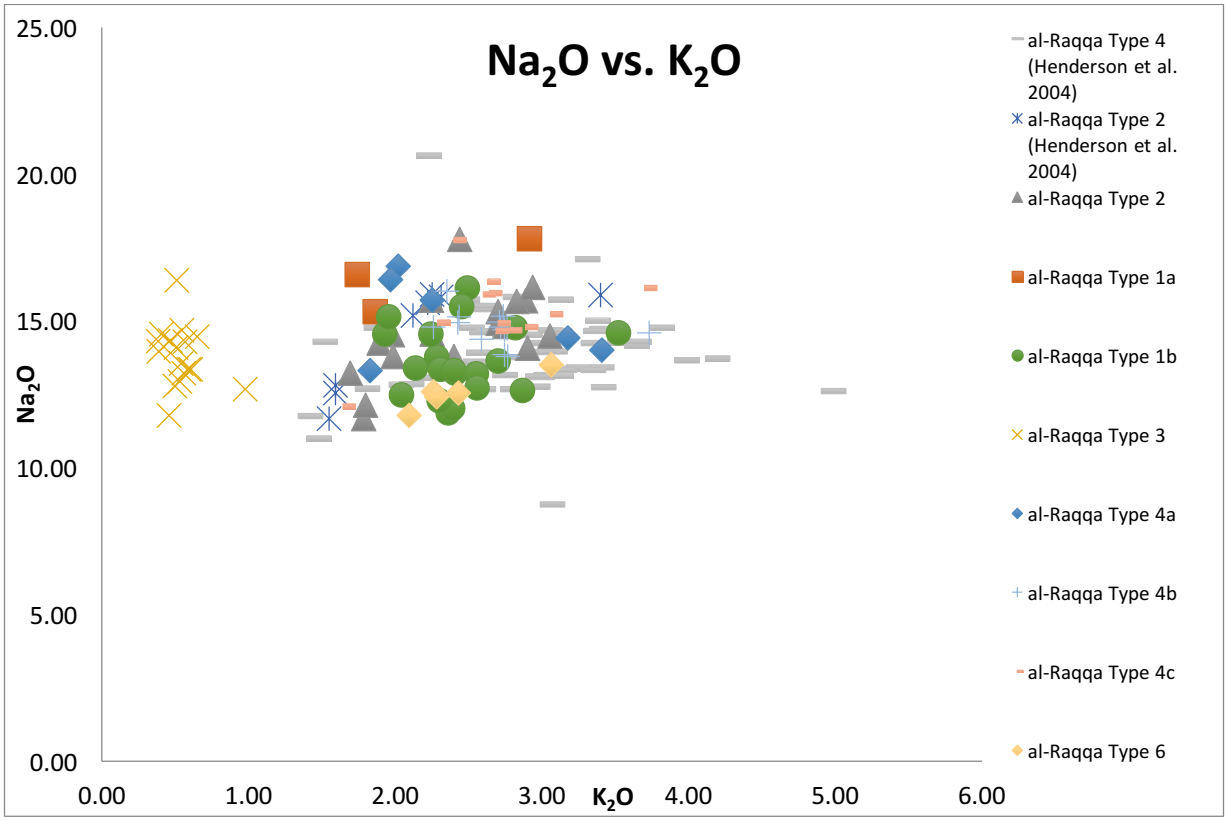


Figure 7.20: A bi-plot of Na_2O versus K_2O for al-Raqqa Types 1a, 1b, 2, 3, 4a, 4b, 4c and 6 glasses from 9th century Tell Zujaj and Tell Abu Ali in al-Raqqa. Data for al-Raqqa Types 2 and 4 glasses: Henderson *et al*. (2004).

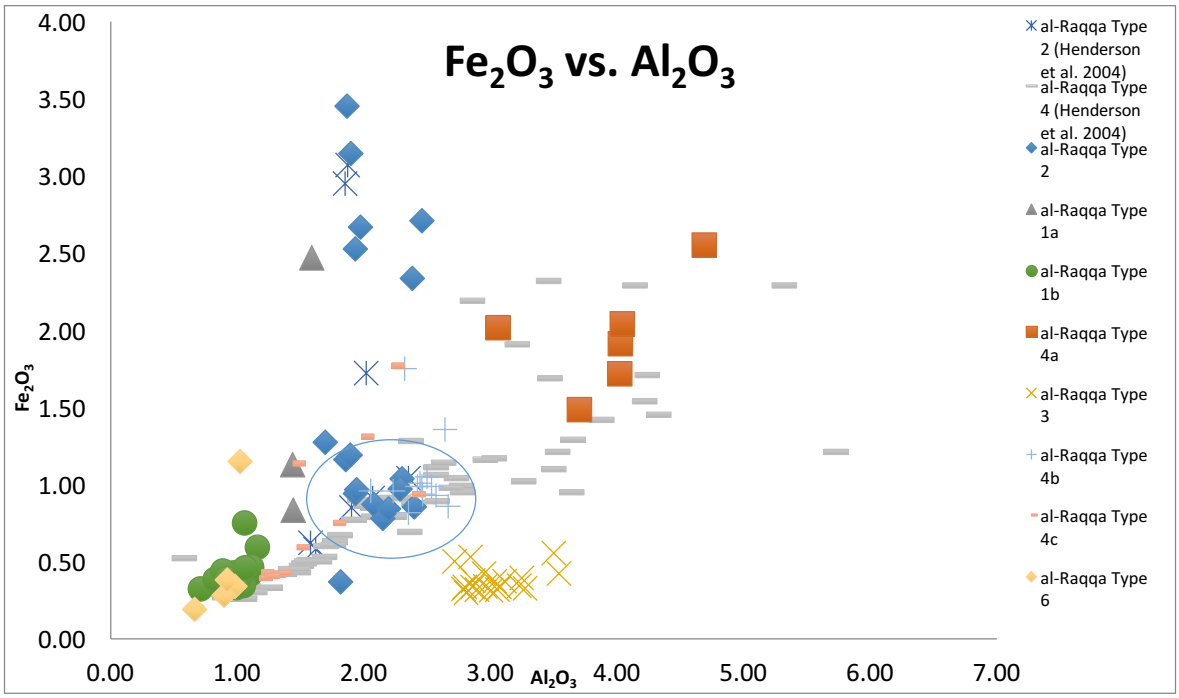


Figure 7.21: A bi-plot of Fe_2O_3 versus Al_2O_3 for al-Raqqa Types 1a, 1b, 2, 3, 4a, 4b, 4c and 6 glasses from 9th century Tell Zujaj and Tell Abu Ali in al-Raqqa. Data for al-Raqqa Types 2 and 4 glasses: Henderson *et al*. (2004).

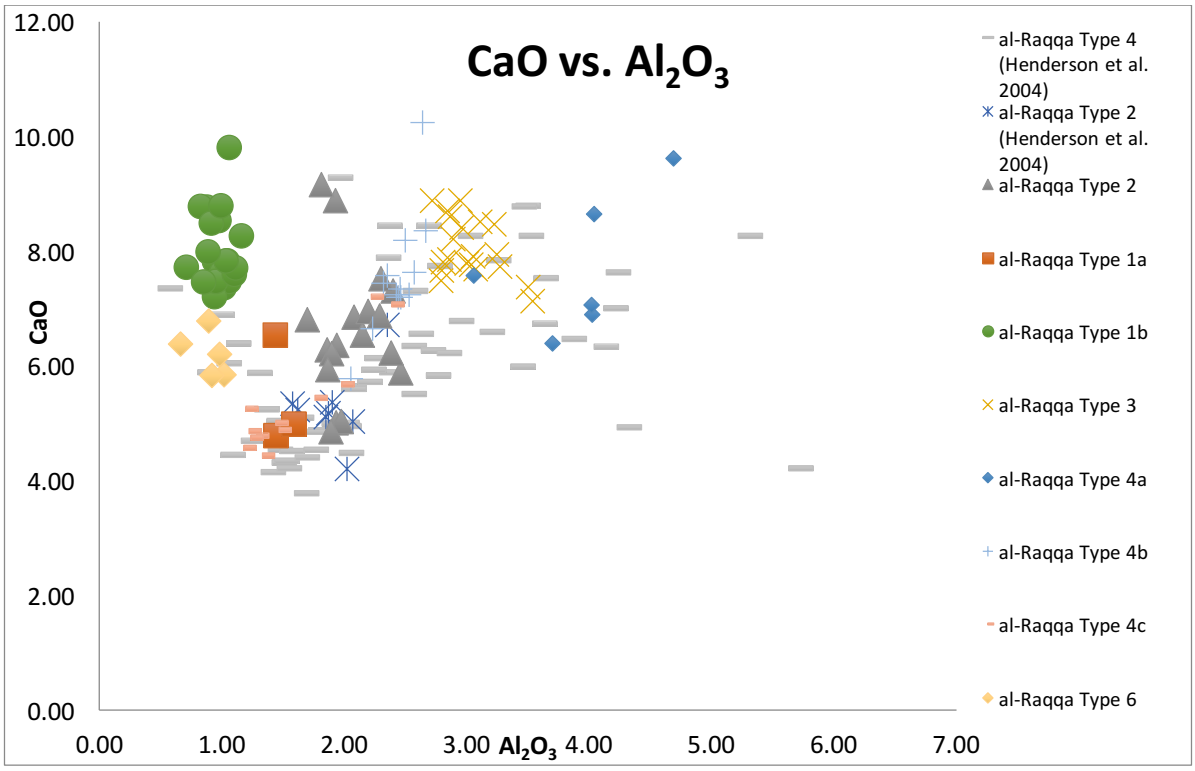


Figure 7.22: A bi-plot of CaO versus Al_2O_3 for al-Raqqa Types 1a, 1b, 2, 3, 4a, 4b, 4c and 6 glasses from 9th century Tell Zujaj and Tell Abu Ali in al-Raqqa. Data for al-Raqqa Types 2 and 4 glasses: Henderson *et al*. (2004).

7.3.12 al-Raqqa Type 2 colourants:

This glass group is highly coloured with blue and dark green colours. Only 4 glasses are colourless. Figure 7.23 shows that the dark green glasses from Type 2 can be divided into two groups: one group with relatively low concentrations of Al_2O_3 (1.70% - 1.89%) and Fe_2O_3 (1.16% - 1.27%) while the other group has higher concentrations of Al_2O_3 (1.87% - 2.38%) and Fe_2O_3 (2.34% - 3.45%). Henderson *et al*. (2004) have also noted that the green glasses from Type 2 have high concentrations of Fe_2O_3 above 1%, which suggests an iron-rich raw material was used to produce these dark green glasses. Figure 7.24 shows that all of the dark green glasses have negligible levels of MnO (0.03% - 0.17%).

As regards the colourless glasses, Figure 7.23 shows that they have a relatively low concentration of Fe_2O_3 (0.37% - 0.96%), which is among the lowest in Type 2 and is likely to be impurity from the raw materials. On the other hand, these colourless glasses have a relatively high concentration of MnO (0.93% - 3.21%) which was deliberately added to decolourise the glasses (Figure 7.24).

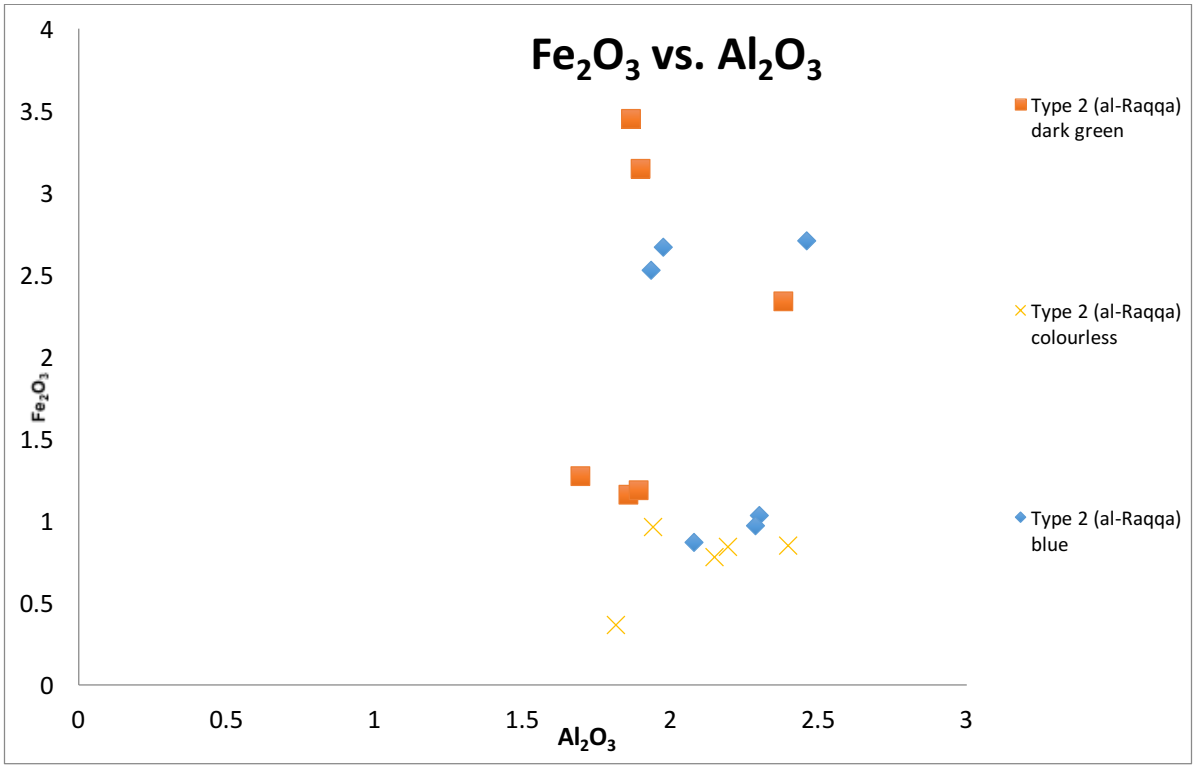


Figure 7.23: A bi-plot of Fe_2O_3 versus Al_2O_3 for al-Raqqa Type 2 glasses from 9th century Tell Zujaj and Tell Abu Ali in al-Raqqa. It is displayed according to colours.

The blue glasses in Type 2 can be divided into two separate groups. The first group (RAQ-10, 45, 42) has high concentrations of Fe_2O_3 (2.53% - 2.71%) (Figure 7.23). It is also accompanied with elevated levels of CoO (0.10% - 0.19%), CuO (0.54% - 0.56%) and ZnO (0.08% - 0.13%). This is similar to the blue glasses from Type 4. It is likely that the blue colour in these glasses was the result of the use of a cobalt-bearing ore (Henderson *et al*. 2004, 462).

On the contrary, the second group (RAQ-17, 60, 74) is characterised by a lower level of Fe_2O_3 (0.87% - 1.04%) (Figure 7.24) and negligible contents of CoO, CuO and ZnO. This is similar to other al-Raqqa blue glasses in which the blue colour was the result of Fe_2O_3 in the form of ferrous ion and the glasses were melted under reducing conditions, which impart a bluish colour.

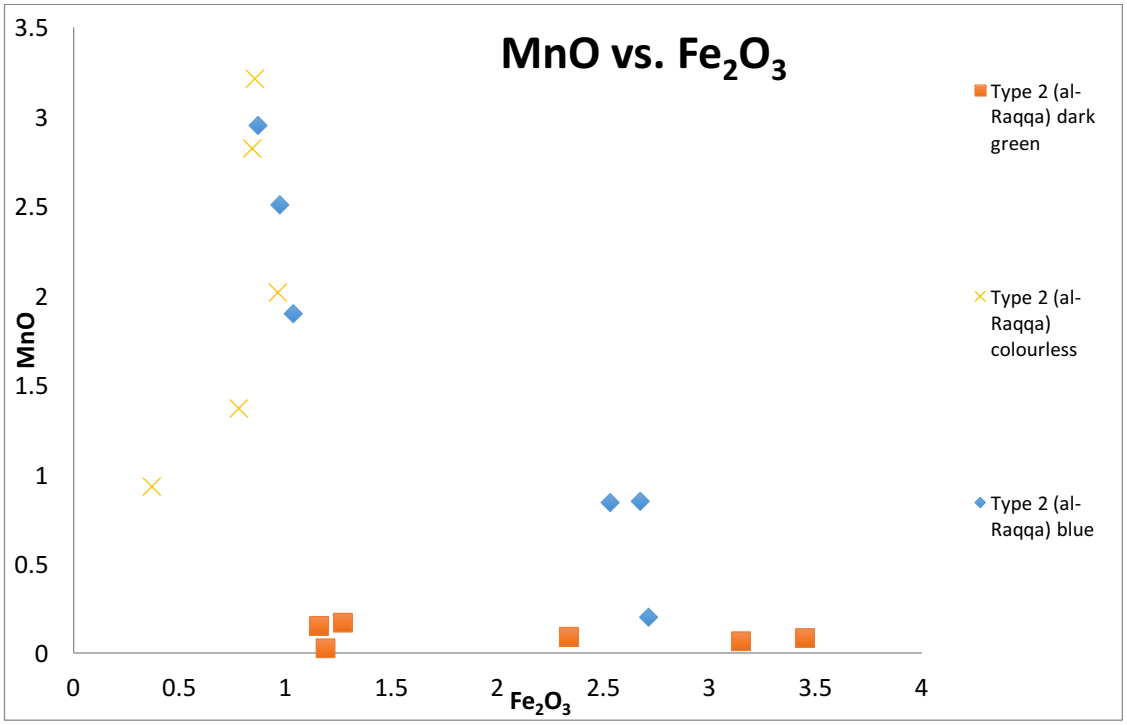


Figure 7.24: A bi-plot of MnO versus Fe_2O_3 for al-Raqqa Type 2 glasses from 9th century Tell Zujaj and Tell Abu Ali in al-Raqqa. It is displayed according to colours.

7.3.13 al-Raqqa Type 6:

Al-Raqqa Type 6 consists of 5 samples from Tell Zujaj. They represent an unknown group that has not been identified previously in the al-Raqqa glass assemblages. This glass group does not belong to al-Raqqa Type 1 or Type 4c (Figure 7.7). This group is characterised by high MgO (4.34% - 5.07%) but low CaO (5.84% - 6.78%) (Figure 7.16) and P_2O_5 (0.08% - 0.15%) levels. However, its total alkali level, Al_2O_3 and Fe_2O_3 levels are low and are similar to glasses from Type 1 (Figures 7.20 and 7.21). No raw glasses were found in this group.

Elements	al-Raqqa Type 6 (wt%) (n=5)
SO_3	0.28 +/- 0.05
P_2O_5	0.11 +/- 0.03
V_2O_5	0.01 +/- 0.01
As_2O_5	0.14 +/- 0.05
Sb_2O_5	0.02 +/- 0.01
SiO_2	70.54 +/- 1.15
TiO_2	0.04 +/- 0.01
SnO_2	0.02 +/- 0.01
Al_2O_3	0.90 +/- 0.14
Cr_2O_3	0.01 +/- 0.01
Fe_2O_3	0.47 +/- 0.39
MgO	4.74 +/- 0.28
CaO	6.21 +/- 0.40
MnO	0.37 +/- 0.07
CoO	0.01 +/- 0.01
CuO	0.06 +/- 0.07
ZnO	0.03 +/- 0.04
BaO	0.03 +/- 0.02
PbO	0.03 +/- 0.02
Na_2O	12.57 +/- 0.61
K_2O	2.43 +/- 0.38
Ag_2O	0.01 +/- 0.01
Cl	0.62 +/- 0.09

Table 7.5: Means and standard deviations of plant ash glass group Type 6 from al-Raqqa.

This glass group does not appear to be the result of recycling. It does not overlap with any of the al-Raqqa glass groups in terms of its major and minor elements.

7.3.14 Colourants for al-Raqqa Type 6:

Three glasses in Type 6 are colourless (RAQ-18, 22, 40), only one glass sample (RAQ-01) is blue and one other sample (RAQ-85) is aqua. The colourless glasses have low concentrations of Fe_2O_3 (0.19% - 0.34%) and MnO (0.28% - 0.41%). Unlike other colourless glasses from al-Raqqa Types 1 and 2, MnO was not deliberately added to decolourise the glass but was introduced to the glass as an impurity. This may relate to the fact that the raw materials used to produce these colourless glasses were relatively purer than the ones used to produce other al-Raqqa glasses.

For the blue and aqua glasses, the blue glass and aqua colour could have been produced by the relatively high concentrations of Fe_2O_3 (1.15% and 0.38% respectively) in the glass.

7.3.15 Fustat:

Two pieces of glass from the early 20th century AD excavations in Fustat were analysed. VA-01 (C.1470-1921) is a frit and VA-02 (C.1471-1921) is a furnace glass. Compositionally, they resemble the low MgO-high Al_2O_3 glasses (al-Raqqa Type 4a) from al-Raqqa. They are characterised by high concentrations of Al_2O_3 (3.31% - 3.62%) and MgO (2.32% - 2.91%) (Figure 7.25). They have elevated levels of Fe_2O_3 (2.0% and 1.90% respectively) (Figure 7.26) and TiO_2 (0.71% and 0.62% respectively). It is likely that they are impurities from the silica source such as sands.

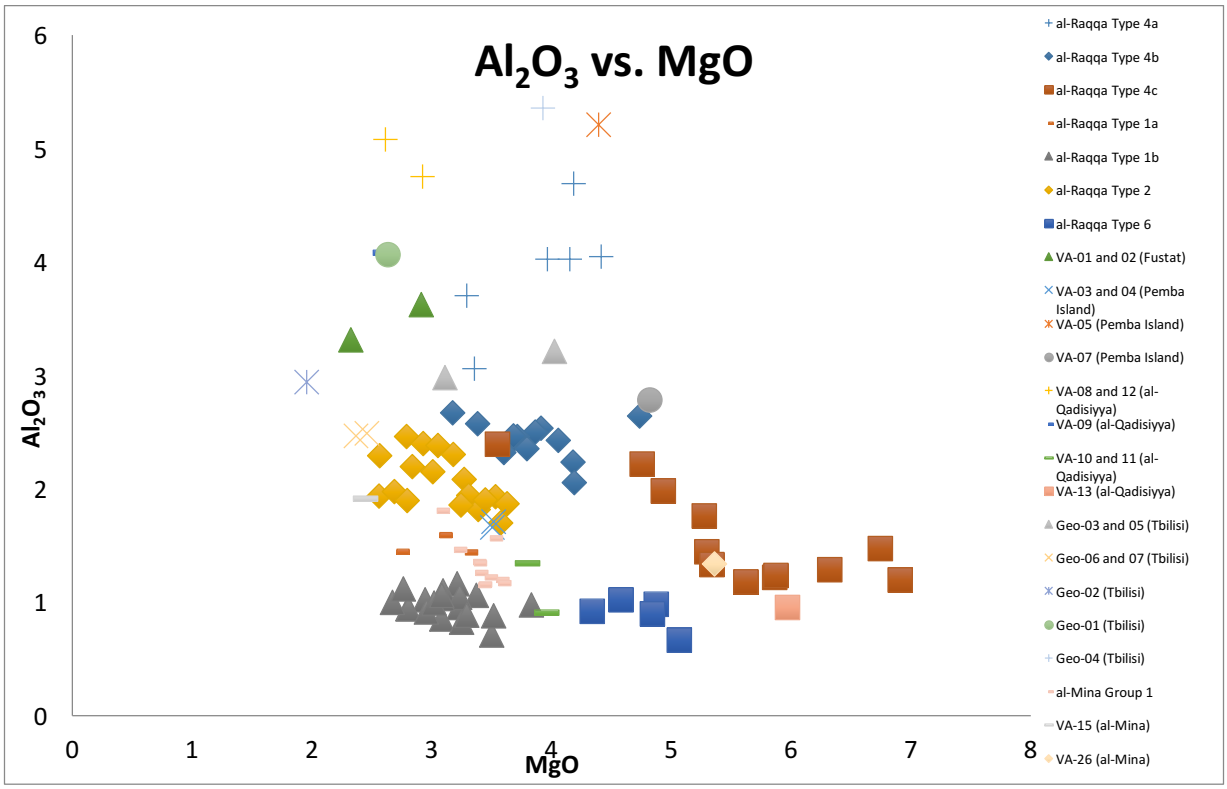


Figure 7.25: A bi-plot of Al_2O_3 versus MgO for plant ash glasses from late 8th - 9th century Tell Zujaj and Tell Abu Ali in al-Raqqa, 9th – 10th centuries al-Mina, Islamic period Fustat, Islamic period Pemba Island, 9th – 10th centuries AD al-Qadisiyya in Samarra and 10th – 14th centuries Tbilisi.

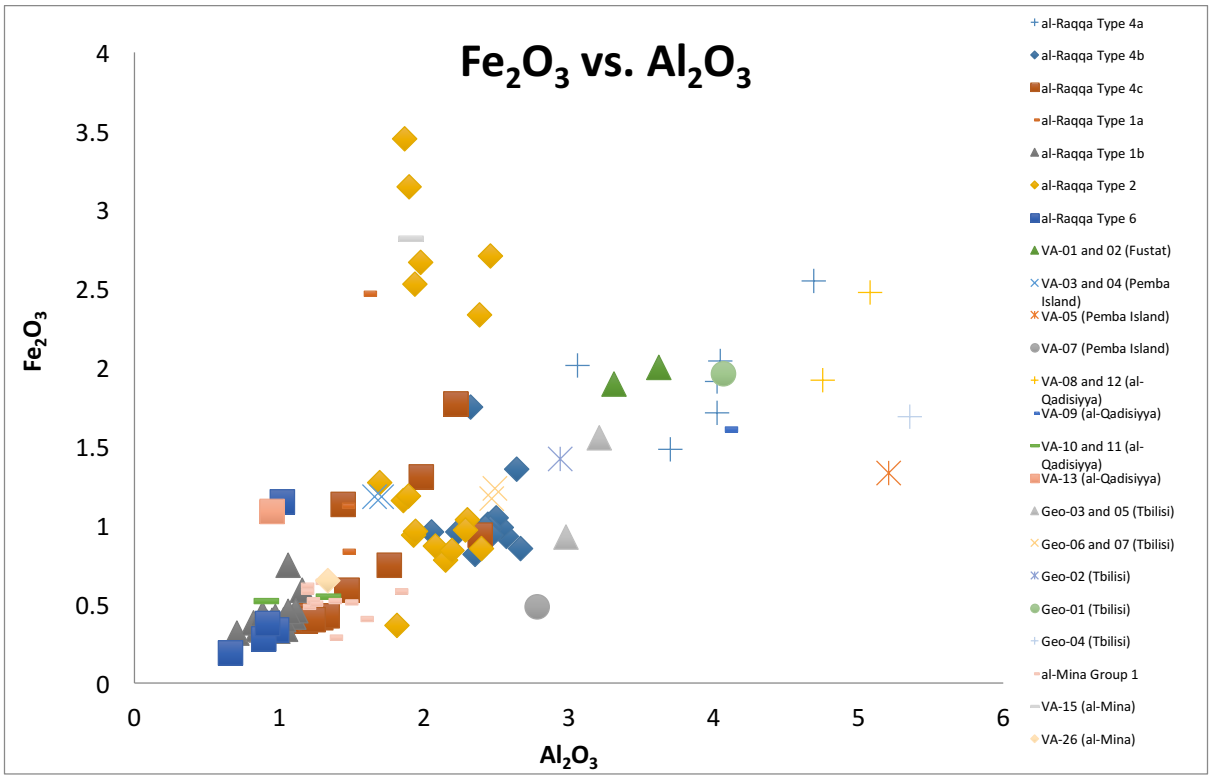


Figure 7.26: A bi-plot of Fe_2O_3 versus Al_2O_3 for plant ash glasses from late 8th - 9th century Tell Zujaj and Tell Abu Ali in al-Raqqa, 9th – 10th centuries al-Mina, Islamic period Fustat, Islamic period Pemba Island, 9th – 10th centuries AD al-Qadisiyya in Samarra and 10th – 14th centuries Tbilisi.

Their CaO (between 5.29% and 5.67%) and MgO levels are fairly low, and plot away from the majority of the high MgO-low Al_2O_3 glasses from al-Raqqa (Figure 7.27). In terms of their alkali level, the concentration of Na_2O in these glasses is relatively low (12.26% - 14.57%), but their K_2O levels are also distinctively low, 1.95% and 1.36% respectively (Figure 7.28). It is also noted that their SO_3 levels are very low, between 0.05% and 0.11%. It is likely that a different composition of plant ash from a different geological environment than the al-Raqqa glasses was used for the production of the Fustat glasses. It is possible that they were made in Fustat.

7.3.16 Colorants for the Fustat glass:

Both Fustat glasses are green colour. This is due to the presence of high concentrations of Fe_2O_3 (1.90% - 2.00%) as ferric ion in the glass.

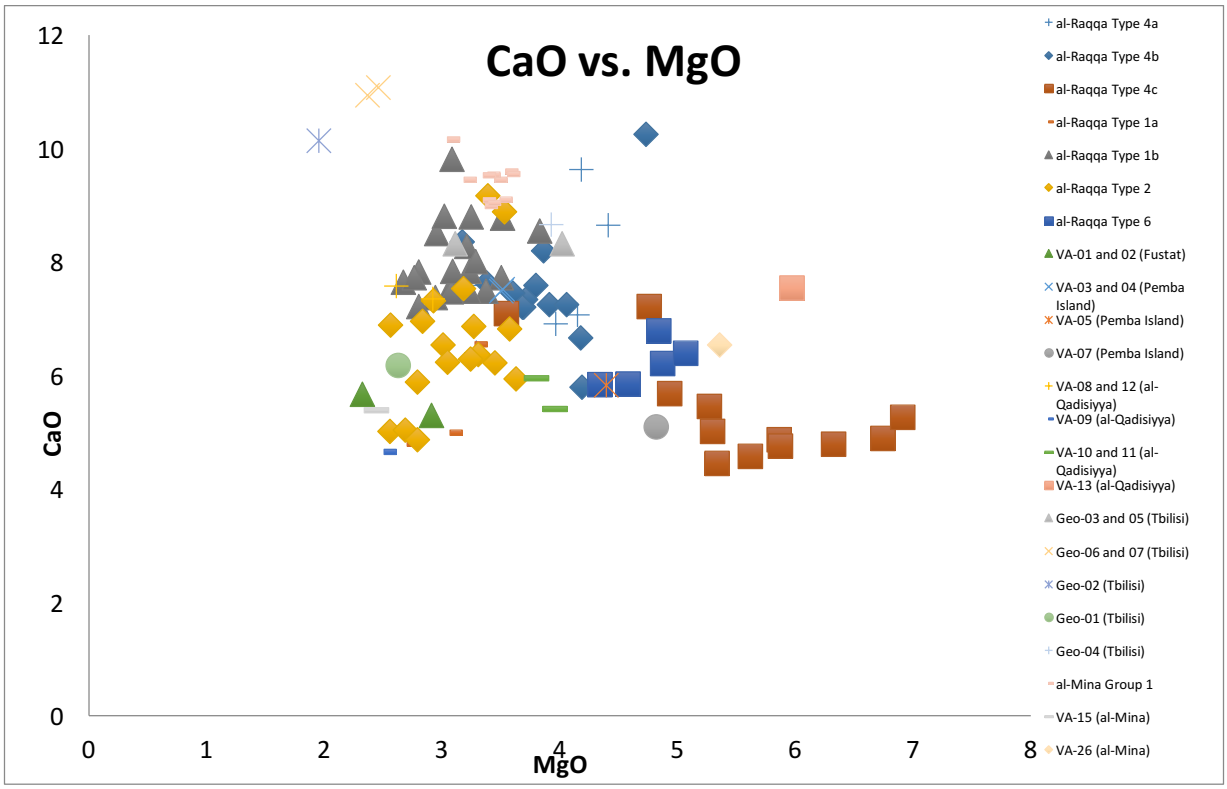


Figure 7.27: A bi-plot of CaO versus MgO for plant ash glasses from late 8th - 9th century Tell Zujaj and Tell Abu Ali in al-Raqqa, 9th – 10th centuries al-Mina, Islamic period Fustat, Islamic period Pemba Island, 9th – 10th centuries AD al-Qadisiyya in Samarra and 10th – 14th centuries Tbilisi.

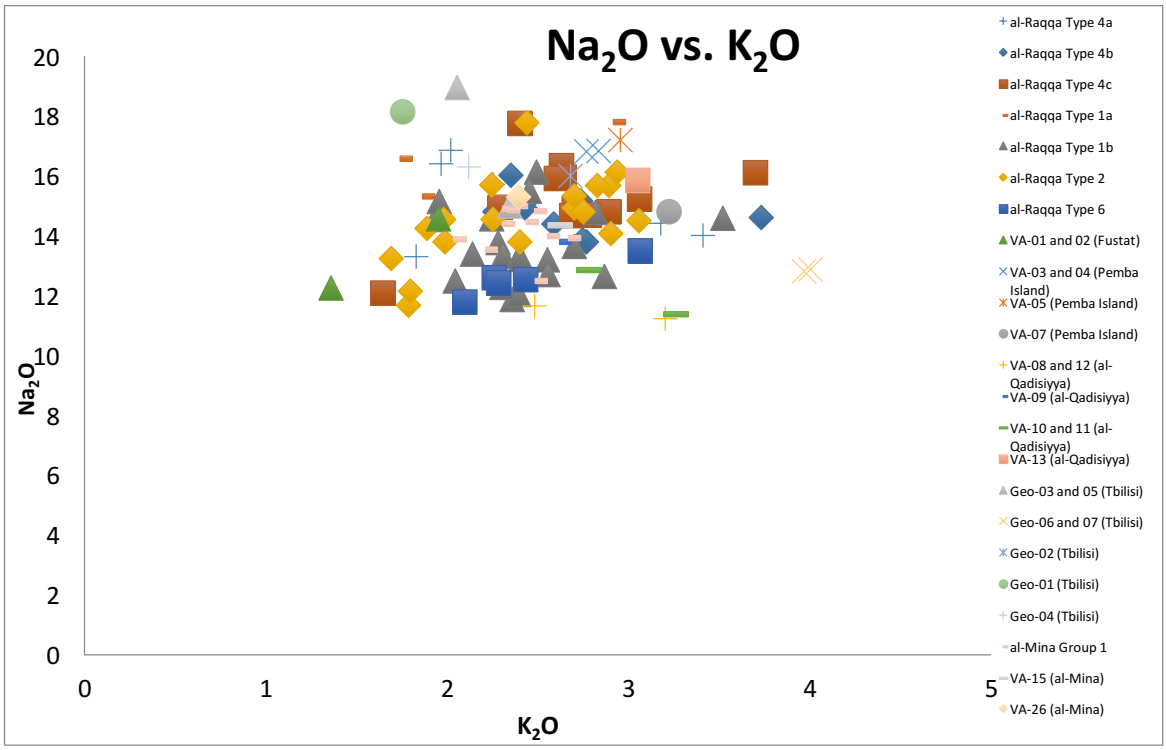


Figure 7.28: A bi-plot of Na_2O versus K_2O for plant ash glasses from late 8th - 9th century Tell Zujaj and Tell Abu Ali in al-Raqqa, 9th – 10th centuries al-Mina, Islamic period Fustat, Islamic period Pemba Island, 9th – 10th centuries AD al-Qadisiyya in Samarra and 10th – 14th centuries Tbilisi.

7.3.17 Pemba Island:

Five fragments of glass from Pemba Island, East Africa, dated to the Islamic period, have been analysed in this study. The results show that they have variable compositions.

7.3.18 VA-03 and 04 from Pemba Island:

Their compositions are relatively homogenous in terms of their major and minor elements. It is possible that they were produced from the same glass batch. They are characterised by low concentrations of Al_2O_3 (1.66% - 1.71%), Fe_2O_3 (1.18%) (Figure 7.26) and TiO_2 (0.07 – 0.08%). It is likely that a relatively pure source of silica, such as quartz or cherts, was used. Plant ashes with relatively low concentration of MgO (3.50% - 3.51%) and K_2O (2.77% - 2.83%) but with high concentrations of CaO (7.48% - 7.52%) and Na_2O (16.82% - 16.83%), were used to produce these two glasses (Figures 7.27 and 7.28). These glasses resemble some of the glasses from al-Raqqa Type 1, Both of which have a similar concentration of CaO and MgO (Figure 7.27). But the higher

concentration of Na_2O in VA-03 and 04 suggests a different composition of plant ashes, possibly from a similar geological environment that contributed the CaO and MgO to the plants, was used.

7.3.19 VA-05 from Pemba Island:

A fragment of flask (VA-05) from Pemba Island is different from VA-03 and 04. This glass has a particularly high Al_2O_3 (5.21%) and Fe_2O_3 (1.33%) levels (Figure 7.26) but low SiO_2 (60.73%). It is likely that an impure source of silica was used.

It has a high concentration of Na_2O (17.20%) and K_2O (2.95%) that is similar to VA-03 and 04 (Figure 7.28). But its CaO level (5.83%) is relatively low (Figure 7.27). This suggests plant ashes from a different geological background was used to produce this fragment of glass compared to VA-03 and 04.

It resembles to the low MgO-high Al_2O_3 glasses from al-Raqqa (Type 4a) in terms of its silica and alkali sources. But this piece of glass has a slightly lower level of CaO and a higher level of MgO than the al-Raqqa glasses (Figure 7.27). Moreover, VA-05 has an unusually high level of PbO of 0.34%. High levels of PbO can only be found in RAQ-26 and RAQ-30, which have only 0.12% and 0.22% of PbO respectively. The differences in CaO and MgO levels suggest this fragment of glass was not produced using the same raw material as the al-Raqqa glasses.

7.3.20 VA-07 from Pemba Island:

VA-07 is similar to the high MgO-low Al_2O_3 glasses from al-Raqqa (Type 4c) (Figure 7.25). It has a lower concentration of Al_2O_3 (2.78%), Fe_2O_3 (0.48%) (Figure 7.26) and TiO_2 (0.08%) but a higher concentration of SiO_2 (67.38%) than VA-05 from Pemba Island. But its silica source derived from an impure sand, unlike VA-03 and 04 from Pemba Island which was made pure source of silica. It has a low concentration of Na_2O (14.79%) and CaO (5.09%). But its MgO (4.82%) and K_2O (3.22%) levels are higher than the majority of the Pemba Island glasses (Figures 7.27 and 7.28).

7.3.21 Colourants for the Pemba Island glass:

The majority of the glasses (VA-03, 04, 05, 06) from Pemba Island are emerald green coloured. Only one glass sample (VA-07) is coloured turquoise. The emerald colour was due to the presence of high level of Fe_2O_3 (1.18% - 1.33%) in the form of ferric ion. On the other hand, the turquoise glass has a relatively low level of Fe_2O_3 (0.48%) and is likely present in the form of ferrous ion which imparts a bluish green colour. All of these glasses have low concentrations of MnO (0.10% - 0.12%).

7.3.22 al-Qadisiyya, Samarra:

Six pieces of raw glass from al-Qadisiyya in Samarra, Iraq that are dated to the 9^{th} – 10^{th} centuries AD were analysed. They show variable chemical compositions based on their major and minor elements.

7.3.23 VA-08, 09 and 12 from al-Qadisiyya, Samarra:

These belong to the low MgO-high Al_2O_3 glasses identified among the al-Raqqa glasses (Type 4a) (Figures 7.25). They have high concentrations of Al_2O_3 (4.08% - 5.08%), Fe_2O_3 (1.61% - 2.48%) (Figure 7.26) and TiO_2 (0.18% - 0.28%) and Al_2O_3 and Fe_2O_3 are positively correlated. This suggests that an alumina-rich and iron-bearing mineral sand source was used to produce these Samarra glasses. It is possible that sand derived from the weathering of crystalline rocks with high concentrations of feldspar and heavy minerals were used to produce these glasses (Henderson 2013, 57).

There are some variations based on the lime and alkali levels. VA-08 and 12 have higher levels of CaO (7.35% and 7.57% respectively) and MgO (4.75% - 5.08%) than VA-09 (CaO of 4.65% and MgO of 2.51%) (Figure 7.27). In terms of the alkali level, VA-08 and 12 have low level of Na_2O (11.22% and 11.66% respectively) but a relatively high level of K_2O (3.20% and 2.48% respectively) (Figure 7.28). It is noted that VA-09 has a higher concentration of Na_2O (13.80%) but a lower concentration of K_2O (2.62%) than VA-08 and 12 (Figure 7.28). It is possible that plants with different physiognomies and geological environment were used to produce these glasses.

7.3.24 VA-10 and 11 from al-Qadisiyya, Samarra:

VA-10 and 11 are two pieces of furnace glasses from al-Qadisiyya in Samarra. They are characterised by very low Al_2O_3 (0.91% - 1.34%) and Fe_2O_3 (0.52% - 0.55%) (Figure 7.26) but high concentrations of SiO_2 (71.96% - 73.28%). When compared to other glasses from Samarra, a purer source of silica with very low levels of impurities was used. Its alkali source is also different from other Samarra glasses. It has low Na_2O (11.37% - 12.85%) but higher K_2O (2.78% - 3.26%) levels (Figure 7.28). Its CaO (5.40% - 5.95%) levels are also significantly lower than VA-08, 09 and 12 from Samarra. And a higher level of MgO (3.80% - 3.96%) is observed in VA-10 and 11 (Figure 7.27). It is likely that a different composition of plant ash from a different geological background was used to produce VA-10 and 11. This glass group resembles al-Raqqa Type 6. This may suggest Samarra was one of the glass production centre that produced this glass type in Iraq and that its product was traded to northern Syria.

7.3.25 VA-13 from al-Qadisiyya, Samarra:

VA-13 is similar to the high MgO-low Al_2O_3 glasses (Figure 7.25). It has low concentrations of Al_2O_3 (0.95%), Fe_2O_3 (1.09%) (Figure 7.26) and TiO_2 (0.05%). This suggests a relatively pure silica source was also used to produce these glasses, which is similar to VA-10 and 11. However, this piece of glass has a distinctively higher level of K_2O (3.05%) and Na_2O (15.84%) than other Samarra glasses (Figure 7.28). VA-13 has a high level of CaO (7.54%), which is higher than the majority of the high MgO-low Al_2O_3 glasses (Figure 7.27). Also, this piece of glass has a very high level of SO_3 concentration of 0.52%. None of which is found in other Samarra glasses. It is likely that a different composition of plant ash (high CaO, MgO, K_2O, SO_3 and Na_2O) from a different geographical origin was used to produce this glass.

7.3.26 Colourants for al-Qadisiyya glass:

The majority of the glasses from al-Qadisiyya in Samarra are emerald green and aqua. Only one sample (a waster VA-13) is coloured in blue. The emerald green colour is likely the result of Fe_2O_3 in the form of ferric ion in the glasses. But the concentrations of Fe_2O_3 in the green glasses varied: VA-10 and 11 have a relatively low level of Fe_2O_3

of 0.52% - 0.55%; while VA-08, 09 and 12 have high contents of Fe_2O_3 of 1.61% - 2.48%, which are likely to have come from the silica source (a rather impure sand source which introduced 4.08% - 5.08% of Al_2O_3 to the glasses). The blue glass (VA-13) has very low levels of CoO (0.05%), CuO (0.02%) and ZnO (0.02%) which suggest the blue colour was produced with the Fe_2O_3 (1.09%) in the glass.

7.3.27 Tbilisi, Georgia:

Seven pieces of glass from Tbilisi in Georgia were analysed. They are dated to the 10^{th} – 14^{th} centuries AD. The results show that they have variable chemical compositions according to their major and minor elements.

7.3.28 Geo-03 and 05 from Tbilisi:

Geo-03 and 05 (dated to the 10^{th} – 13^{th} centuries AD) from Tbilisi have a relatively high concentration of Al_2O_3 (3.21% and 2.98% respectively), Fe_2O_3 (1.56 and 0.93% respectively) (Figure 7.26), and TiO_2 (0.14 and 0.12% respectively). It is likely that a rather different source of impure silica (e.g. sands) were used for the Tbilisi glasses. This glass group has relatively high levels of CaO (both have 8.32%) and MgO (4.02% and 3.11% respectively) (Figure 7.27).

It is noted that this group has high concentrations of SO_3 (0.52% and 1.46% respectively) and P_2O_5 (0.42% and 0.85% respectively), which may indicate the use of a different plant ash composition.

7.3.29 Geo-02, 06 and 07 from Tbilisi:

These glasses are dated to the 12^{th} – 14^{th} centuries AD. In terms of their silica source, they have high levels of Al_2O_3 (2.47% - 2.94%), Fe_2O_3 (1.17% - 1.42%) (Figure 7.26) and TiO_2 (0.13% - 0.16%). But a relatively low level of SiO_2 (61.41% - 62.20%) is observed. These values are very similar to Geo-03 and 05 from Tbilisi. It is possible that a similar sand source was used to produce these glasses.

Geo-02, 06 and 07 have a higher concentration of lime (10.14% - 11.08%) but contain a lower concentration of MgO (1.95% - 2.46%) than Geo-03 and 05 from Tbilisi (Figure 7.27). It is unlikely that the high level of CaO comes from the silica source because there is no correlation between Al_2O_3 and CaO (Figure 7.29).

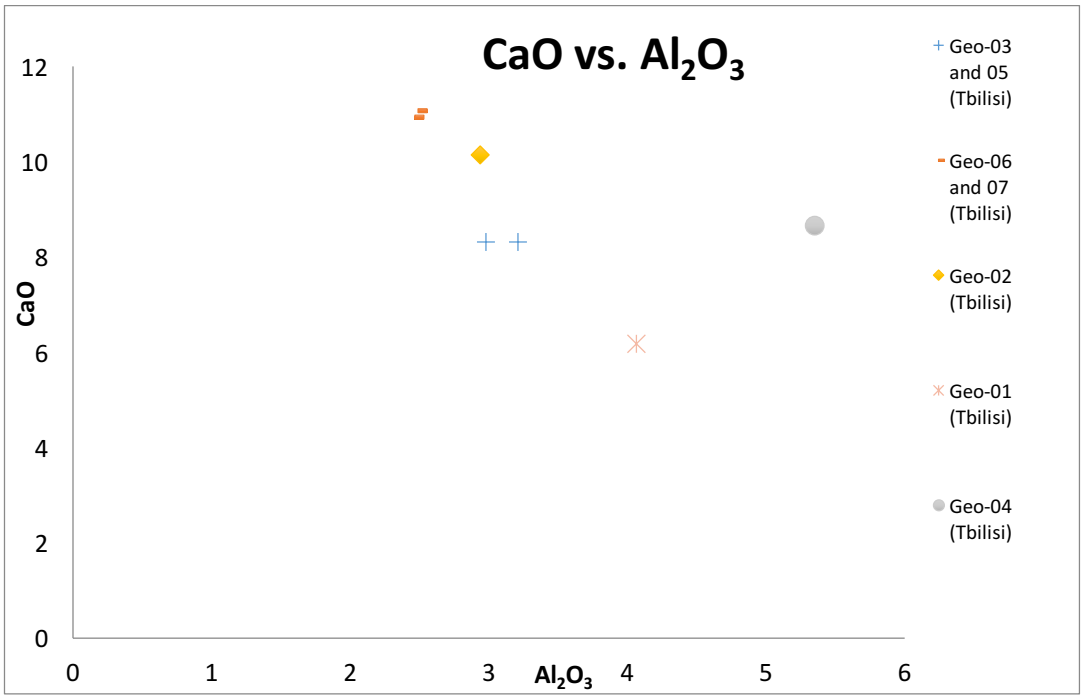


Figure 7.29: A bi-plot of CaO versus Al_2O_3 for plant ash glasses from 10^{th} – 14^{th} centuries Tbilisi.

There are some differences between Geo-02, 06 and 07 based on their alkali levels. Geo-06 and 07 have a lower concentration of Na_2O (12.80% - 12.88%) but with a higher level of K_2O (3.97% - 4.0%) than Geo-02 (Figure 7.28). The latter has a high concentration of Na_2O (16.01%) and low content of K_2O (2.68%) which are similar to Geo-03 and 05 from Tbilisi (Figure 7.28). Their P_2O_5 and SO_3 levels are also different. Geo-06 and 07 have a significantly higher level of P_2O_5 (1.48% - 1.64%) than Geo-02 (0.69%). But Geo-06 and 07 has a lower concentration of SO_3 (0.20% - 0.22%) than Geo-02 (0.69%). It is likely that a different composition of plant ash was used to produce these glasses.

7.3.30 Geo-01 from Tbilisi:

Geo-01 is dated to the 10^{th} – 13^{th} centuries AD. It displays similar characteristics as the low MgO-high Al_2O_3 glasses (Figure 7.25). It has high concentrations of Al_2O_3 (4.07%), Fe_2O_3 (1.96%) (Figure 7.26) and TiO_2 (0.20%). But its SiO_2 concentration (60.98%) is significantly lower than other low MgO-high Al_2O_3 glasses. It is likely that a rather impure sand source with low concentration of SiO_2 was chosen as the silica source.

In terms of the alkali source, it has a high concentration of Na_2O (18.13%) but a relatively low K_2O (1.75%) compared with other low MgO- high Al_2O_3 glasses (Figure 7.28). The level of CaO (6.18%) in this glass is relatively low but is very similar to other glasses in the low MgO- high Al_2O_3 group (Figure 7.27).

This piece of glass contains an unusually high concentration of SO_3 (0.51%) and P_2O_5 (0.36%) than other low MgO-high Al_2O_3 glasses. Both elements derive from the plant ashes. The only comparable parallel would be VA-13 from Samarra which has 0.52% of SO_3 but its P_2O_5 level (0.16%) is significantly lower than Geo-01. It is likely that this plant ash composition has different alkali, SO_3 and P_2O_5 levels than those used to produce the low MgO- high Al_2O_3 glasses from al-Raqqa, Pemba Island, Fustat and al-Qadisiyya.

7.3.31 Geo-04 from Tbilisi:

Geo-04 is dated to the 10^{th} – 12^{th} centuries AD. It is broadly similar to Geo-01 with high concentrations of Al_2O_3 (5.36%), Fe_2O_3 (1.69%) (Figure 7.26) and TiO_2 (0.25%) but low SiO_2 (58.69%) (Appendix Table 2). However, the differences between the two are their lime and alkali levels. Geo-04 has a significantly high level of CaO (8.66%) and MgO (3.93%) that is similar to other low MgO- high Al_2O_3 glasses (Figure 7.27). But Geo-04 has a lower concentration of Na_2O (16.29%) and higher level of K_2O (2.12%) than Geo-01 (Figure 7.28). Geo-04 is closely related to other low MgO- high low Al_2O_3 glasses in this study. Such differences could be due to the use of different compositions of plant ashes from a different geological background.

7.3.32 Colourants for the Tbilisi glass:

It is noted that all of the Tbilisi plant ash glasses are coloured in various shades of green (olive green (Geo-01 and 03), green (Geo-06 and 07), light green (Geo-02) and dark green (Geo-04 and 05)). Regardless of their varying compositions, Figure 7.26 shows that the Fe_2O_3 in these glasses is likely to have originated from the silica source and is responsible for the colouration of the glasses. These glasses were likely melted in a furnace(s) in varying degrees of oxidising conditions, which produced the various shades of green colour.

7.3.33 al-Mina:

Thirteen fragments of glasses from al-Mina were analysed and the results show that they were made with plant ashes. They are dated to the 9^{th} – 10^{th} centuries AD. Two groups of glass are found in this assemblage.

7.3.34 al-Mina Group 1:

Eleven glasses from al-Mina (VA-14, 16, 17, 18, 20, 21, 22, 23, 24, 25, 28) belong to al-Mina Group 1. They are fairly homogenous in terms of the soda (12.49% - 15.0%), lime (8.98% - 10.16%) and magnesium (3.04% - 3.54%) concentrations. This group has a low concentration of Al_2O_3 (1.15% - 1.80%, Fe_2O_3 (0.29% - 0.64%) (Figure 7.26) and TiO_2 (0.07% - 0.10%). There is a slight variation in the concentration of Al_2O_3 within this glass group. Five glasses (VA-16, 17, 20, 24 and 28) have a higher concentration of Al_2O_3 (1.34% - 1.80%) than the rest of the glasses in this group (1.15% - 1.22%). It is likely that two different batches of glass with different concentrations of Al_2O_3 are involved. In terms of the lime and alkali levels, this group has a relatively high concentration of CaO but a relatively low concentration of Na_2O and K_2O (Figures 7.27 and 7.28).

Elements	al-Mina Group 1 (wt%) (n=11)
SO_3	0.21 +/- 0.04
P_2O_5	0.30 +/- 0.04
V_2O_5	0.01 +/- 0.01
As_2O_5	0.14 +/- 0.07
Sb_2O_5	0.01 +/- 0.01
SiO_2	66.63 +/- 0.99
TiO_2	0.09 +/- 0.01
SnO_2	0.02 +/- 0.03
Al_2O_3	1.33 +/- 0.21
Cr_2O_3	0.01 +/- 0.01
Fe_2O_3	0.52 +/- 0.10
MgO	3.37 +/- 0.15
CaO	9.40 +/- 0.34
MnO	0.77 +/- 0.36
CoO	0.01 +/- 0.00
CuO	0.17 +/- 0.53
ZnO	0.02 +/- 0.01
BaO	0.03 +/- 0.01
PbO	0.05 +/- 0.06
Na_2O	14.21 +/- 0.75
K_2O	2.38 +/- 0.17
Ag_2O	0.01 +/- 0.01
Cl	0.74 +/- 0.05

Table 7.6: Means and standard deviations of plant ash glass from al-Mina Group 1

VA-25 has a slightly different composition than other glasses in al-Mina Group 1. It has an elevated level of CuO (1.75%) and PbO (0.21%) which is not found in other glasses from al-Mina Group 1. This may indicate that VA-25 was the result of glass recycling/mixing.

7.3.35 VA-15 from al-Mina:

VA-15 is different from other al-Mina glasses. It has a relatively high concentration of Al_2O_3 (1.91%) and Fe_2O_3 (2.82%) (Figure 7.26). This fragment is similar to al-Raqqa Type 2 in terms of its lime and alkali contents (Figures 7.27 and 7.28).

7.3.36 VA-26 from al-Mina:

VA-26 has a similar characteristic to the high MgO-low Al_2O_3 group (Figure 7.25). It has low concentrations of Al_2O_3 (1.34%), Fe_2O_3 (0.65%) (Figure 7.26) and TiO_2 (0.09%). These suggest a relatively pure silica source was also used to produce these glasses. The total alkaline level is also similar to other high MgO-low Al_2O_3 glasses (Figure 7.28). The difference is that it has a higher level of CaO (6.53%) than the majority of the high MgO-low Al_2O_3 glasses (Figure 7.27).

7.3.37 Colourants for al-Mina glass:

The majority of the glasses (VA-14, 18, 21, 22, 23, 24, 28) from al-Mina Group 1 are coloured aqua. Two glasses (VA-16 and 17) are coloured deep brown, one glass (VA-20) is colourless and one (VA-25) is emerald green. VA-15 is coloured blue and VA-26 is coloured aqua. Despite their varying compositions, the aqua glasses in al-Mina Group 1 and VA-26 have similar concentrations of Fe_2O_3 of 0.49% - 1.34% (Figure 7.30). Curiously, these aqua glasses also have high concentrations of MnO of 0.73% - 1.16%, which suggest Mn-rich raw material was added deliberately to decolourise the glass (Figure 7.31). It is fairly similar to the aqua glasses in al-Raqqa Types 4b and 4c which have high concentrations of MnO in the glasses.

The emerald green glass is quite distinctive from other emerald green glass in this study. It has similar levels of Fe_2O_3 (0.62%) and MnO (0.78%) as the aqua glasses from al-Mina Group 1. However, it is noted that this emerald green glass has high contents of CuO of 1.75% and PbO of 0.21%. This combination can sometimes be found in opaque red glasses (Henderson 2000, 33). However, the lead oxide in this glass is less than 1% and it is coloured emerald green. The more likely explanation is that the high concentrations of CuO and PbO were the result of recycling and the green colour was produced by the presence of Fe_2O_3 in the glass.

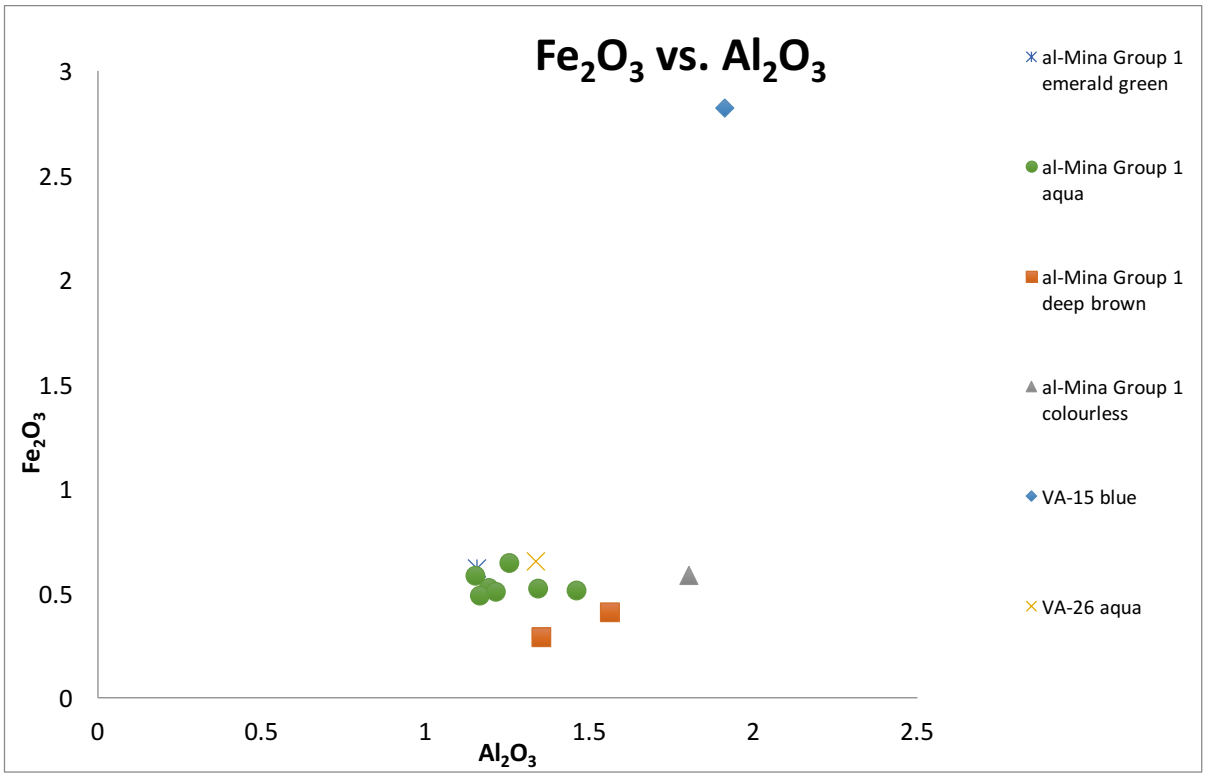


Figure 7.30: A bi-plot of Fe_2O_3 versus Al_2O_3 for plant ash glasses from 9th – 10th centuries AD al-Mina. It is displayed according to colours.

For the deep brown glasses, their levels of Fe_2O_3 (0.29% - 0.41%) and MnO (0.20% - 0.26%) are among the lowest in al-Mina Group 1 (Figures 7.30 and 7.31). It is likely that the Fe_2O_3 was present as ferric ions and the glasses were melted with short melting times and were melted in oxidising conditions, which impart a brown colour (Pollard and Heron 2008, 164; Sanderson and Hutchings 1987, 105).

As regards the colourless glass, it has the highest concentration of MnO (1.59%) among the al-Mina glasses (Figure 7.31). Manganese-rich raw material was added to decolourise the glass.

The blue glass has a high concentration of Fe_2O_3 (1.11%) (Figure 7.30) along with elevated levels of CoO (0.28%), CuO (0.56%) and ZnO (0.05%). The blue colour is likely produced with cobalt-bearing raw material.

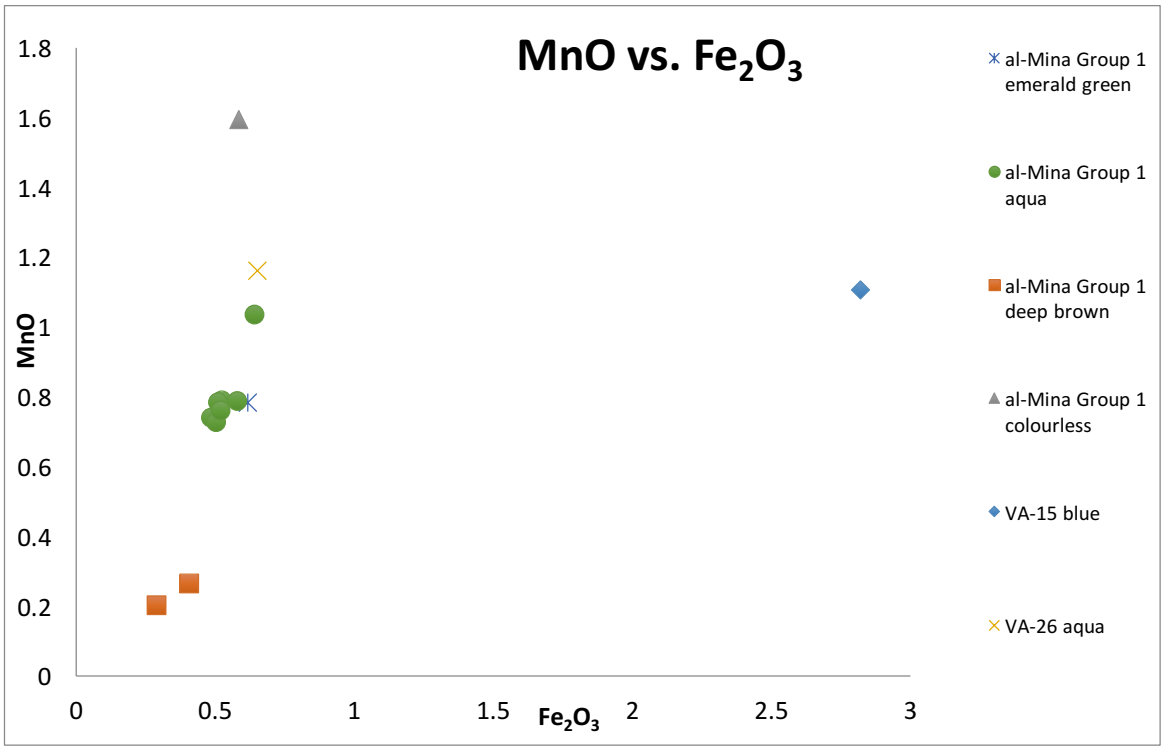


Figure 7.31: A bi-plot of MnO versus Al_2O_3 for plant ash glasses from 9th – 10th centuries AD al-Mina. It is displayed according to colours.

7.3.38 Zeyrek Camii:

Fifteen fragments of glass from the 11th – 12th century AD Zeyrek Camii in Istanbul were analysed. The result shows that three glass groups are present based on their major and minor elements.

Elements	Zeyrek Camii Group 1 (wt%) (n=7)	Zeyrek Camii Group 2 (wt%) (n=8)
SO_3	0.21 +/- 0.03	0.19 +/- 0.06
P_2O_5	0.29 +/- 0.04	0.29 +/- 0.13
V_2O_5	0.01 +/- 0.01	0.02 +/- 0.01
As_2O_5	0.16 +/- 0.11	0.20 +/- 0.18
Sb_2O_5	0.01 +/- 0.01	0.02 +/- 0.02
SiO_2	67.50 +/- 1.67	66.43 +/- 1.32
TiO_2	0.08 +/- 0.01	0.16 +/- 0.06
SnO_2	0.05 +/- 0.04	0.03 +/- 0.02
Al_2O_3	1.20 +/- 0.23	2.45 +/- 0.51
Cr_2O_3	0.01 +/- 0.01	0.01 +/- 0.01
Fe_2O_3	0.47 +/- 0.15	1.25 +/- 0.39
MgO	3.28 +/- 0.36	2.03 +/- 0.47

CaO	9.05 +/- 0.81	7.72 +/- 0.69
MnO	1.11 +/- 0.52	0.82 +/- 0.26
CoO	0.01 +/- 0.01	0.03 +/- 0.06
CuO	0.05 +/- 0.03	0.19 +/- 0.09
ZnO	0.02 +/- 0.01	0.06 +/- 0.10
BaO	0.06 +/- 0.05	0.04 +/- 0.03
PbO	0.05 +/- 0.06	0.18 +/- 0.11
Na_2O	13.39 +/- 0.94	14.29 +/- 1.17
K_2O	2.34 +/- 0.15	2.10 +/- 1.01
Ag_2O	0.02 +/- 0.01	0.01 +/- 0.01
Cl	0.80 +/- 0.13	0.78 +/- 0.15

Table 7.7: Means and standard deviations of plant ash glass groups from Zeyrek Camii.

7.3.39 Zeyrek Camii Group 1:

Seven glasses (ZC-08, 09, 10, 11, 12, 13 and 15) belong to Zeyrek Camii Group 1. It is characterised by relatively low concentration of Al_2O_3 (0.90% - 1.42%), Fe_2O_3 (0.31% and 0.74%) and TiO_2 (0.07% - 0.09%) (Figure 7.32). This suggests a relatively pure source of silica, such as chert or quartz, was used. These glasses also have a relatively high Na_2O (13.51% - 14.18%) concentration and CaO (8.04% and 10.15%) that are similar to Brill (2005)'s low boron plant ash glasses and Henderson *et al*. (2004)'s al-Raqqa Type 1 (Figures 7.33 and 7.34).

It is also noted that this glass group has a high concentration of MnO (0.96% - 2.21%). It is likely that MnO was added deliberately to the glass but for different purposes: MnO was likely used to decolourise the colourless glasses (ZC-08, 11, 12, 13 and 15) and MnO was used to colourise the lilac (ZC-09) and purple (ZC-10) glasses.

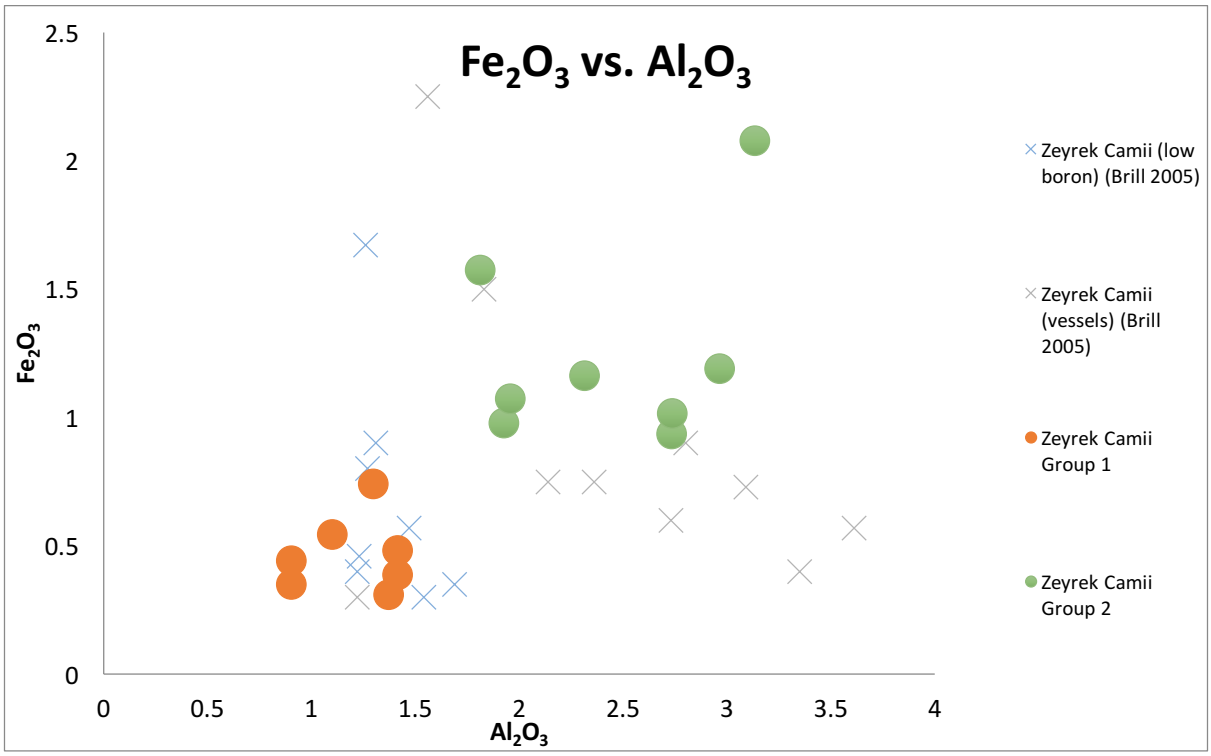


Figure 7.32: A bi-plot of Fe_2O_3 versus Al_2O_3 for plant ash glasses from 11th – 12th centuries AD Zeyrek Camii. Two glass groups are identified, Zeyrek Camii Groups 1and 2. Data for Zeyrek Camii glasses: Brill (2005).

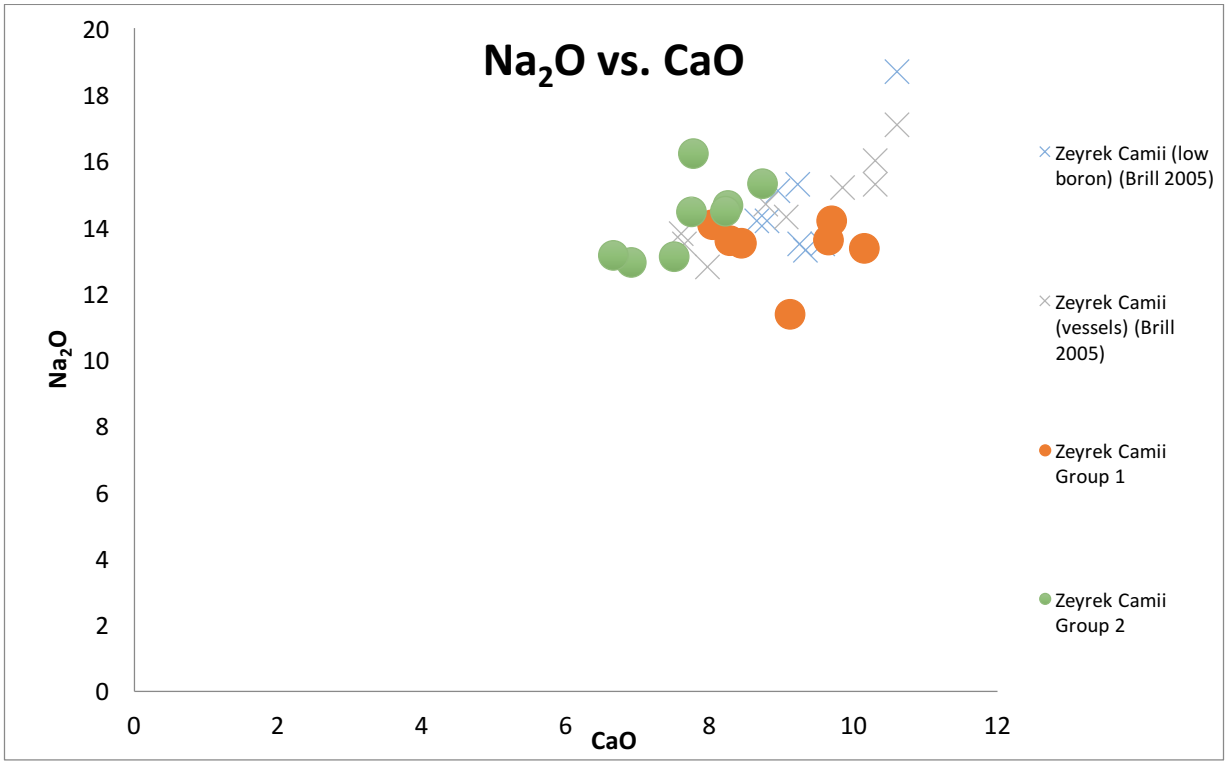


Figure 7.33: A bi-plot of Na_2O vs. CaO for plant ash glasses from 11th – 12th centuries AD Zeyrek Camii. Two glass groups are identified, Zeyrek Camii Groups 1and 2.

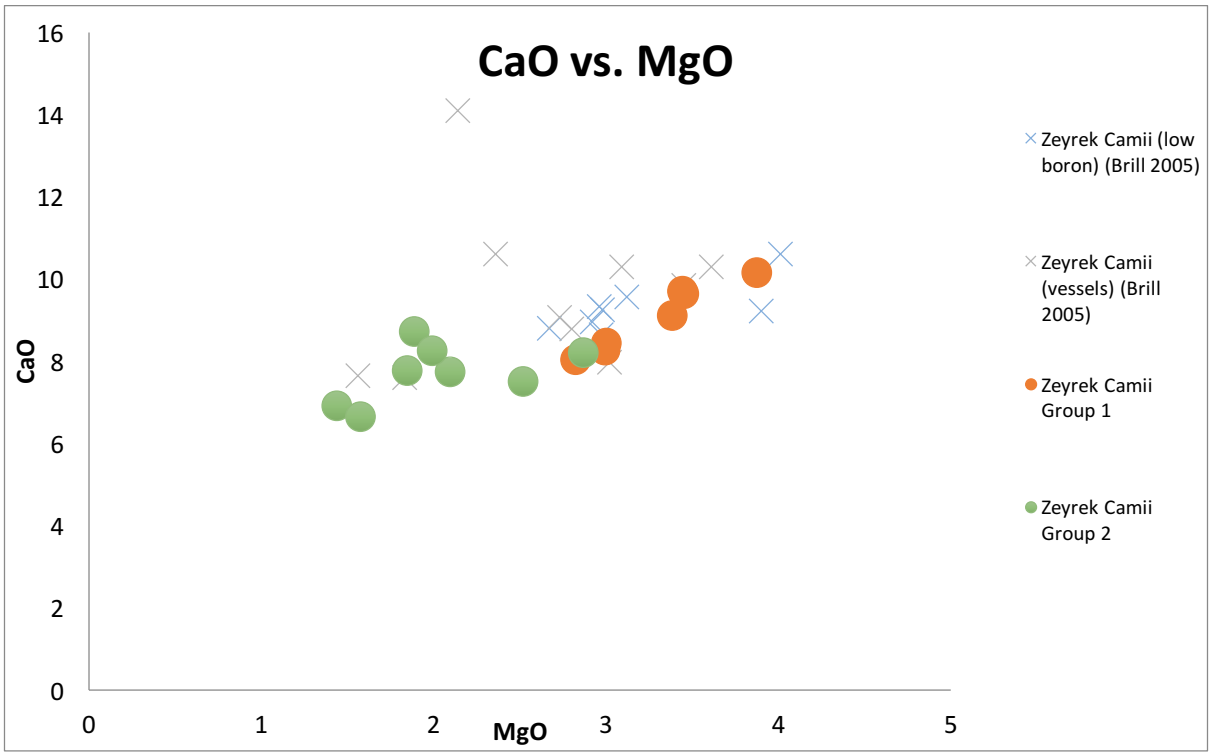


Figure 7.34: A bi-plot of CaO versus MgO for plant ash glasses from 11th – 12th centuries AD Zeyrek Camii. Two glass groups are identified, Zeyrek Camii Groups 1and 2.

7.3.40 Zeyrek Camii Group 2:

Zeyrek Camii Group 2 consists of 8 samples. Its composition is significantly different from other Zeyrek Camii glass groups. It is characterised by relatively high Al_2O_3 (1.81% - 3.13%), Fe_2O_3 (0.94% - 2.08%) (Figure 7.32), TiO_2 (0.11% - 0.29%). No correlation between Al_2O_3 and Fe_2O_3 is observed (Figure 7.32). This group has relatively low MgO (1.44% - 2.87%), K_2O (1.28% - 4.41%) and CaO (6.91% - 8.73%) (Figures 7.33 and 7.34).

Many of these glasses are highly coloured. The yellowish-green and green colours in glasses ZC-01, 02, 04 and 05 are likely the result of Fe_2O_3 (0.69% - 1.34%) as ferric ion introduced as impurities from the raw materials (Figure 7.32). As regards the colourless glass (ZC-06 and 14), MnO (0.72% - 0.99%) was added to the glasses to decolourise them. The blue glasses (ZC-03 and 07) were likely coloured by cobalt-bearing materials because they contain elevated levels of CoO (0.11% - 0.15%), CuO (0.28% - 0.32%), ZnO (0.11% - 0.30%) and PbO (0.18%).

7.3.41 High alumina glass (Tbilisi Geo-08, Pemba Island VA-06):

Samples Tbilisi Geo-08 (a 10th – 13th centuries AD glass ring from Tbilisi) and Pemba Island VA-06 (mould-blown phial) are unusual. These glasses have high concentrations of Al_2O_3 that range from 8.10% to 11.98%. They are considerably higher than the natron (<3.54%) and plant ash glasses (<5.39%) analysed in this study. Both have high concentrations of Fe_2O_3 (1.51% - 1.95%) and TiO_2 (0.15% - 0.27%).

Figure 7.35 shows that Geo-08 and VA-06 have higher concentrations of Na_2O (18.57% - 18.88%) and K_2O (3.20% - 3.26%) than the majority of the plant ash glasses in this study. They also contain low levels of CaO (2.76% - 3.23%) and MgO (1.36% - 3.53%).

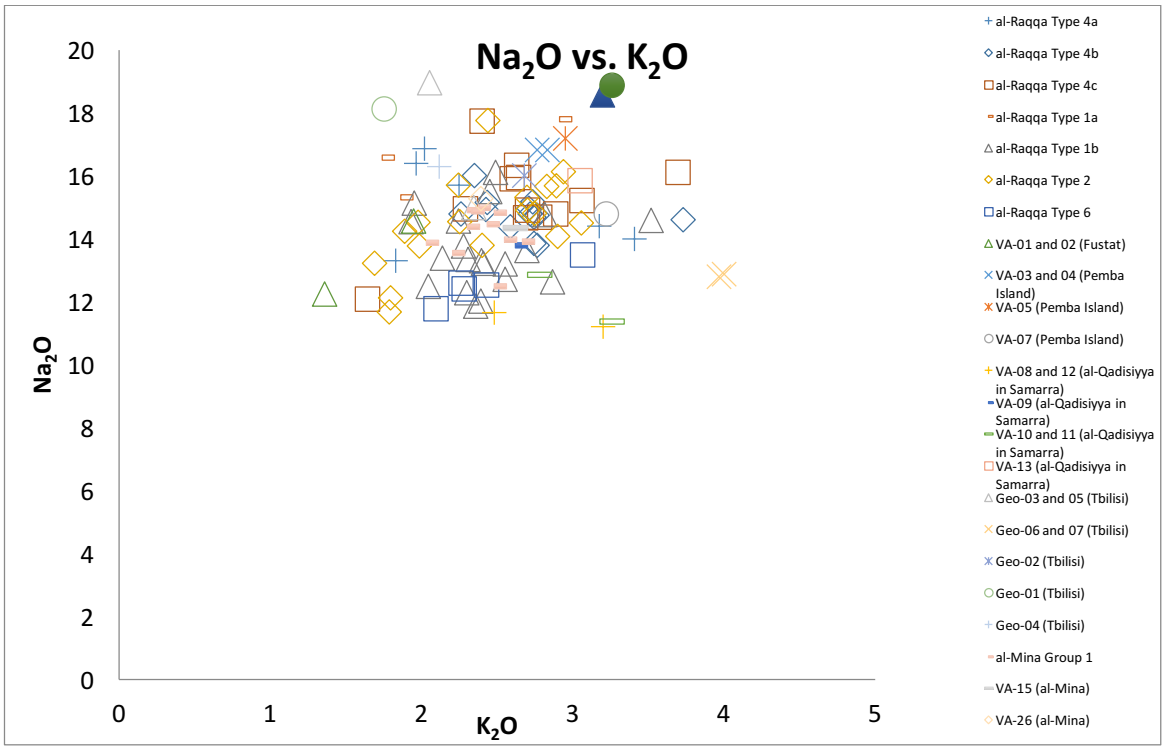


Figure 7.35: A bi-plot of Na_2O versus K_2O for the high alumina glasses from 10th – 13th centuries AD Tbilisi and Islamic Pemba Island, compared with plant ash glasses from al-Raqqa, Tbilisi, al-Qadisiyya in Samarra, al-Mina, Fustat and Pemba Island.

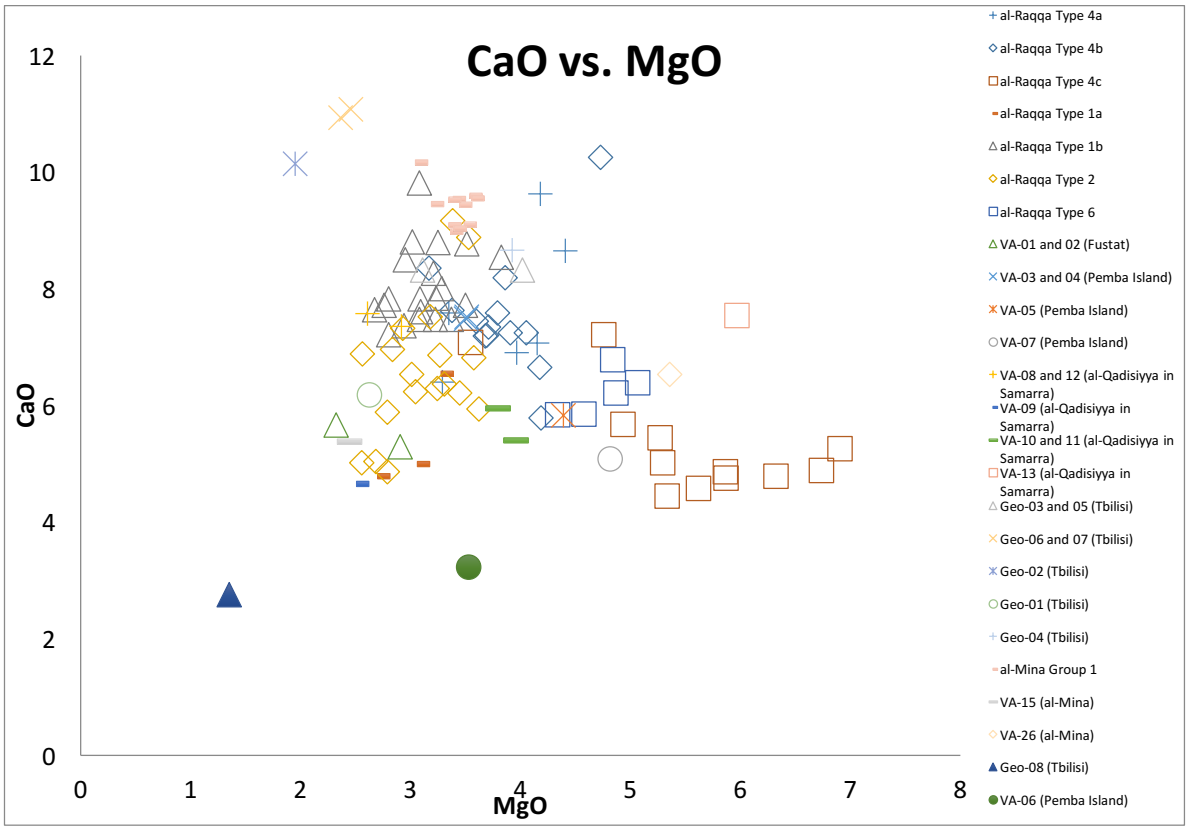


Figure 7.36: A bi-plot of CaO versus MgO for the high alumina glasses from 10th – 13th centuries AD Tbilisi and Islamic Pemba Island, compared with plant ash glasses from al-Raqqa, Tbilisi, al-Qadisiyya in Samarra, al-Mina, Fustat and Pemba Island.

In terms of colour, all of these glasses are emerald green (VA-06) and green (Geo-08). The green colour is due to the high concentrations of Fe_2O_3 and are in the form of Fe^{2+}.

7.4 Summary:

This chapter shows that natron glasses are present in the glass assemblages of al-Raqqa in northern Syria, al-Mina in Turkey and Tbilisi in Georgia. They can be divided into four different types of natron glass: (1) al-Raqqa Type 3, (2) al-Raqqa Type 5, (3) al-Mina VA-19 and 27, and (4) Tbilisi Geo-09.

Plant ash glasses are present in all glass assemblages. Seven groups of plant ash glasses were found in the al-Raqqa assemblage including al-Raqqa Types 1a and 1b, Type 2, Types 4a, 4b and 4c and Type 6. The furnace glass (VA-02) and the frit (VA-01) from Fustat are identified as plant ash glasses and are similar to al-Raqqa Type 4a. Five

fragments of glass from Pemba Island are identified as plant ash glasses: (1) VA-03 and 04, (2) VA-05 and (3) VA-07.

All of the furnace glasses and a glass waste from al-Qadisiyya in Samarra are plant ash glasses and can be divided into three different types of plant ash glasses: (1) VA-08, 09 and 12 are similar to al-Raqqa Type 4a, (2) VA-10 and 11 resemble al-Raqqa Type 6, and (3) VA-13 resembles al-Raqqa Type 4c. Five glass samples (Geo-02, 06 and 07, Geo-01, Geo-03) from Tbilisi belong to plant ash glasses and resemble the low MgO-high Al_2O_3 glasses (al-Raqqa Type 4a) from al-Raqqa. For the al-Mina glass assemblage, al-Mina Group 1 resemble the al-Raqqa Type 1 plant ash glasses and VA-15 resemble al-Raqqa Type 2 glasses. As regards the glasses from Zeyrek Camii, seven of them belong to Zeyrek Camii Group 1 which is plant ash glasses resembling al-Raqqa Type 1 glasses.

High alumina glasses are present in the Tbilisi (Geo-08) and Pemba Island (VA-06) glass assemblages and are characterised by high concentrations of Al_2O_3, Na_2O and K_2O. Mixed natron-plant ash glasses are found in the Tbilisi (Geo-03 and 05) and Zeyrek Camii (Zeyrek Camii Group 2) glass assemblages and are characterised by high Al_2O_3, low MgO and K_2O.

In the next chapter, the results of this study will be compared with existing chemical data on Islamic and Byzantine glasses dated to the late 8^{th} – 14^{th} centuries AD and to explore the relationships between chemical compositions, colours, and vessel forms.

Chapter 8: Discussion – raw materials, recycling, and the relationships between composition, vessel forms and colours

8.1 Introduction:

In this chapter, the results of this study will be placed into a wider context and compared with existing chemical data on Islamic and Byzantine glasses dated to the late 8th – 14th centuries AD. The relationships between raw materials and compositions, colours and compositions, evidence of recycling/mixing, the provenance of the glass groups and finally the relationship between vessel forms and compositions will be discussed.

8.2 A brief summary of raw materials used for glass production in the late 8th – 14th centuries AD:

During the 8th – 9th centuries AD, natron glasses continued to be used in Israel and Egypt (Henderson *et al*. 2004, 454). The primary raw materials for natron glasses are natron, which is a relatively pure source of sodium carbonate, and it was mixed with beach sands, which are impure and provided the necessary SiO_2 for the glass. The lime source in natron glass was also provided by sands since natron does not contribute any calcium to the glass. And because beach sands are impure and contain various heavy minerals, characteristic elements such as Al_2O_3, Fe_2O_3 and TiO_2 are usually found in natron glasses. They can be used to identify the possible locations of the sand sources and production zones.

On the other hand, plant ash glasses were produced in Iraq and Iran during the Sassanian period and introduced to Syria, Israel, Lebanon and Egypt during the Islamic period (late 8th – 14th centuries AD). They were produced with plant ashes and a relatively pure source of silica such as quartz and sand. Plant genera that are sodium rich are suitable for glassmaking. These include *Anabasis*, *Arthrocnemum*, *Halopeplis*, *Hammada* (*Haloxylon*), *Salicornia* and *Salsola* which belong to the halophytic plants of the Chenopodiaceae family. Plant ashes also provide the necessary level of CaO to stabilise the glass. Soda-rich species have CaO values between 1.63% and 23.10%

(Barkouda and Henderson 2006, 297; Henderson 2013, 23; Rehren 2008, 2566; Tite *et al.* 2006, 1286-1287, Tables 1 and 2).

As we can see from Chapter 3, the plant's physiognomy determines the alkali levels (sodium and potassium oxides) in plant ashes but it is the geological background of the plants that determined the level of CaO in plant ashes (Barkoudah and Henderson 2006, 306-307, 317; Henderson 2013, 41). This can be illustrated with the following examples: the level of CaO in *Salsola* ashes in plants growing on gypsiferous limestone of the Balikh valley in northern Syria is double the amount found in *Salsola* ashes from nongysiferous areas of northerm Syria (Henderson 2013, 40). On the other hand, *Salsola* plants growing on the gypsiferous limestone of the Balikh valley and on the Jaboul evaporate deposit have similar ratios of sodium to potassium (Henderson 2013, 41).

It should be noted that the compositions of plant ash glasses do not necessarily reflect the actual compositions of the plant ashes used to produce them. This is because the relative levels of oxides in the plant ashes may have been disrupted in the process of glassmaking (Henderson 2013, 39). For instance, the maximum content of lime in soda-lime-silica glass is determined by the melting temperature. Experimental work shows that the level of CaO rises from 6% at 900 ^{o}C to 10% at 1000 ^{o}C (Rehren 2008, 1348).

It has also been demonstrated by Tanimoto and Rehren (2008) that an increased level of sodium chloride leads to a decrease of potassium that goes into the glass. But it will increase the intake of sodium in the glass (Rehren 2008, 1350; Tanimoto and Rehren 2008, 2569). Unless both alkalis are present as fully reactive carbonates, the ratio of potash to soda in the glass would be different from the ratio in the ashes (Rehren 2008, 1350).

The alkali rich mineral *reh* was possibly used to produce high alumina glasses in south and southeast Asia such as India, Sri Lanka, Bangladesh, Vietnam, Malaysia and Thailand, and east Africa such as Kenya. It contains sodium carbonate, sodium sulphate and sodium chloride (Henderson 2013, 53).

Soda-rich evaporate associated with borax deposits in western Turkey are found to have been used to produce high alumina-boron glasses in Turkey during the middle Byzantine period (Tite *et al.* 2016, 62-64).

8.3 Raw materials, provenance and glass compositions:

8.3.1 Natron glass in the Middle East and Southern Caucasus:

In Figure 8.1, Types 3 and 5 from the late 8^{th} - 9^{th} century AD al-Raqqa, natron glasses from 9^{th} – 10^{th} centuries AD al-Mina and Medieval Tbilisi are put in a broader context. They are compared with major natron glass groups dated to the mid – late first millennium AD. Six known groups of natron glasses were manufactured in the Middle East during this period: Levantine I (5^{th} – 7^{th} centuries AD) and II (7^{th} – 8^{th} centuries AD), Egypt I (8^{th} century AD) and II (8^{th} – 9^{th} centuries AD), and HIMT 1 and 2 (late 4^{th} – 5^{th} centuries AD) (Freestone 2005, 197, Table 1).

Figures 8.1 and 8.2 show that Type 3 is closely related to the 6^{th} – 7^{th} centuries AD Byzantine glass weights of Levantine I composition. This group is characterised by high levels of Al_2O_3 (~3.05%) and CaO (~8.07%), a relatively high concentration of Na_2O (about 13% - 16%) and low concentration of MgO (Conte *et al.* 2014, 8, Table 1; Freestone 2005, 201, Figure 5; Schibille *et al*. 2016, 8).

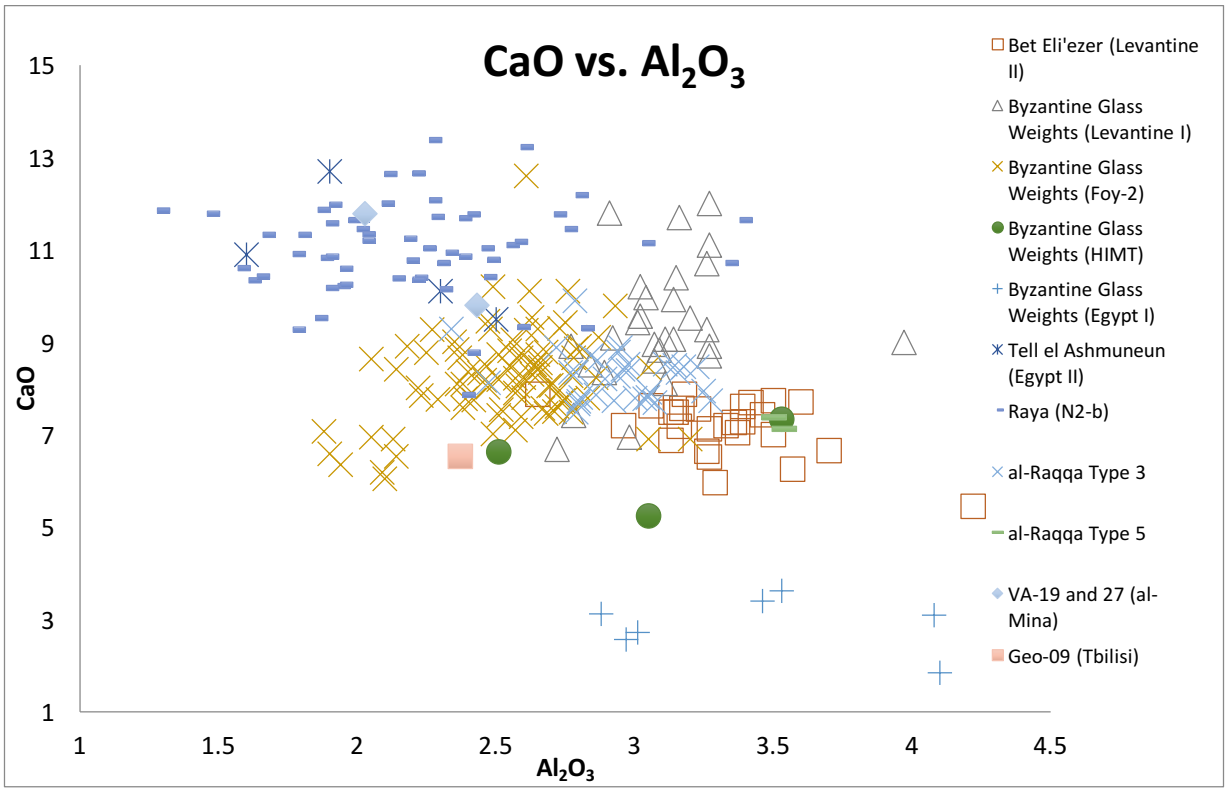


Figure 8.1: A bi-plot of CaO versus Al_2O_3 for natron glasses from 9th century AD al-Raqqa, 9th – 10th century al-Mina and medieval Tbilisi. It is displayed according to composition groups. Data for Levantine I glasses: 6th – 7th centuries AD Byzantine glass weights, Schibille *et al*. (2016). Data for HIMT glasses: 6th – 7th centuries AD Byzantine glass weights, Schibille *et al.* (2016). Data for Levantine II glasses: Bet Eli'ezer, Freestone *et al*. (2000); Data for Egypt I glasses: 6th – 7th centuries AD Byzantine glass weights, Schibille *et al*. (2016). Data for Egypt II glasses: Tell el-Ashmuneun, Bimson and Freestone (1988); Raya N2-b, Kato *et al*. (2009). Data for Foy-2: 6th – 7th centuries AD Byzantine glass weights, Schibille *et al*. (2016).

Another characteristic of this glass group is its low concentrations of Fe_2O_3, TiO_2 and MnO. Figure 8.4 show that there are no correlations between Fe_2O_3 and TiO_2 (Conte *et al.* 2014, 8; Freestone 2005, 201, Figure 5; Freestone *et al.* 2008, 72-73, Table 1; Tal *et al.* 2004, 62, Table 1). The same can be observed in Type 3.

These would suggest impure sands from the Israeli coast were used to provide the high CaO and Al_2O_3 in the glasses. The feldspar and calcium carbonate from sands in the Israeli coast would have provided the levels of Al_2O_3 and CaO found in these glasses (Freestone 2006, 10; 2008, 87; Henderson *et al*. 2004, 454). The narrow range of chemical compositions in Type 3 suggests they were produced using a common sand source.

The existing data on Levantine I glasses from Tell Zujaj analysed by Henderson *et al*. (2004) shows that fifty-one percent of all the analysed glasses at Tell Zujaj and Tell Abu Ali were made with natron and beach sands (Henderson *et al*. 2004, 443-450). The natron glasses from Tell Zujaj and Tell Abu Ali shared the same chemical fingerprint in terms of the major and minor elements.

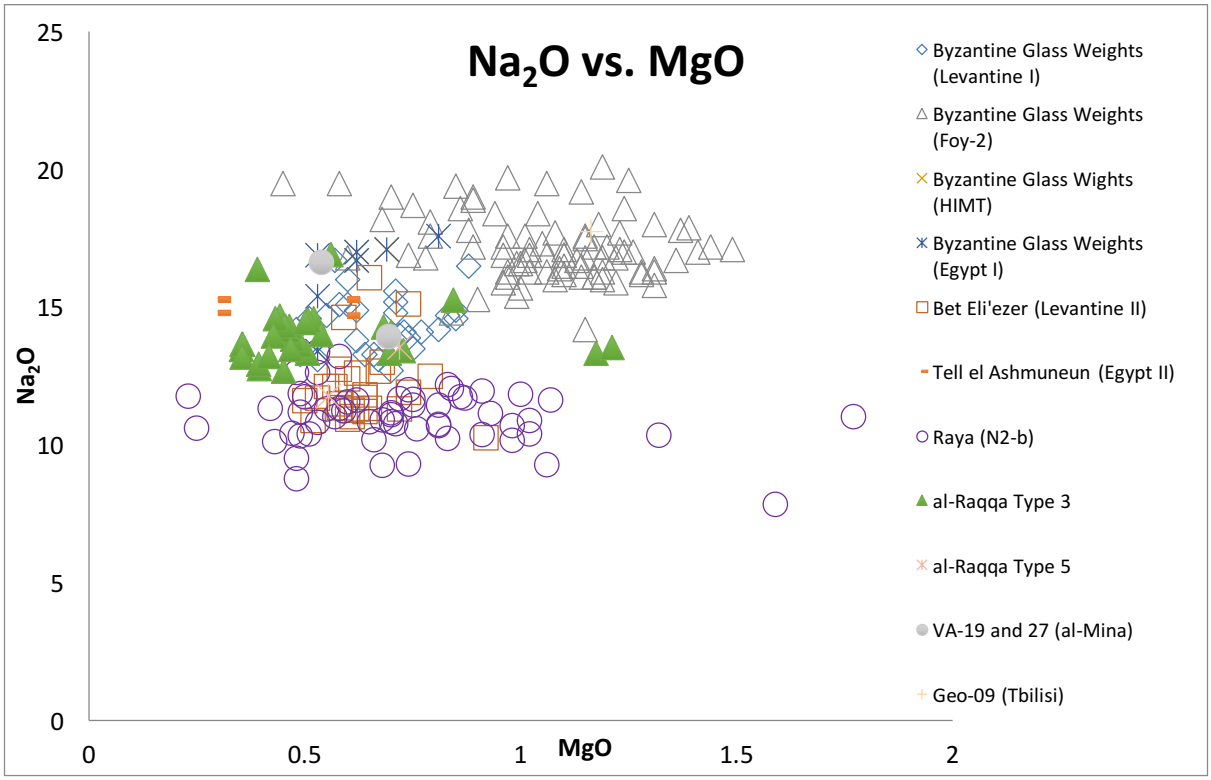


Figure 8.2: A bi-plot of Na_2O versus MgO for natron glasses from 9th century AD al-Raqqa, 9th – 10th century al-Mina and medieval Tbilisi. It is displayed according to composition groups.

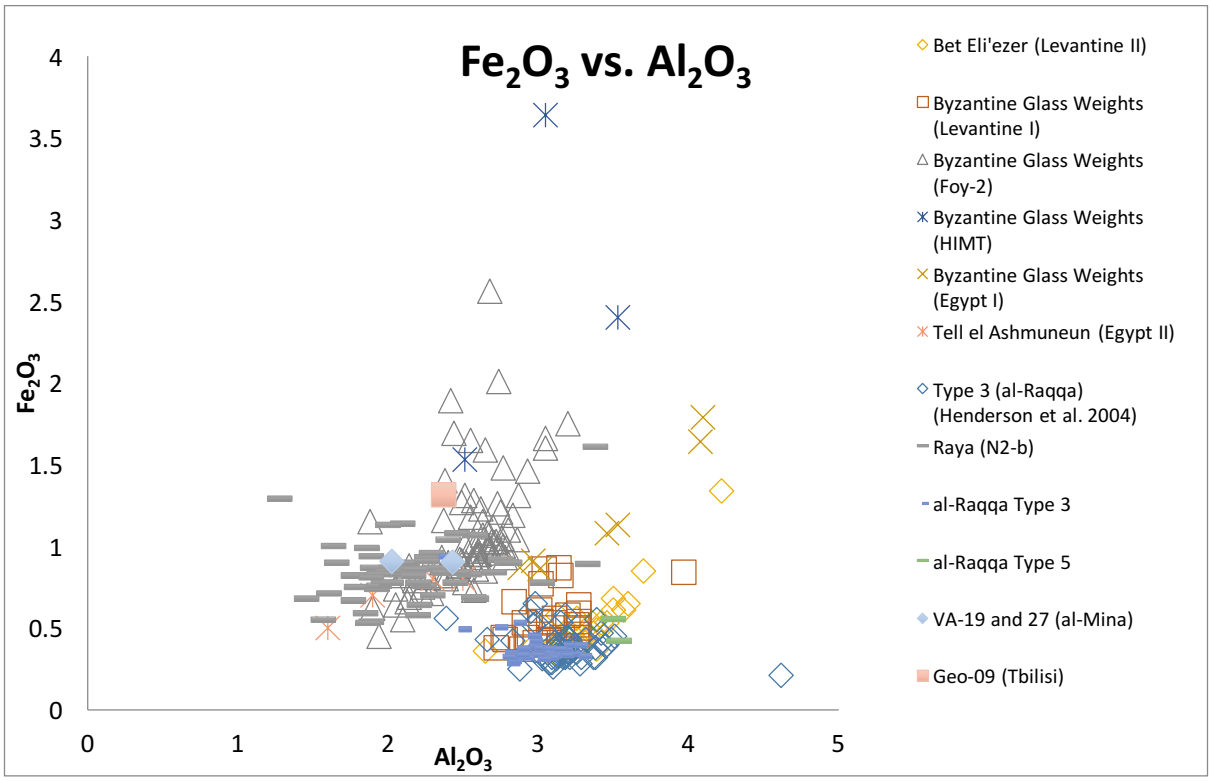


Figure 8.3: A bi-plot of Fe_2O_3 versus Al_2O_3 for natron glasses from 9th century AD al-Raqqa, 9th – 10th century al-Mina and medieval Tbilisi. It is displayed according to composition groups.

Archaeological excavations and chemical analysis of raw glasses suggest Levantine I glasses were produced in primary glass production centres at Apollonia and Dor in the 6th – 7th centuries AD (Freestone *et al*. 2008, 72-73, Table 1; Tal *et al*. 2004, 62, Table 1). This glass group was used widely in Syria, Israel, Egypt and the western Mediterranean during the 6th – 9th centuries AD, such as Ramla (6th – 7th century AD), Caesarea (6th – 8th centuries AD), Butrint (4th – 6th centuries AD) and Raya (8th century AD) (Brill 1999b, 200-201, Table VII S; Freestone *et al.* 2008, 72-73, Table 1; Kato *et al*. 2009, 1703; Tal *et al.* 2004, 62; 2008, 89). The discovery of Levantine I glasses in the late 8th and 9th centuries AD glassworkshop at Tell Zujaj suggests this glass type continued to be used (though is unlikely to have been produced) in northern Syria during this period.

On the other hand, Type 5 from al-Raqqa is significantly different from Type 3 and its associated glasses. It is closely related to glasses from Bet Eli'ezer dated to the 7th – 8th centuries AD and is termed Levantine II (Freestone *et al.* 2000, 71; 2015, 52). This glass group is characterised by a lower concentration of CaO (5.96% - 7.88%) and Na_2O (11% - 13%) (Figure 8.2), but with a higher concentration of SiO_2 (73% - 76%)

(Freestone *et al*. 2000, 71). The majority of Levantine II glasses were confined to Israel. It is likely that a different composition of sands from the Israeli coast was used to produce this glass type. The sites where Levantine II glasses are found are in HaGolan Street in Tel Aviv, Jerusalem, Nahal Shoval, Ramla, Tel Rosh and Ahihud in Israel (Freestone *et al.* 2015, 51; Phelps *et al*. 2016, 60-61).

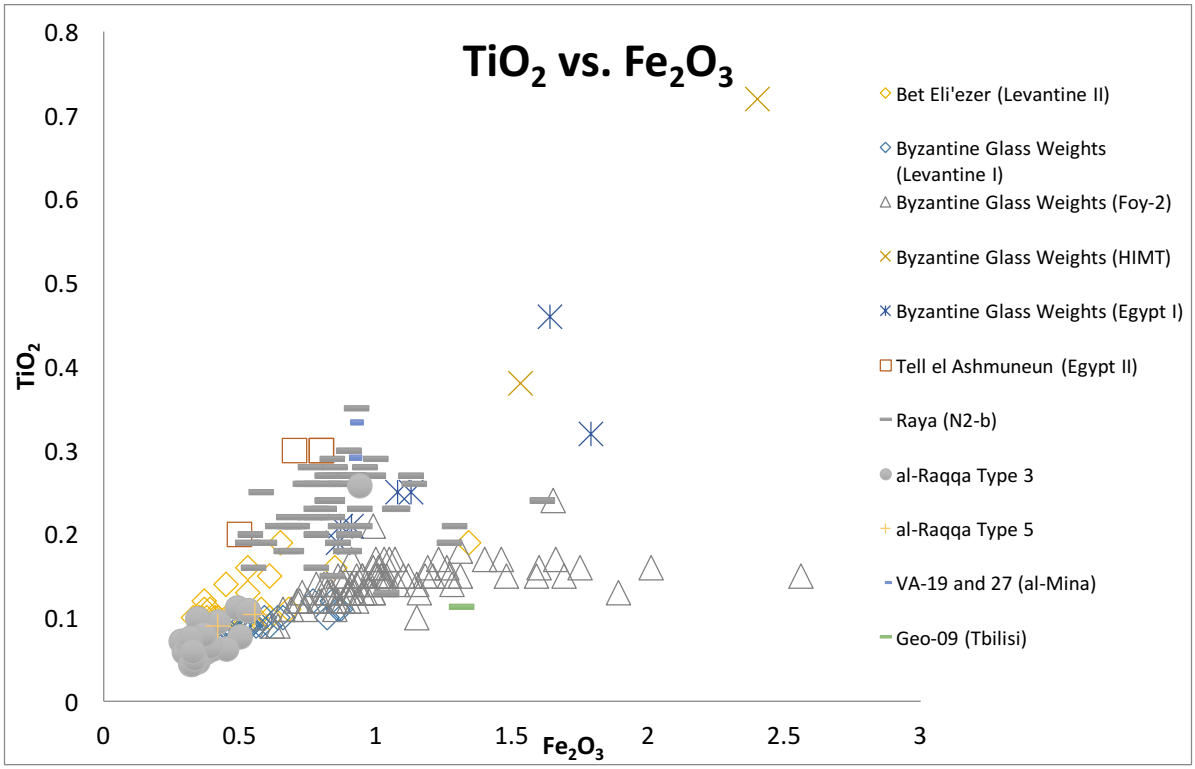


Figure 8.4: A bi-plot of TiO_2 versus Fe_2O_3 for natron glasses from 9th century AD al-Raqqa, 9th – 10th century al-Mina and medieval Tbilisi. It is displayed according to composition groups.

It is also noted that Type 5 have a higher concentration of Al_2O_3, Fe_2O_3 and TiO_2 than Type 3 and its associated glasses (Figures 8.3 and 8.4). This reflects a different source of silica along the Israeli coast was used to produce Type 3 glasses.

The two samples VA-19 and 27 from al-Mina are clearly separated from the Levantine glass groups with their low Al_2O_3 and high CaO levels. They resemble closely the Egypt II glass group which was produced in Tell el Ashmuneun during the 8th – 9th centuries AD (Bimson and Freestone 1988, 240). This glass group is characterised by lower concentrations of Al_2O_3 (1.6% - 2.5%) but with much higher concentrations of CaO (9.5% - 12.7%) than the Levantine glasses (Figure 8.1) (Bimson and Freestone 1988, 240). Moreover, it is noted that Egypt II glasses have a higher level of impurities

of Fe_2O_3 and TiO_2 than the Levantine glasses. They also display a positive correlation between Al_2O_3, Fe_2O_3 and TiO_2 (Figures 8.3 and 8.4). Another example of Egypt II glasses is found in Raya, Egypt where a large group of 9th century AD Egypt II glasses (Group N2-b) was found. Similar glass groups were also found in Fustat (Kato *et al.* 2009, 1705).

The bracelet (Geo-09) from Tbilisi is compositionally different from al-Mina and al-Raqqa natron glasses. Figures 8.1, 8.3 and 8.4 show that an impure sand source with low contents of Al_2O_3 and CaO, but with high concentrations of Fe_2O_3 and TiO_2, was used to produce this glass. This composition resembles Foy-2 glass group that is dated to the 5th – 7th centuries AD (Schibille *et al*. 2016, 9). Another characteristic of Foy-2 glasses is that it has higher levels of Na_2O and MgO (Figure 8.2) and a lower level of CaO than glasses produced in Israel and the later Egypt II glasses (Schibille *et al*. 2016, 9). The Tbilisi glass fits in neatly with Foy-2 glasses.

8.3.2 Plant ash glass in the late 8th - 10th centuries AD:

In Figures 8.5 – 8.12, glasses from Tell Zujaj and Tell Abu Ali from al-Raqqa (late 8th - 9th centuries AD), Pemba Island (medieval period), al-Mina (9th – 10th centuries AD), Fustat (Islamic period, possibly between 8th – 12th centuries AD) and al-Qadisiyya in Samarra (9th – 10th centuries AD) are placed in a broader context. They are compared with published data from al-Raqqa (late 8th and 9th centuries AD), Fustat (AD 750 – 850), Nishapur (9th – 10th centuries AD), Samarra (9th – 10th centuries AD), Khirbat al-Minya (8th century AD), Ctesiphon (3rd -7th, 9th – 10th centuries AD), Serce Limani (AD 1025) and Raya (9th century AD) (Brill 1995, 1999, 2009; Henderson *et al*. 2004, 2016; Kato *et al*. 2010).

Four types of glass can be identified: (1) low MgO-high Al_2O_3 glasses; (2) high MgO-low Al_2O_3 glasses; (3) high MgO-CaO; (4) low Al_2O_3-MgO-high CaO glasses.

Types of glass	Glass groups and individual glass samples
Low MgO-high Al_2O_3	Al-Raqqa Type 4a, VA-08, VA-09 and VA-12 from al-Qadisiyya, Fustat glasses, Geo-01 and 04 from Tbilisi and VA-05 from Pemba Island
High MgO-low Al_2O_3	al-Raqqa Type 4c, VA-07 from Pemba Island, VA-13 from al-Qadisiyya and VA-26 from al-Mina
Low Al_2O_3-CaO	al-Raqqa Type 6, VA-10 and 11 from al-Qadisiyya
Low Al_2O_3-MgO-high CaO	al-Raqqa Types 1a and 1b, al-Mina Group 1 and VA-03 and 04 Pemba Island

Table 8.1: Descriptions of glass types.

8.3.2.1 Low MgO-high Al_2O_3 glass:

Figure 8.5 shows that Type 4a from al-Raqqa, VA-08, VA-09 and VA-12 from al-Qadisiyya in Samarra, VA-01 and 02 from Fustat, Geo-01 and 04 from Tbilisi and VA-05 from Pemba Island are associated with some of the low MgO-high Al_2O_3 coloured glasses from al-Raqqa in Syria, Henderson *et al*. (2016)'s Ctesiphon coloured glasses and Brill (1999b)'s 3rd century AD - Islamic period Ctesiphon glass in Iraq and Nishapur coloured glasses in Iran. The chemical composition and dating of the Sassanian glass from Ctesiphon suggest this type of glass was made in Iraq as early as the Sassanian period and continued to be produced by the Muslims in the late 8th – 9th centuries AD.

All of these glasses have elevated levels of MgO and CaO (Figure 8.5). The coloured glasses from Nishapur (Brill 1995 and Henderson *et al*. 2016), a colourless bowl from Nishapur analysed by Henderson *et al*. (2016), VA-05 (a mould-blown flask) from Pemba Island, VA-01 (furnace raw glass) and 02 (frit) from Fustat, VA-08 (tank furnace glass), VA-09 (tank furnace glass) and VA-12 (glass waste) from al-Qadisiyya in Samarra, and glasses from Type 4a have similar levels of MgO (3% - 4.75%) and CaO (6% - 10.25%). It shows that they were made with plant ashes that are rich in calcium and magnesium. High levels of magnesium and calcium in the glass would increase the glass melting temperature and produce a 'shorter' glass, i.e. the glassmaker/glassworker would have less time to work on the glass (Henderson 2013,

36). It is also noted that this type of glasses is characterised by an elevated level of Al_2O_3 and Fe_2O_3 (Figure 8.6).

However, the various levels of major and minor elements show that these products were were manufactured in different regions, possibly using different raw materials and/or derived from different geological environments. It has been demonstrated by recent studies on plant ash glasses that variations in the compositions of glass (e.g. MgO, CaO, Na_2O, Al_2O_3 and Fe_2O_3) are related to the use of different raw materials or raw materials derived from different geological environments in various glass production zones (Henderson 2013, 323-324; Henderson *et al*. 2016, 134). For instance, Islamic glasses made in Iraq and Iran would have higher MgO levels than glasses made in Syria or the Levant. Therefore, a different plant genus or plants growing from a different geological environment (possible Iraq/Iran) would have been used to produce high MgO glasses in Iraq and Iran (Henderson 2013, 323; Henderson *et al*. 2016, 140).

The study of raw glasses and a glass frit from al-Raqqa, Fustat and Samarra suggests there were at least three variants of low MgO-high Al_2O_3 glasses produced in these three regions during the late 8^{th} – 10^{th} centuries AD.

Figure 8.5 shows that al-Qadisiyya VA-08 and VA-12 have a relatively low MgO (2.61% - 2.92%) level, but instead of a low CaO level like some of the al-Raqqa and Nishapur glasses, they have an elevated CaO level (7.35% - 7.57%). This makes them similar to the Sassanian glass and 9^{th} – 10^{th} centuries AD Ctesiphon coloured glasses from Iraq. In terms of the alkali source, these two Samarra glasses also have lower Na_2O levels than the low MgO-high Al_2O_3 glasses from al-Raqqa (Figure 8.7). Their alkali levels are closely related to some of the Raya and Nishapur colourless glasses, Sassanian and Islamic glass from Ctesiphon and Samarra colourless and coloured glasses. The differences in CaO and alkali levels between Samarra VA-08 and VA-12 and al-Raqqa Type 4a may reflect the use of different compositions of plant ashes (different plant genus) and/or plant ashes derived from different geological environments (possibly in Iraq and Syria respectively). The al-Qadisiyya glasses are closely related to glasses made in Iraq and Iran, especially Samarra and Ctesiphon (3^{rd} – 10^{th} centuries AD). Given that Samarra VA-08 and VA-12 came from a tank furnace(s)

in Samarra, it is possible that they were made with raw materials from areas in or around Samarra in Iraq.

Strontium isotope analysis of some plant ash glasses (raw glass and vessel fragments) from al-Raqqa and plant ashes from the surroundings of the city shows that they have the same range of strontium isotope values (Henderson *et al.* 2005, 670; Henderson *et al.* 2009, 418-419). This strongly suggests local raw materials were used to produce low MgO-high Al_2O_3 glasses in al-Raqqa and Samarra.

Another variant of low MgO-high Al_2O_3 glasses can be found in al-Qadisiyya VA-09 and Fustat VA-01 and VA-02 glasses. These glasses have very low levels of CaO and MgO (Figure 8.5). They closely resemble a small number of Henderson *et al*. (2004)'s al-Raqqa Type 4 glasses and some of Brill (1995)'s and Henderson *et al*. (2016)'s Nisahpur coloured glasses. They are characterised by low levels of CaO and MgO (Figure 8.5). Curiously, the Fustat glasses VA-01 and VA-02 do not resemble to any of Brill (1999)'s Fustat glasses, which have a higher concentration of MgO and CaO, and this suggests plant ashes from different geological environments or a different plant genus were used to produce the Fustat glasses. Al-Qadisiyya VA-09 and Fustat VA-01 and 02 also have a similar level of Na_2O and K_2O as the Nishapur coloured glasses and some of Brill (1999)'s Fustat glasses with low Na_2O and K_2O (Figure 8.7).

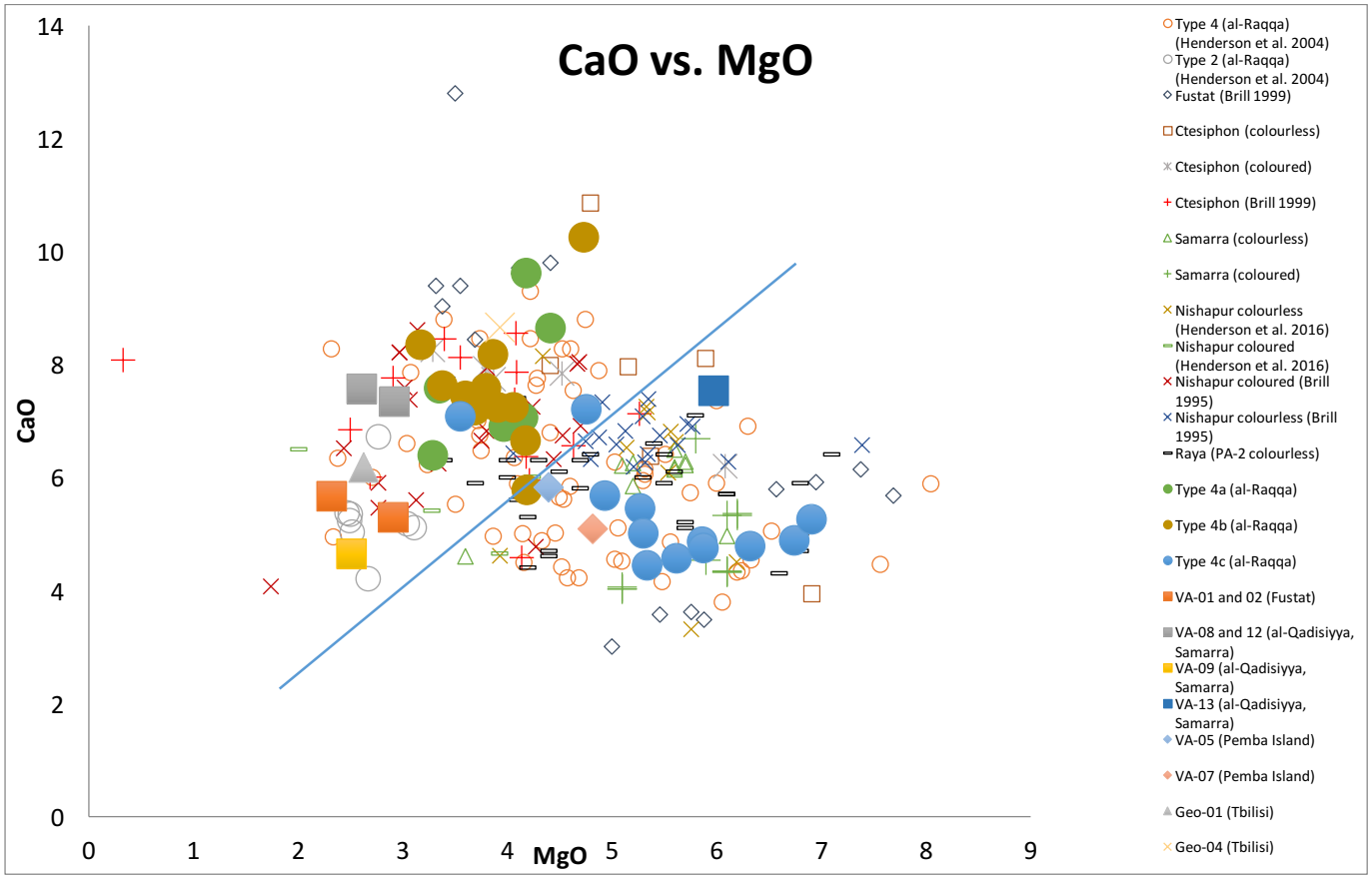


Figure 8.5: A bi-plot of CaO versus MgO for low MgO-high Al_2O_3 and high MgO-low Al_2O_3 glasses from late 8th - 9th century AD al-Raqqa, 9th – 10th century al-Qadisiyya in Samarra, Islamic Pemba Island and medieval Tbilisi. It is displayed according to composition groups and sites. Data for al-Raqqa glasses: Henderson *et al*. (2004); Fustat glasses: Brill (1999b); glasses from Ctesiphon and Samarra: Brill (1999b), Henderson *et al*. (2016); Nishapur colourless and coloured glasses: Brill (1995) and Henderson *et al*. (2016); Raya glasses: Kato *et al*. (2010).

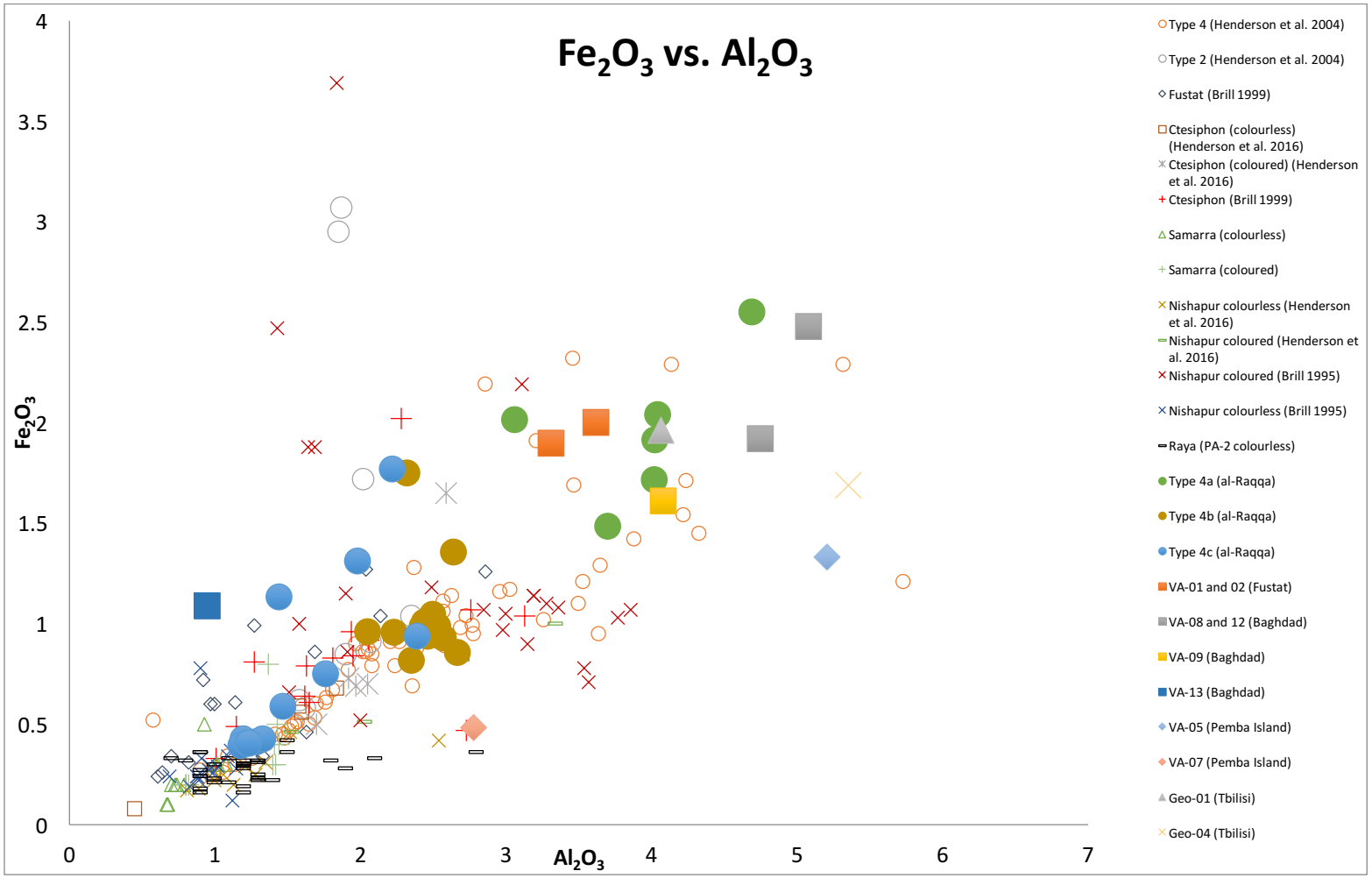


Figure 8.6: A bi-plot of Fe_2O_3 versus Al_2O_3 for low MgO-high Al_2O_3 and high MgO-low Al_2O_3 glasses from late 8th - 9th century AD al-Raqqa, 9th – 10th century al-Qadisiyya in Samarra, Islamic Pemba Island and medieval Tbilisi. It is displayed according to composition groups and sites.

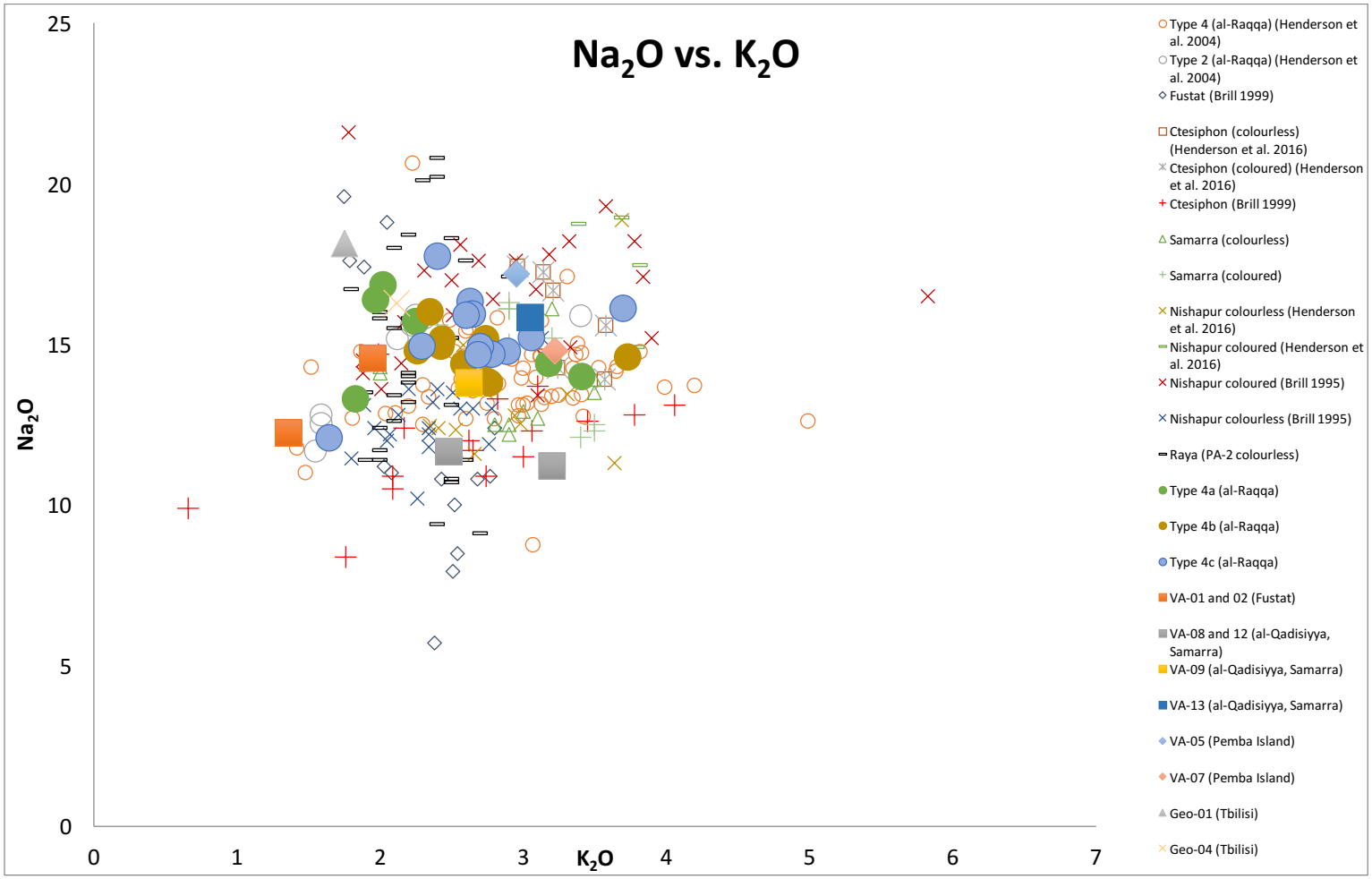


Figure 8.7: A bi-plot of Na_2O versus K_2O for low MgO-high Al_2O_3 and high MgO-low Al_2O_3 glasses from late 8th - 9th century AD al-Raqqa, 9th – 10th century al-Qadisiyya in Samarra, Islamic Pemba Island and medieval Tbilisi. It is displayed according to composition groups and sites.

However, it is likely that local plant ashes were used to produce these glasses from al-Qadisiyya and Fustat. It is noted that the Cl levels in the Fustat glasses (0.94% - 0.98%) are higher than the glasses from al-Qadisiyya VA-09 (Cl=0.59%) and al-Raqqa Type 4a (Cl=0.11% - 0.21%) glasses. Moreover, their K_2O levels (1.36% - 1.95%) appear to be quite low as well. Higher chloride (likely to be sodium chloride) content in the ashes would have resulted a lower level of K_2O in the final glass. It is possible that the plant ashes used to produce the Fustat glasses were grown on soils with higher salinity (Rehren 2008, 1350). A group of Brill (1999b)'s Fustat glasses is also characterised by low K_2O and Na_2O, it is possible that a similar composition of plant ashes (but from different geological backgrounds) was used to produce Fustat VA-01 and 02 and Brill's (1999b) Fustat glasses (Figure 8.5).

Studies of plant ashes from Egypt, such as *Salsola* from Wadi Natrun, *Suaeda* from Barnug and Taposiris Magna and *Anabasis articulata* from Taposiris Magna, show that some Egyptian plant ashes have high level of Cl (13.7% - 34.9%) compared to plant ashes from Syria and the Levant (2.00% - 15%) (Tite *et al*. 2006, 1286-1287).

Therefore, it is possible that low MgO-high Al_2O_3 glasses from Nishapur, Fustat, al-Raqqa and Samarra were produced using plant ashes with elevated levels of MgO and CaO. But the scientific analysis of the glasses and raw materials suggests local plant ashes with various chemical compositions were likely to have been used to produce these glasses. There is no evidence to suggest that plant ashes were transported between regions in this period.

For the Pemba Island vessel glasses, VA-05 (a flask) closely resembles the Nishapur coloured glasses and some of Henderson *et al*.'s (2016) Nishapur coloured glasses' levels of Na_2O, K_2O, CaO and MgO, but has a significantly higher level of Al_2O_3 (Figures 8.5 – 8.7) (Henderson *et al*. 2016, 144). It is possible that it was produced with plant ashes that are similar to the Nishapur coloured glasses but was mixed with a sand source that is rather impure. But there is a possibility that this piece of glass came from Iraq/Iran.

The Georgian glasses Geo-01 and Geo-04 (bracelets) are compositionally associated with the low MgO-high Al_2O_3 glasses from al-Raqqa Type 4a and the Nishapur

coloured glasses. But there are some differences. Geo-04 has similar levels of CaO and MgO to the al-Raqqa and Nishapur glasses (Figure 8.5). On the other hand, Geo-01 has a distinctively lower level of MgO and CaO than the Geo-04 and it associates with al-Raqqa Type 4 glasses that have low CaO and MgO (Figure 8.5).

Their levels of Na_2O and K_2O also closely resemble the al-Raqqa Type 4a and Nishapur coloured glasses (Figure 8.7). But their levels of SO_3 (0.48% - 1.46%) are significantly higher than other glasses. This suggests Geo-01 and 04 were possibly made in Georgia, using a slightly different composition of plant ashes and/or plant ashes from a different geological environment to produce these glasses. This is because no Iraqi/Iranian, Egyptian and Syrian plant ash glasses had SO_3 more than 0.30% (Henderson *et al*. 2016, 144). But the similarity in terms of the glass compositions suggests medieval Georgian glassmakers were influenced by northern Syrian and Iranian glassmaking technology.

8.3.2.2 High MgO-low Al_2O_3 glass:

Figure 8.5 shows that the high MgO-low Al_2O_3 glasses from al-Raqqa Type 4c, VA-07 (a mould-blown flask) from Pemba Island, VA-13 (a glass waster) from al-Qadisiyya in Samarra and VA-26 (a tonged decorated bowl) from al-Mina are associated with glasses from Fustat (8^{th} – 9^{th} centuries AD), Raya (PA-2 colourless), Samarra, 9^{th} – 10^{th} centuries AD Ctesiphon, Henderson *et al*. (2016)'s Nishapur colourless glasses and the Nishapur colourless glass. Unlike the low MgO-high Al_2O_3 glasses, they have low concentrations of Al_2O_3 and Fe_2O_3, which suggests a relatively pure source of silica, such as quartz or quartz sands, was used (Figure 8.6) (Henderson 2013, 284; Henderson *et al*. 2004, 458).

Similar to the low MgO-high Al_2O_3 glasses, raw materials rich in calcium and magnesium were used to produce these glasses. But it is likely that plants belonging to different genera and/or different geological contexts were used to produce the high MgO-low Al_2O_3 and low MgO-high Al_2O_3 glasses (Henderson 2013, 284). In contrast with the low MgO-high Al_2O_3 glasses, this glass group has a higher level of MgO between 4.67% and 6.91%. But it is also noted that this glass group has a lower level of CaO between 4.45% and 7.21% (Figure 8.5) (Henderson *et al*. 2016, 138). This

suggests plants derived from a different geochemical environment, possibly from Mg-rich alluvium, were used to produce this type of glass (Kato *et al*. 2010, 1392).

The variation of the concentrations of these two elements within this group helps us to identify how different production zones used different types of raw materials. This is because glassmakers in different production centres had used plants belonging to different genera and/or different geological environments (Henderson *et al*. 2016, 134). But it should be noted that an additional source of calcium could have been used to make plant ash glasses. As we have mentioned in Chapter 3, certain species of plant ashes have negligible CaO to make Islamic glass of known compositions (Barkoudah and Henderson 2006, 306). Therefore, a separate CaO rich material, such as feldspar and bone ash, was used to make glass. It has been noted by Henderson (2013) that there is a positive correlation between Al_2O_3 and CaO in al-Raqqa Type 4 and this is confirmed in this study (al-Raqqa Types 2, 4b and 4c) (Figure 7.22 in Chapter 8) (Henderson 2013, 284). It is likely that feldspar, which contributes both Al_2O_3 and CaO into the glass, was used as a third primary raw material to produce these al-Raqqa glasses.

The CaO and MgO contents in Type 4c are fairly similar to a subgroup of the Nishapur colourless glass analysed by Henderson *et al*. (2016), the Samarra colourless and coloured glasses, VA-13 (a glass waster) from al-Qadisiyya in Samarra, a subgroup of glasses from Raya and Fustat (Figure 8.5) (Henderson *et al*. 2016, 140). As regards the alkali levels, the majority of Type 4c glasses and VA-13 have a higher concentration of Na_2O and K_2O than the Nishapur colourless glasses and some of the Fustat and Raya glasses (Figure 8.7). Therefore, the similarity in CaO and MgO levels suggests Type 4c and VA-13 were produced in a similar geological environment but the differences in the alkali level suggest a rather different genus of plant was used to produce these glass. This is because the alkali level in plants is determined by the plant's physiognomy and the calcium and magnesium levels are determined by the geological environment in which the plant grows (Barkoudah and Henderson 2006, 306-307, 317).

No high MgO-low Al_2O_3 raw glasses were found in al-Raqqa and there is no evidence to suggest that it was ever produced in al-Raqqa. It is possible that high MgO-low Al_2O_3 glass was only produced in Iraq (one possible area is Samarra) and Iran (possibly in or

around Nishapur) during the late 8th – 10th centuries AD. It was imported to al-Raqqa from Iraq/Iran during the late 8th and 9th century AD.

A small mould-blown flask (VA-07) from the Pemba Island is similar to the glasses from al-Raqqa Type 4c and Raya (PA-2 colourless). The levels of CaO and MgO in VA-07 shows that it may be associated with the al-Raqqa and Raya glasses (Figure 8.5). Its alkali level also shows that it closely resembles these glasses (Figure 8.7). This suggests that it may have been produced from raw materials that are similar to those used to manufacture the al-Raqqa and Raya glasses and might have been imported from the Middle East.

A tonged decorated bowl (VA-26) from al-Mina is fairly similar to the colourless glasses from Nishapur and Raya in terms of its CaO and MgO contents. It is also noted that its Na_2O and K_2O contents are also similar to each other. Surprisingly, it is different from the al-Raqqa glasses due to its higher concentration of CaO. It is possible that a similar composition of plant ash (due to similar alkali level) from the same geological region (due to similar CaO and MgO levels) as the Nishapur and Raya glasses was used to produce VA-26. Therefore, this piece of glass could have been imported to al-Mina from Iran during the 9th – 10th centuries AD.

8.3.2.3 Low Al_2O_3-CaO glass:

Al-Raqqa Type 6 and al-Qadisiyya VA-10 and 11 belong to this glass group and are different from other groups in this period. They are characterised by a low Al_2O_3 and low CaO levels. Figure 8.8 shows that they clearly do not associate with the high MgO-low Al_2O_3 glasses.

Figure 8.8 shows that these two glass groups are closely resembled to some of the colourless glass from Raya and Henderson *et al*. 's (2016) colourless glasses from Nishapur and Samarra. It should be noted that the colourless glasses from Raya are compositionally varied in terms of CaO, MgO, Na_2O and K_2O (Figures 8.8 and 8.9). They can be divided into three different compositional subgroups based on these oxides. And all three subgroups have parallels in the Nishapur and Samarra colourless glasses. This may suggest the use of different compositions of plant ashes from different

geochemical contexts. It is clear from Figure 8.8 that there were at least three different sources of plant ashes that were exploited for the production of this type of glass. Only two subgroups (a and c) of Raya PA-2 colourless glass are similar to Type 6 and al-Qadisiyya VA-10 and 11 compositionally.

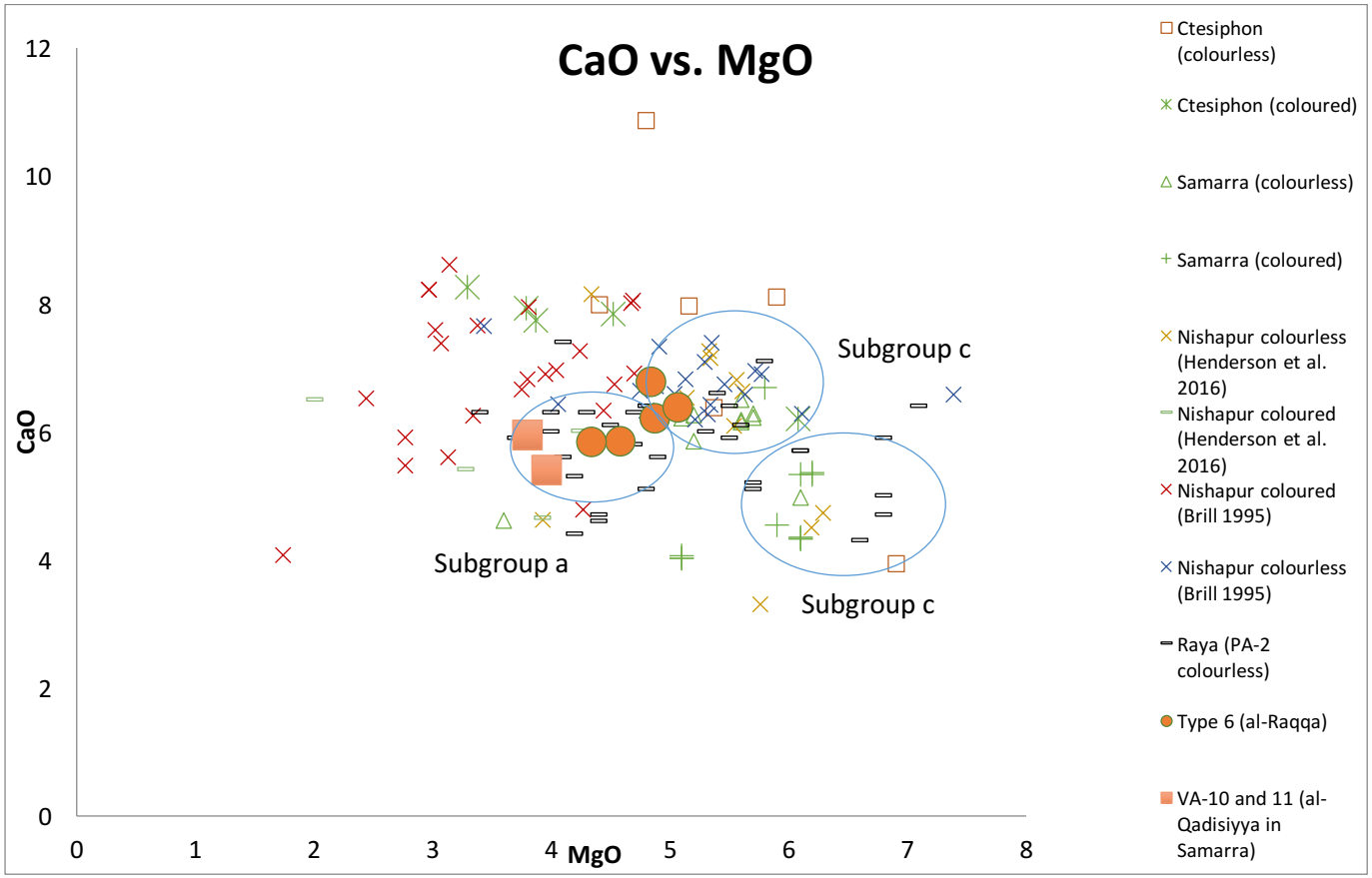


Figure 8.8: A bi-plot of CaO versus MgO for al-Raqqa Type 6 from late 8th - 9th century AD al-Raqqa, Samarra VA-10 and 11 from 9th – 10th century al-Qadisiyya in Samarra. It is displayed according to composition groups and sites. Data for al-Raqqa glasses: Henderson *et al*. (2004); glasses from Ctesiphon and Samarra: Henderson *et al*. (2016); Nishapur colourless and coloured glasses: Brill (1995) and Henderson *et al*. (2016); Raya glasses: Kato *et al*. (2010).

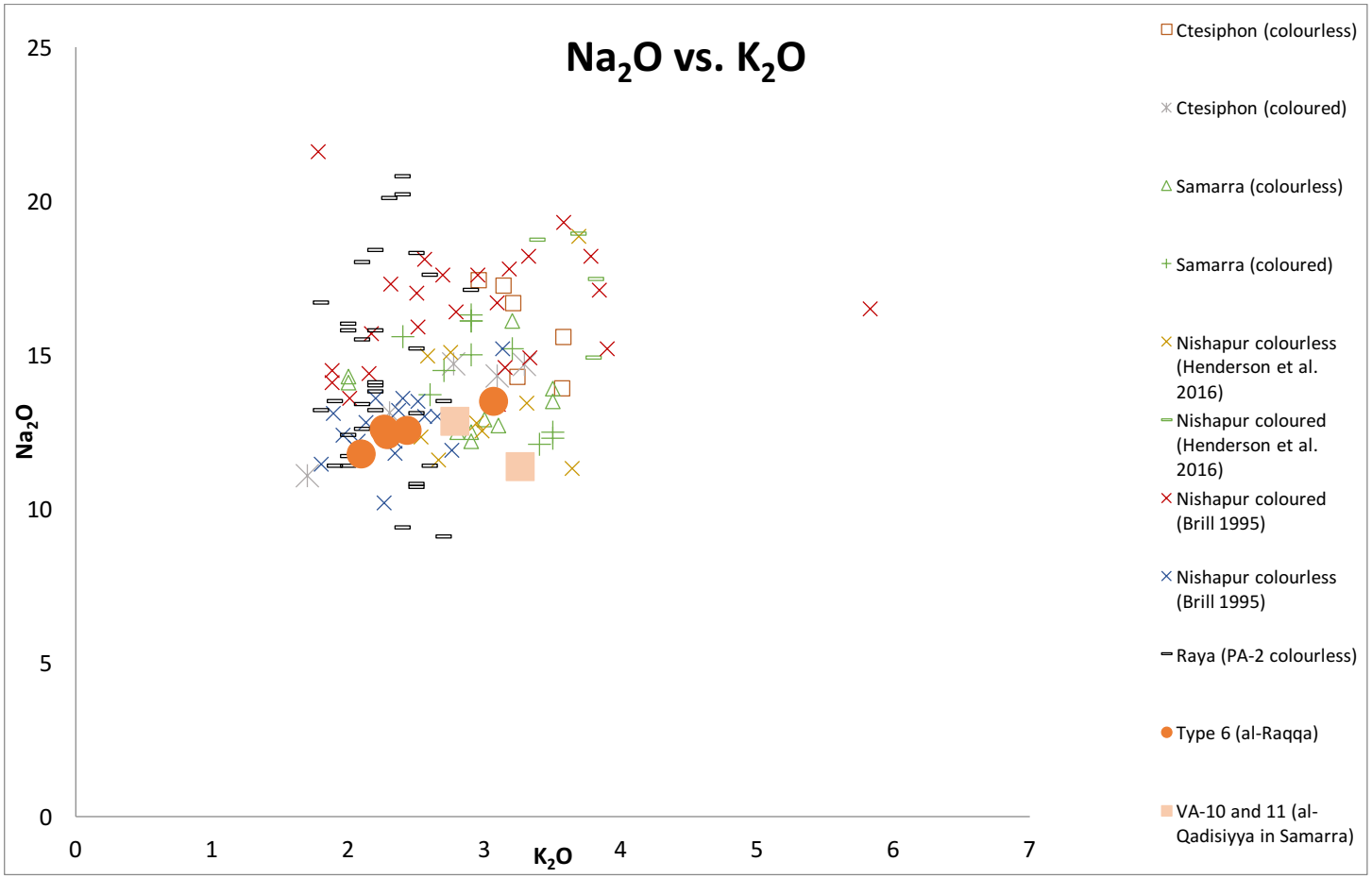


Figure 8.9: A bi-plot of Na_2O versus K_2O for al-Raqqa Type 6 from late 8th - 9th century AD al-Raqqa, Samarra VA-10 and 11 from 9th – 10th century al-Qadisiyya in Samarra. It is displayed according to composition groups and sites.

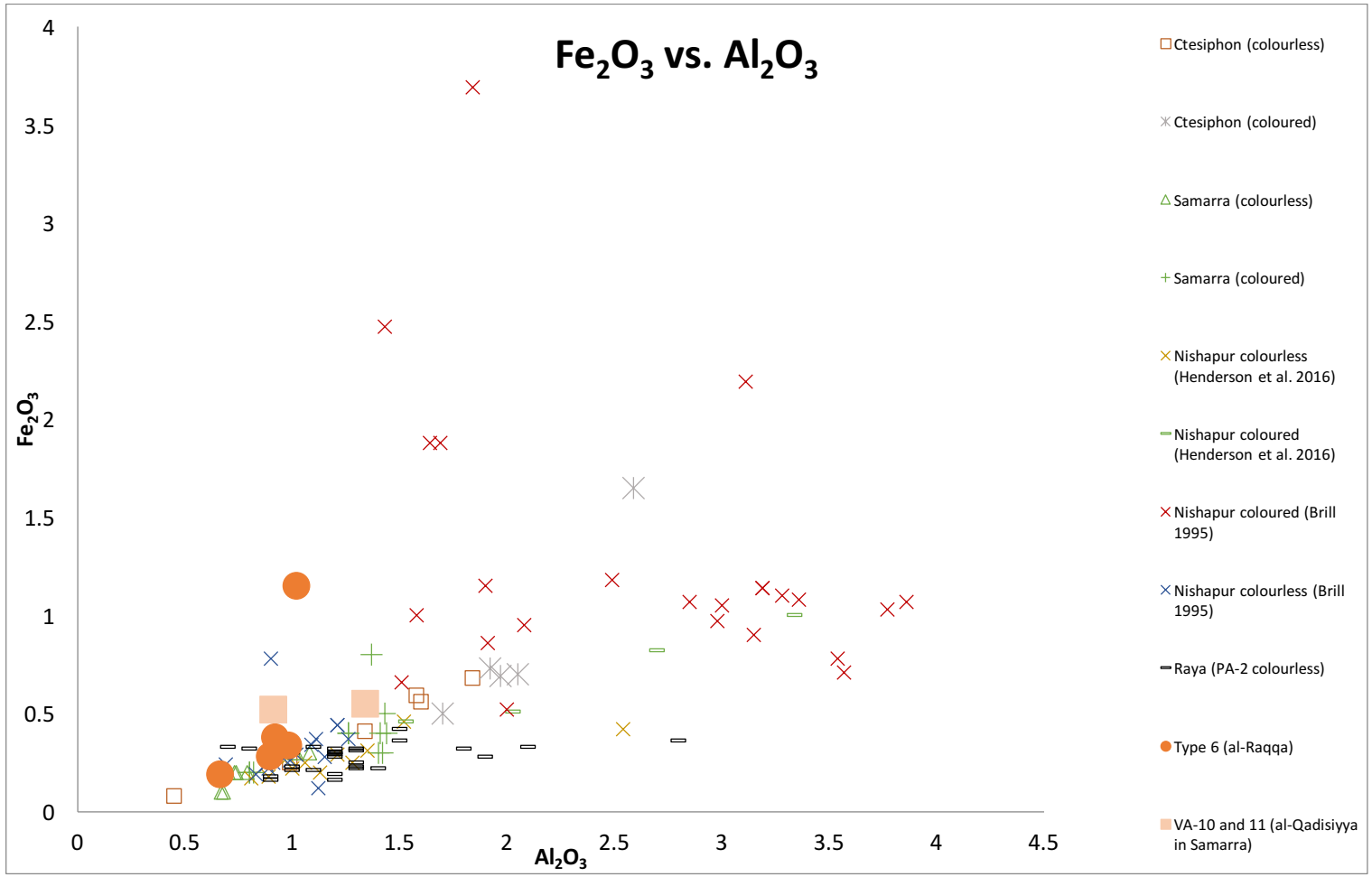


Figure 8.10: A bi-plot of Fe_2O_3 versus Al_2O_3 for al-Raqqa Type 6 from late 8th - 9th century AD al-Raqqa, Samarra VA-10 and 11 from 9th – 10th century al-Qadisiyya in Samarra. It is displayed according to composition groups and sites.

The low levels of Al_2O_3 and Fe_2O_3 in al-Raqqa Type 6 and al-Qadisiyya VA-10 and 11 suggest a pure source of silica such as crushed quartz or quartz sands was used (Figure 8.10). They are characterised by low levels of CaO (5.40% - 6.78%) and MgO (3.80% - 5.07%) (Figure 8.8). Type 6 and Samarra VA-10 and 11 belonged to two subgroups of this glass type found in Samarra, Nishapur and Raya: subgroup a is characterised by low levels of CaO (5.40% - 6.21%) and MgO (3.80% - 4.87%) while subgroup b is characterised by an elevated level of CaO (5.30% - 7.39%) and MgO (4.84% - 6.28%) (Figure 8.8).

The levels of Na_2O and K_2O in these glasses also suggest Type 6 glasses and al-Qadisiyya VA-10 and 11 are similar to both Brill's (1995) and Henderson *et al*.'s (2016) Nishapur colourless glass, Samarra coloured and colourless glasses and a group of Raya colourless glasses with low levels of Na_2O and K_2O levels (Figure 8.9). Therefore, the similarity in the alkali level suggests similar species of plants were used to produce Type 6, VA-10 and 11, Nishapur, Samarra and Raya glasses and the plant ahses might have come from similar geochemical backgrounds due to similar levels of CaO and MgO.

Kato *et al.* (2010) have suggested that the Raya colourless glasses came from Iraq and Iran (Kato *et al.* 2010, 1392). Indeed, the presence of tank furnace raw glasses of this compositional group in Samarra suggests it was one of the workshops that had produced this glass type. The majority of the glasses from al-Raqqa Type 6 are colourless. No raw glass was found in this group in al-Raqqa, which suggest Type 6 was not made in al-Raqqa and is likely imported from Iraq/Iran.

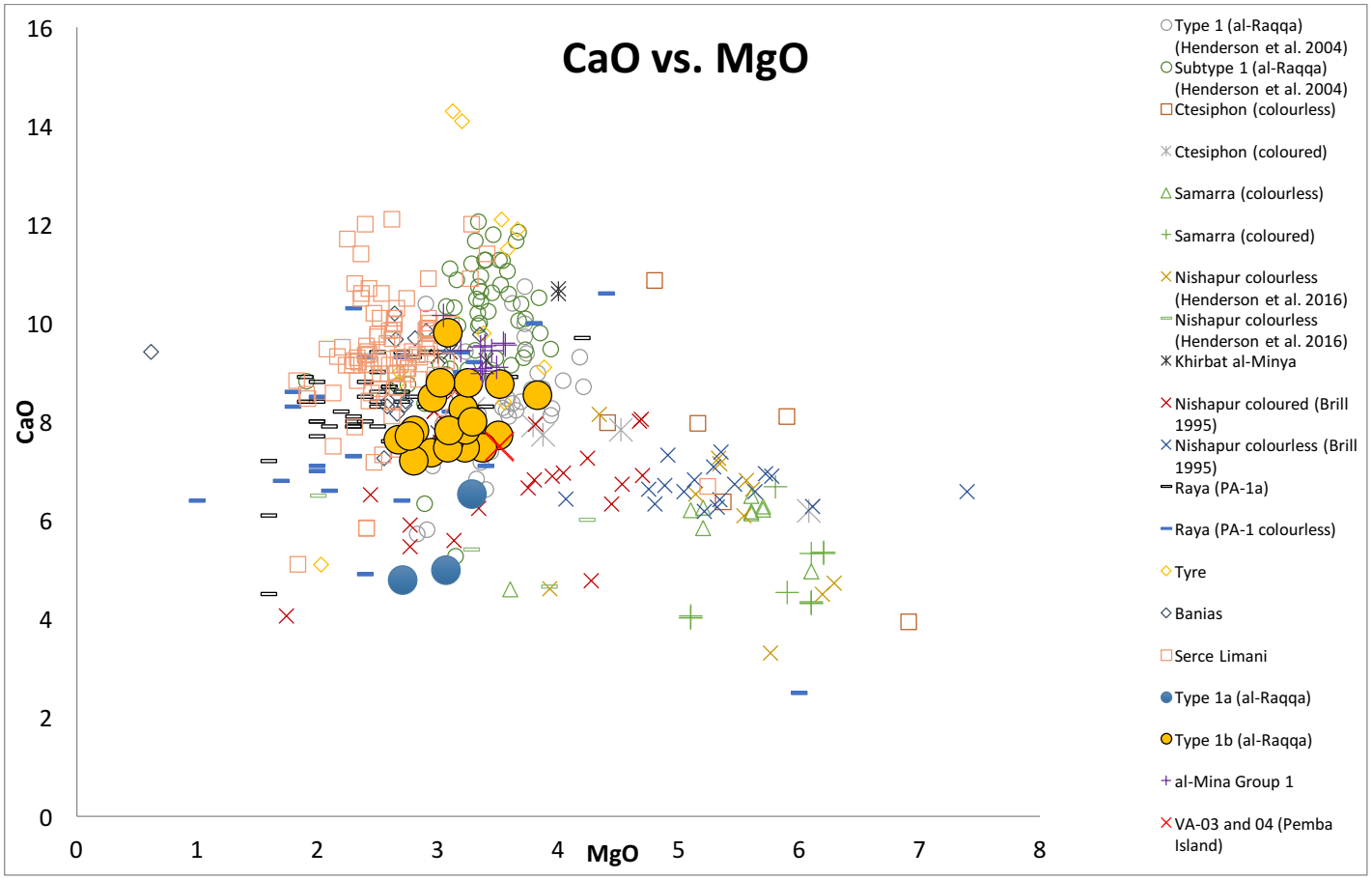


Figure 8.11: A bi-plot of CaO versus MgO for Types 1a and 1b glasses from late 8th - 9th century AD al-Raqqa, 9th – 10th century, VA-03 and 04 from Islamic Pemba Island and al-Mina Group 1 from 9th – 10th centuries AD al-Mina. It is displayed according to composition groups and sites. Data for al-Raqqa glasses: Henderson *et al*. (2004); glasses from Ctesiphon, Khirbat al-Minya and Samarra: Henderson *et al*. (2016); Nishapur colourless and coloured glasses: Brill (1995) and Henderson *et al*. (2016); Raya glasses: Kato *et al*. (2010); Tyre glasses: Freestone (2002); Banias glasses: Freestone *et al*. (2000); Serce Limani glasses: Brill (2009).

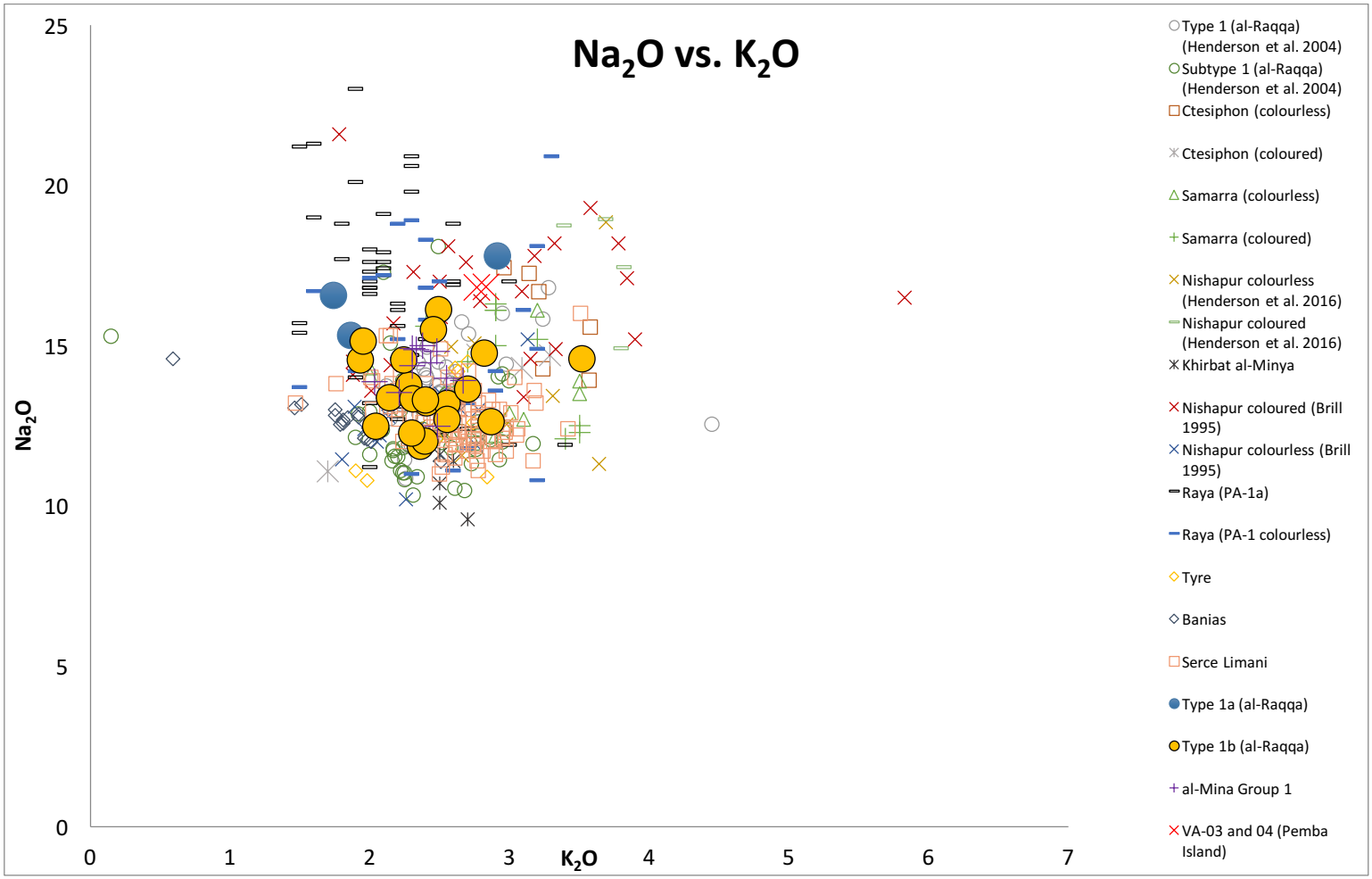


Figure 8.12: A bi-plot of Na_2O versus K_2O for Types 1a and 1b glasses from late 8th - 9th century AD al-Raqqa, 9th – 10th century, VA-03 and 04 from Islamic Pemba Island and al-Mina Group 1 from al-Mina. It is displayed according to composition groups and sites.

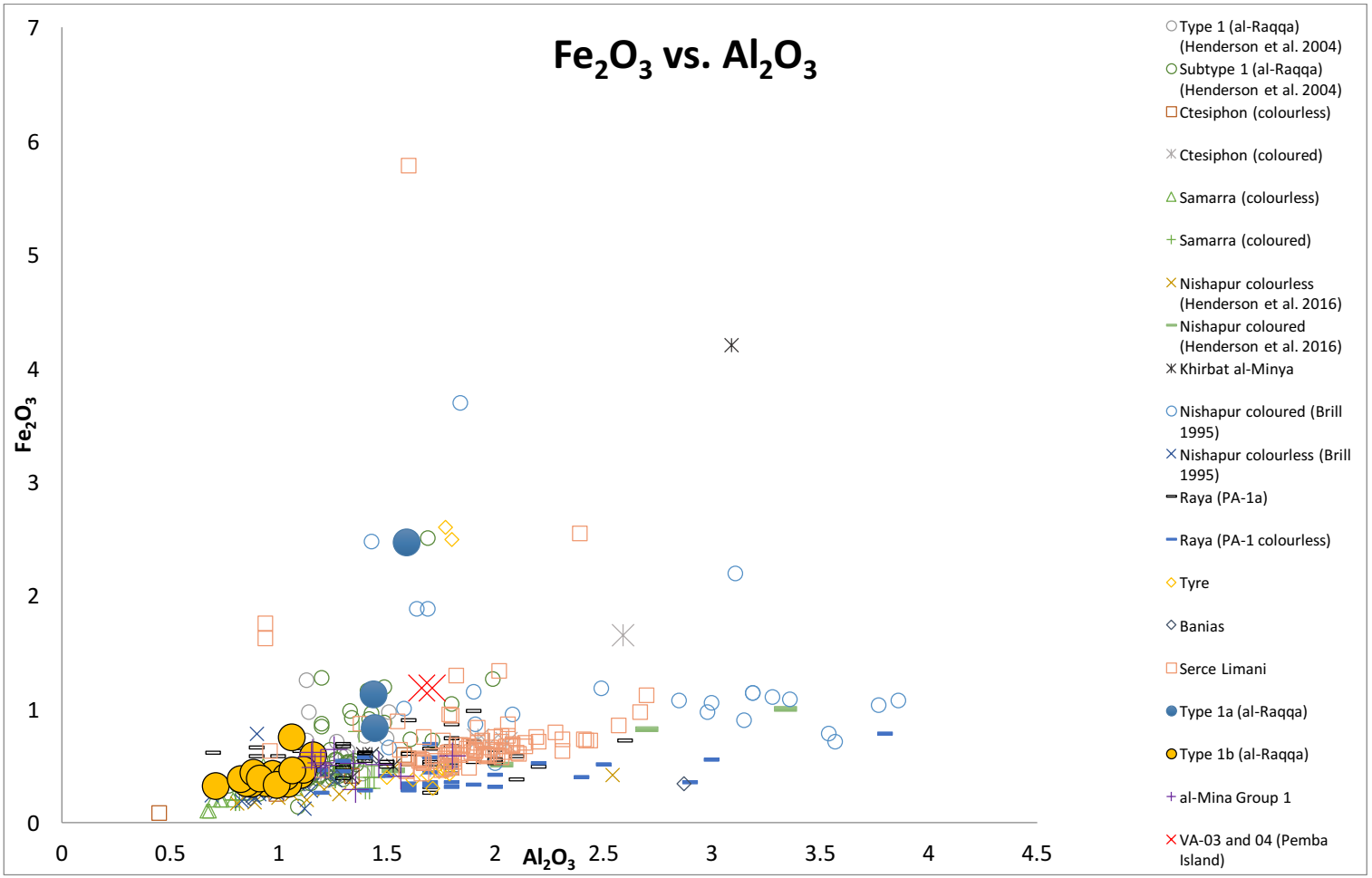


Figure 8.13: A bi-plot of Fe_2O_3 versus Al_2O_3 for Types 1a and 1b glasses from late 8th - 9th century AD al-Raqqa, 9th – 10th century, VA-03 and 04 from Islamic Pemba Island and al-Mina Group 1 from al-Mina. It is displayed according to composition groups and sites.

8.3.2.4 Low Al_2O_3-MgO-high CaO glass:

By the 9th and 10th centuries AD, a 'new' type of plant ash glass was (re-) introduced to the previously natron glass-dominated Israel, Syria, Lebanon and Egypt. This type of glass is relatively homogenous. It is characterised by low levels of Al_2O_3 and MgO and a relatively high CaO content (Henderson *et al.* 2004, 454). One of the earliest examples of this type of plant ash glass is found in al-Raqqa (Type 1) identified by Henderson *et al.* (2004). This glass group is dated to the late 8th and 10th centuries AD.

Figures 8.11 and 8.12 show that Types 1a and 1b are very similar to Henderson *et al*.'s (2004) Type 1 and they are significantly different from glasses produced in Iraqi/Iranian glass production centres. Types 1a and 1b and Henderson *et al*.'s (2004) Type 1 have low concentrations of CaO but have high levels of Na_2O (Henderson *et al.* 2004, 455). These groups are significantly different from the 11th century AD subtype 1 glass group from al-Raqqa. Subtype 1 is characterised by lower Na_2O and higher CaO and Al_2O_3 than Type 1 (Henderson *et al.* 2004, 455). It should be noted that glasses from Type 1a are dated to the 11th century AD, which may suggest either Type 1 glasses continued to be produced in al-Raqqa until the 11th century AD or glassmakers were recycling 9th century AD glass.

But there are some differences between Types 1a and 1b in this study and Type 1 from Henderson *et al.* (2004)'s study. Type 1a in this study has a higher concentration of Al_2O_3 and Fe_2O_3, and lower concentrations of CaO and K_2O than the majority of the glasses in Type 1 (Figures 8.11 – 8.13). The higher concentration of Fe_2O_3 in Type 1a results a dark green colour in the glasses. On the other hand, Type 1b in this study has a lower concentration of MgO and Na_2O than Henderson *et al*. (2004)'s Type 1 (Figures 8.11 and 8.13). But its concentrations of Al_2O_3, CaO and K_2O are broadly similar to Type 1 (Figures 8.11 – 8.13). This may suggest there were some varitation in raw material selection and melting conditions.

Al-Mina Group 1 is very similar to the majority of Henderson *et al.*'s (2004) Type 1 glasses from al-Raqqa. Both groups have low concentrations of Al_2O_3 and Fe_2O_3 which suggests that a pure source of silica was used to produce these two glass groups (Figure 8.13).

In terms of the alkali source, both groups have very similar concentrations of Na_2O and K_2O which suggest they were made with a very similar composition of plant ash, possibly of the same genera (Figure 8.12). However, the difference between these two groups is that al-Mina Group 1 has a slightly higher concentration of CaO than al-Raqqa Type 1 and is very similar to subtype 1 from al-Raqqa (Figure 8.11). This may indicate similar species of plant ashes (due to similar alkali level) from a similar geological bedrock (due to similar CaO level) as the al-Raqqa Type 1 and subtype 1 glasses were used or it is even possible that they were made in the same place.

The plant ash glasses from al-Raqqa and al-Mina are compositionally different from plant ash glasses produced in Israel such as Khirbat al-Minya (8^{th} century AD) in Israel and Tyre (10^{th} – 11^{th} centuries AD) in Lebanon. These plant ash glasses have a higher concentration of Al_2O_3 but a lower concentration of SiO_2 than the glasses from northern Syria (Freestone 2002, 70-71; Henderson *et al.* 2004, 443-448; 2016, 144). The level of CaO in the Levantine plant ash glasses is also different; glasses from Khirbat al-Minya and Tyre have higher concentrations of CaO than the Syrian glasses (Figure 8.11). Some have CaO up to 14%. The alkali level in the Levantine and Syria glasses is also different. The level of Na_2O in glasses from Khirbat al-Minya and Tyre are significantly lower than those from northern Syria. But the level of K_2O in the Levantine glasses is fairly similar to the northern Syrian glasses (Figure 8.12).

Similar compositions of plant ash glasses are also found in the 11^{th} century Serce Limani shipwreck and Raya in Egypt. Both of them display similar characteristics to glasses from Khirbat al-Minya and Tyre. Therefore, it is possible that different silica and alkali sources were used in the Levantine and northern Syria glass workshops. And it is not impossible that the glasses from Serce Limani and Raya originated from the Israel and Lebanon rather than from northern Syria. Trace element analysis of the glasses from Israel (Khirbat al-Minya) further proves that a different sand source was

used to produce Levantine glasses. They have a lower concentration of Cr (associated with sand) than northern Syrian glasses (al-Raqqa) (Henderson *et al*. 2006, 138).

VA-03 and 04 from Pemba Island are very similar to some of the glasses from Tyre with its elevated concentrations of Al_2O_3 and MgO. However, its CaO and Na_2O levels are significantly different from the Levantine plant ash glasses (Figures 8.11 and 8.12). Instead, they resemble closely Henderson *et al.* (2004) and this study's Type 1 glasses from al-Raqqa. It is possible that a similar source of plant ashes as the al-Raqqa glasses was used to produce this glass group. Further trace element analysis of the glasses could be used to investigate whether the Pemba Island glasses were made in northern Syria.

8.3.3 Plant ash glasses in the 11th – 12th centuries AD:

8.3.3.1 Zeyrek Camii Group 1:

Zeyrek Camii Group 1 from Istanbul is compared with existing data on Zeyrek Camii and Kariye Camii glasses analysed by Brill (2005) and Henderson and Mango (1995) in Figures 8.14 – 8.16. It shows that Zeyrek Camii Group 1 corresponds to Brill's (2005) low boron plant ash glasses (Brill 2005, 215). Both groups are characterised by a relatively low Al_2O_3 and Fe_2O_3 which suggests a pure source of silica, such as quartz, was used (Figure 8.14). Both groups have a relatively high CaO level between 8.04% - 9.57% (Figure 8.15). They also have a relatively high concentration of Na_2O and K_2O (Figure 8.16). Figures 8.15 and 8.16 show that they are tightly grouped together. It is possible that they were produced on the same production site using the same source of raw materials. These two groups are significantly different from the high boron plant ash glasses from Zeyrek Camii identified by Brill (2005) (Brill 2005, 215). The latter are characterised by a lower concentration of MgO and K_2O and has significant level of B_2O_3 in the glasses (Brill 2005, 215-217).

It is also noted that Zeyrek Camii Group 1 and Brill's low boron glasses from Zeyrek Camii have similar CaO, MgO, Na_2O and K_2O levels to some of the 12th – 14th centuries AD plant ash glasses from Tyre, Damascus and 11th – 13th centuries AD Banias (Figures 8.15 and 8.16) (Freestone 2002, 70-71; Freestone *et al*. 2000, 78;Henderson *et al*. 2016, 144). This may suggest a common source of plant ashes (similar plant pecies from

similar geological environments) was used to produce these glasses during the 11th – 14th centuries AD. It is possible that glasses from Zeyrek Camii Group 1 were made in Israel, Lebanon or Syria. According to the Jewish traveller Benjamin of Tudela, there were about ten glassmakers in Tyre or Antioch in the 12th century AD where plant ash was used to manufacture glass (Boas 1999, 151).

Without any chemical data on contemporary glasses from Turkey, the similarity between Zeyrek Camii and Islamic glasses from Tyre, Damascus and Banias in terms of the calcium and alkali levels suggests the Zeyrek Camii glasses were made with in either Israel, Lebanon or Syria using similar raw materials.

However, as Brill (2005) noted, the analysis does not reveal 'where the window glass was formed, who painted the windows, when and where they were painted, or what inspired their creation' (Brill 2005, 217).

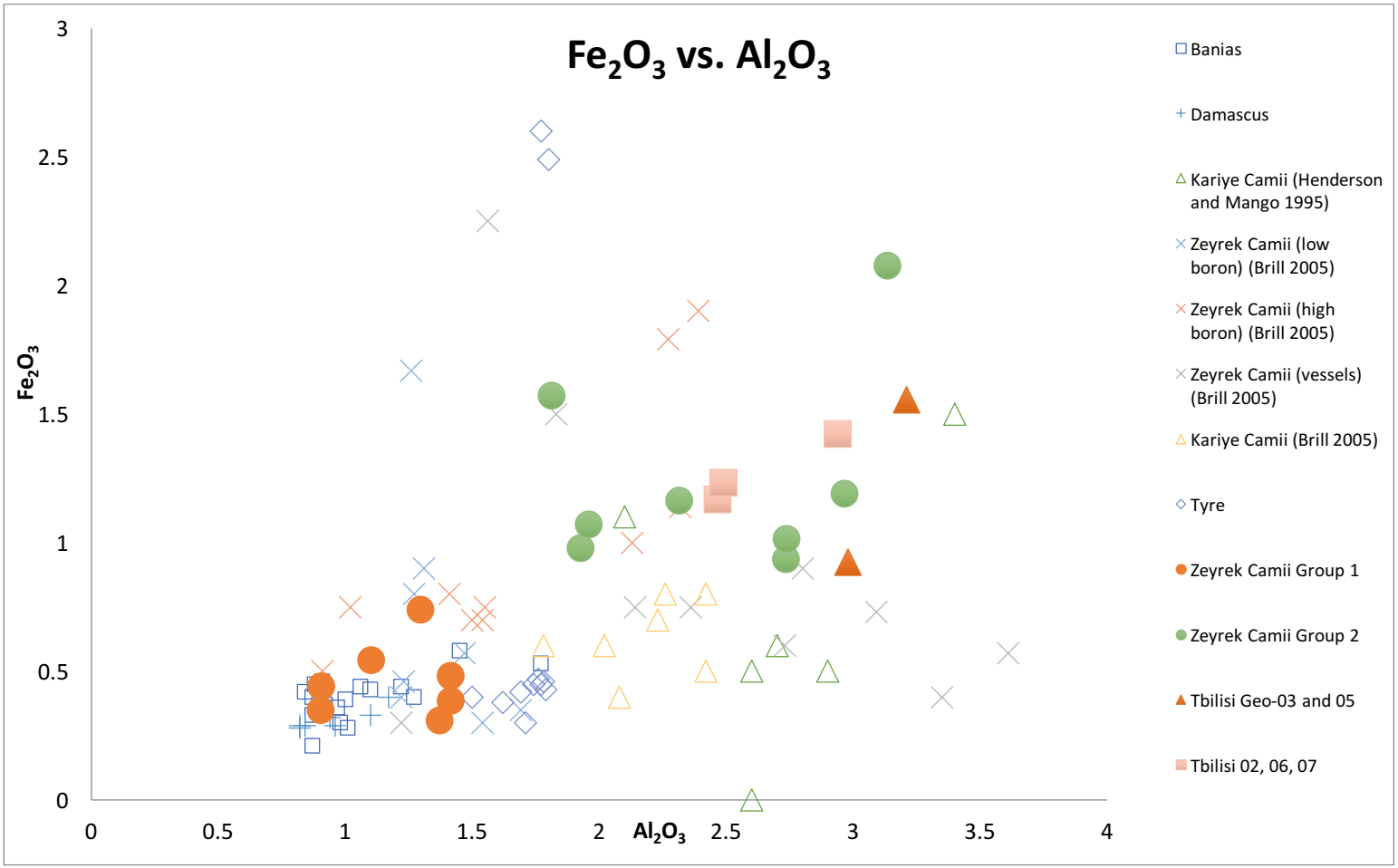


Figure 8.14: A bi-plot of Fe_2O_3 versus Al_2O_3 for Zeyrek Camii Groups 1, 2 and 3 from 11th – 12th centuries AD Zeyrek Camii, Tbilisi Geo-03 and 05, and Tbilisi Geo-02, 06 and 07 from 10th – 14th centuries Tbilisi. It is displayed according to composition groups and sites. Data for Tyre glasses: Freestone (2002); Banias glasses: Freestone *et al*. (2000); Damascus glasses: Henderson *et al*. (2016); Kariye Camii glasses: Brill (2005), Henderson and Mango (1995); Zeyrek Camii glasses: Brill (2005).

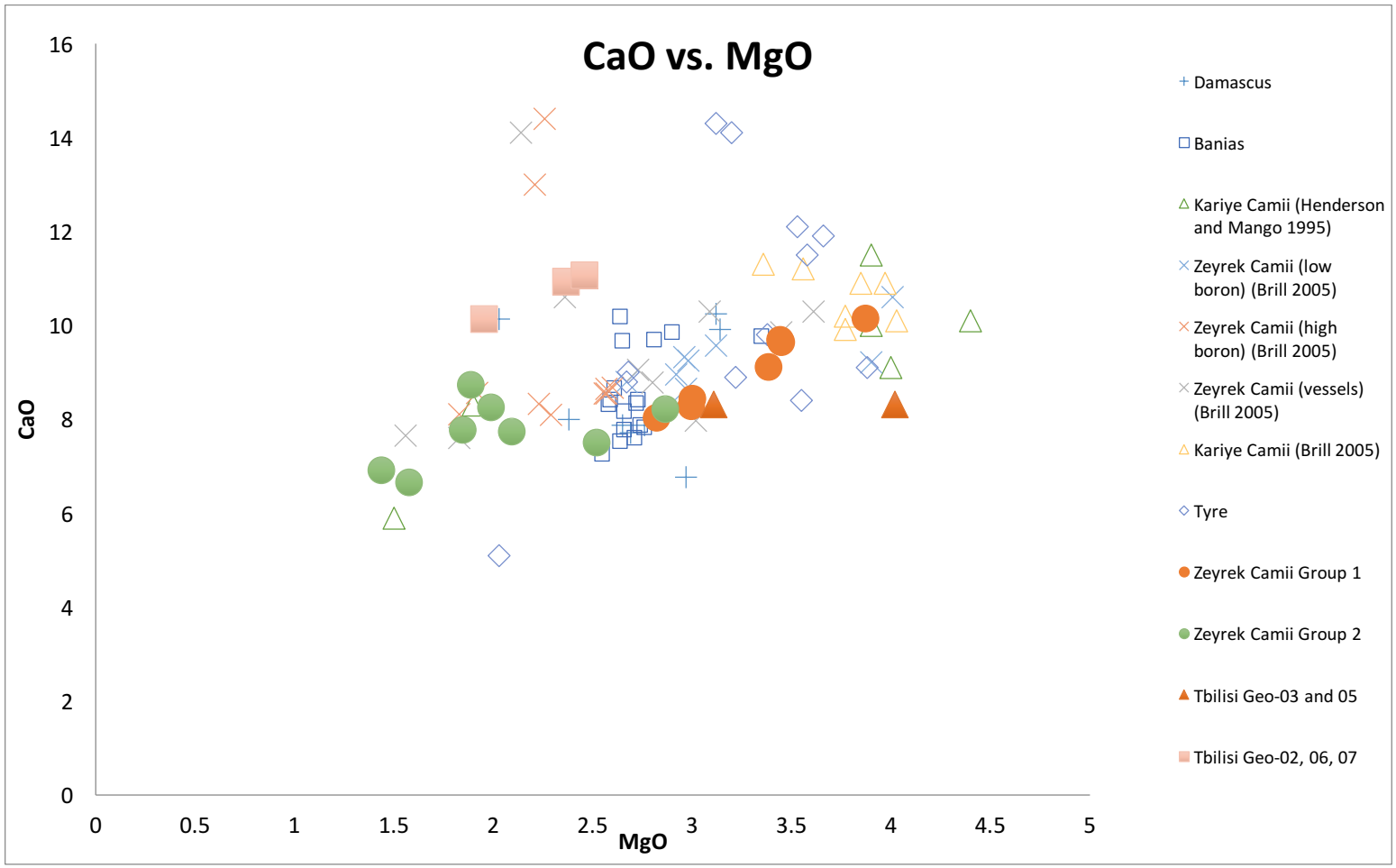


Figure 8.15: A bi-plot of CaO versus MgO for Zeyrek Camii Groups 1, 2 and 3 from 11th – 12th centuries AD Zeyrek Camii, Tbilisi Geo-03 and 05, and Tbilisi Geo-02, 06 and 07 from 10th – 14th centuries Tbilisi. It is displayed according to composition groups and sites.

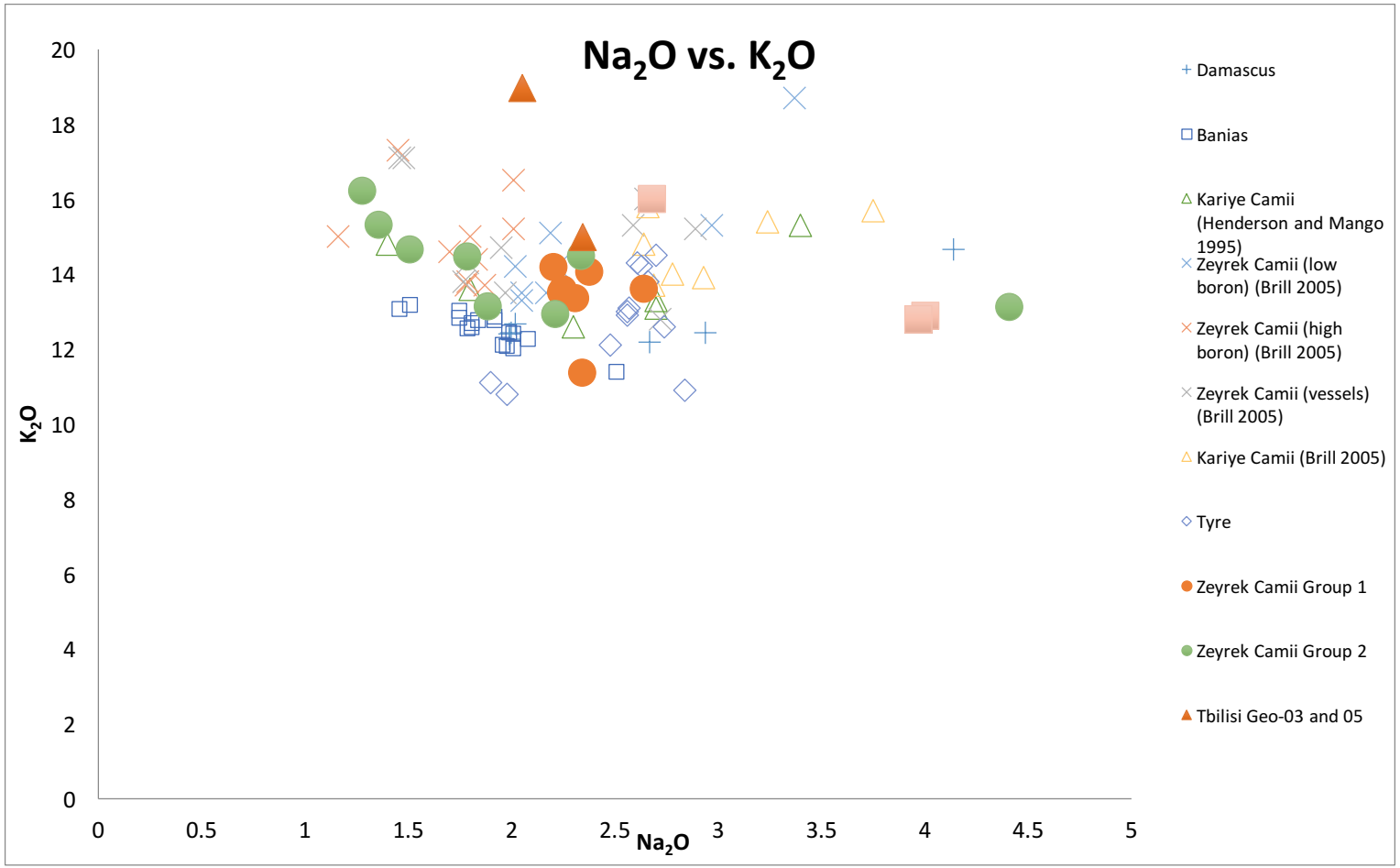


Figure 8.16: A bi-plot of Na_2O versus K_2O for Zeyrek Camii Groups 1, 2 and 3 from 11^{th} – 12^{th} centuries AD Zeyrek Camii, Tbilisi Geo-03 and 05, and Tbilisi Geo-02, 06 and 07 from 10^{th} – 14^{th} centuries Tbilisi. It is displayed according to composition groups and sites.

8.3.3.2 Tbilisi Geo-02, 06 and 07:

Tbilisi Geo-02, 06 and 07 are similar to the plant ash glasses from the Serce Limani shipwreck and Tyre (Figures 8.14 – 8.16). The levels of K_2O and P_2O_5 in these glasses are relatively high, between 2.68% and 4% and between 0.69% - 1.64%. This suggests they are not mixed-natron plant ash glasses (which usually have K_2O level below 2.5%) but plant ash glasses. But even so, their CaO, MgO and Na_2O levels are very similar to the Serce Limani and Tyre glasses (Figures 8.15 and 8.16). The relatively high levels of K_2O and P_2O_5 suggest glasses from the Tbilisi glasses were made with a different composition of plant ash that provides a similar level of CaO, MgO and Na_2O as the Levantine glasses.

The high levels of SO_3 and P_2O_5, which are not found in any Syrian, Levantine, Egyptian, Iraqi and Iranian glasses (Henderson *et al*. 2016, 144), but only in the Tbilisi glasses, suggest Georgian glassmakers might have used a locally sourced plant ash to produce glasses.

8.3.3.3 High alumina glass (Tbilisi Geo-08 and Pemba Island VA-06):

It has been reported by researchers that medieval high alumina glasses originated from India, East Africa, Sri Lanka and southeast Asia in the 9^{th} – 19^{th} centuries AD (Boulogne and Henderson 2009, 71; Dussubieux *et al*. 2008, 798; 2010, 1646; Henderson 2013, 297-300; Schibille 2011, 9). The only Middle Eastern example of high alumina glasses was reported by Boulogne and Henderson (2009) in their study of Mamluk-Ottoman period bracelets from Tell Abu Sarbut and Khirbat Faris in Jordan. They have suggested that the high alumina glasses were the result of mixing plant ash glasses (with K_2O >4%) from Central Asia (e.g. Afghanistan) and high alumina glasses (made from a high alumina raw material *reh*) (Boulogne and Henderson 2009, 72-73). Further west in the Mediterranean, Dussubieux *et al*. (2010) and Schibille (2011) have reported that high alumina glasses were found in Sardis and Pergamon in western Turkey (Dussubieux *et al*. 2010, 1652; Schibille 2011, 9-10). The glasses from Pergamon are also accompanied with elevated levels of B_2O_3 which are not found in other high alumina glasses from India, East Africa, Sri Lanka and southeast Asia (Schibille 2011, 10). Recent analysis of hot springs in western Turkey (Afyon-Gazligol

and Urganli) shows that they contain elevated B_2O_3 contents and could have been exploited to produce glasses in Pergamon in the middle and late Byzantine period (Tite *et al*. 2016, 63-64). This suggests western Turkey was one of the area where high alumina (with elevated level of B_2O_3) glasses were produced during the 9^{th} – 15^{th} centuries AD (Schibille 2011, 10).

Figures 8.17, 8.18 and 8.19 compare the high alumina glasses from Tbilisi and Pemba Island with high alumina glasses from east Africa, western Turkey and western India. The composition of Tbilisi Geo-08 is different from the Pergamon, Sardis and Jordanian glasses. It is very similar to the high alumina glasses from Kenya identified by Dussubieux *et al.* (2010). The levels of CaO, MgO, K_2O and Na_2O are similar to the high alumina glasses from Mtwapa in Kenya identified by Dussubieux and co-workers (Dussubieux *et al.* 2010, 1649, Table 2; Schibille 2011, 4, Table 2). For Pemba Island VA-06, it is also fairly similar to the Kenyan glasses from Mtwapa in terms of its total alkali, CaO and Al_2O_3 levels and is different from the Pergamon, Sardis and Jordanian glasses (Figures 8.17 – 8.19). However, its MgO level is significantly higher than other high alumina glasses, even higher than Jordanian high alumina glasses that were mixed with relatively high MgO plant ash glasses from Central Asia (e.g. plant ash glasses from Afghanistan, Kuva and Akhsiket have MgO less than 6%) (Brill 1999, 341-343; Rehren *et al*. 2010, 98) (Figure 8.18).

It has been estimated that *reh*, an alkali rich mineral that is commonly found in south and southeast Asia, contributes high levels of Al_2O_3 (about 10%), Na_2O (up to 36%) and K_2O (3% - 6%) and relatively low levels of MgO (about 1%) and CaO (about 3%) to the glass (Boulogne and Henderson 2009, 72; Lankton and Dussubieux 2006, 132-133; Henderson 2013, 53). It is possible to say that a rather impure source of silica, possibly granite sands that contains high levels of Al_2O_3, Fe_2O_3, TiO_2 was used (Dussubieux *et al.* 2010, 1647).

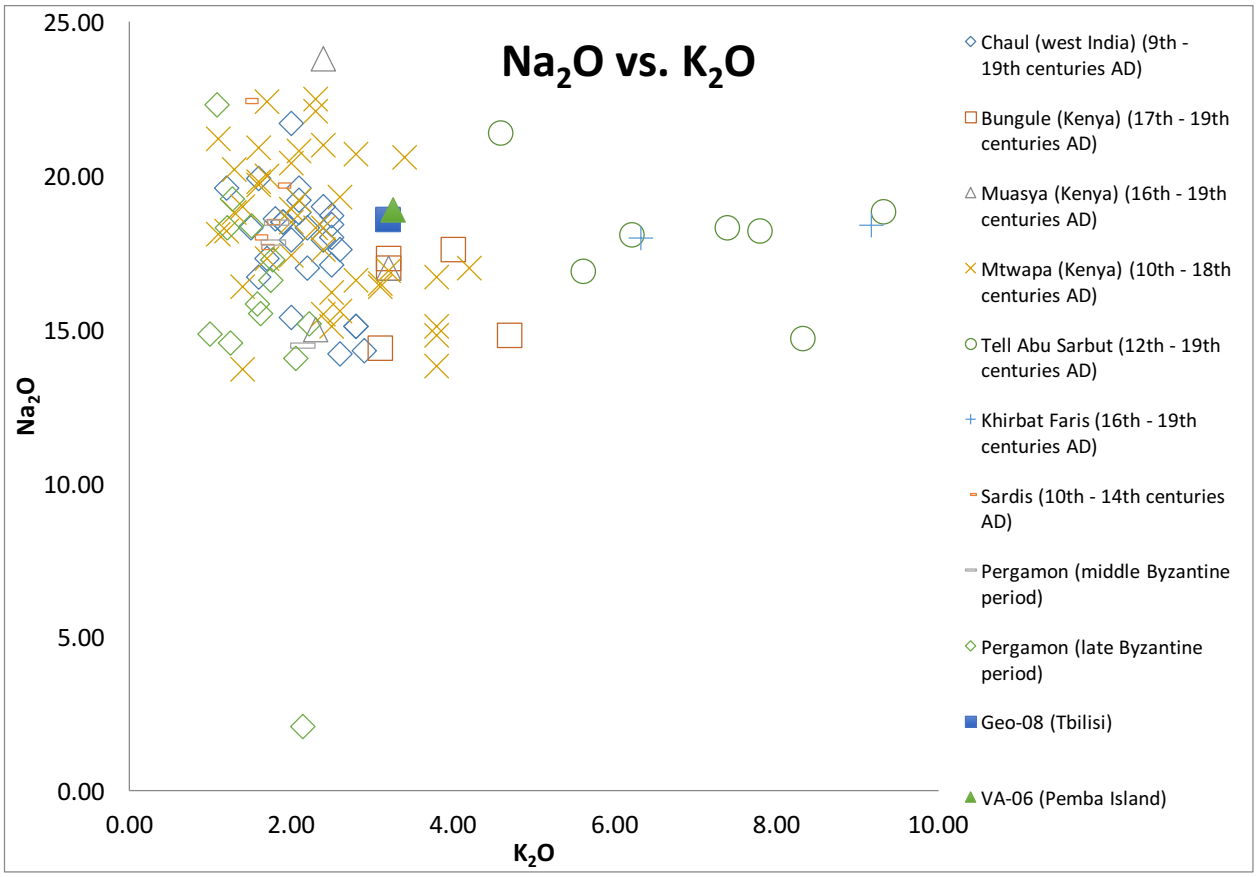


Figure 8.17: A bi-plot of Na_2O versus K_2O for the high alumina glasses from 10^{th} – 13^{th} centuries AD Tbilisi, Islamic Pemba Island and late 8^{th} – 9^{th} centuries AD al-Raqqa. Data for Chaul, Bungule, Musaya and Mtwapa glasses: Dussubieux *et al*. 2010; Tell Abu Sarbut and Khirbat Faris glasses: Boulogne and Henderson 2009; Sardis glasses: Brill (1999) and Brill and Stapleton (2012); Pergamon glasses: Schibille (2011).

Given that the K_2O level in VA-06 is significantly lower than the mixed plant ash-high alumina glasses from Jordan, it is likely that the high MgO content in VA-06 is the result of mixing plant ash glasses, possibly from Central Asia (with MgO as high as 6% and K_2O less than 3.5%) (Figures 8.11 and 8.12), with high alumina glasses similar to the high alumina glasses from Kenya. Dussubieux *et al*. (2008) have suggested that the glasses from Mtwapa were circulated between the east coast of Africa and Madagascar and the west coast of India (Dussubieux *et al*. 2008, 817). It is likely that the high alumina glasses from Pemba Island and Tbilisi were originated from these regions.

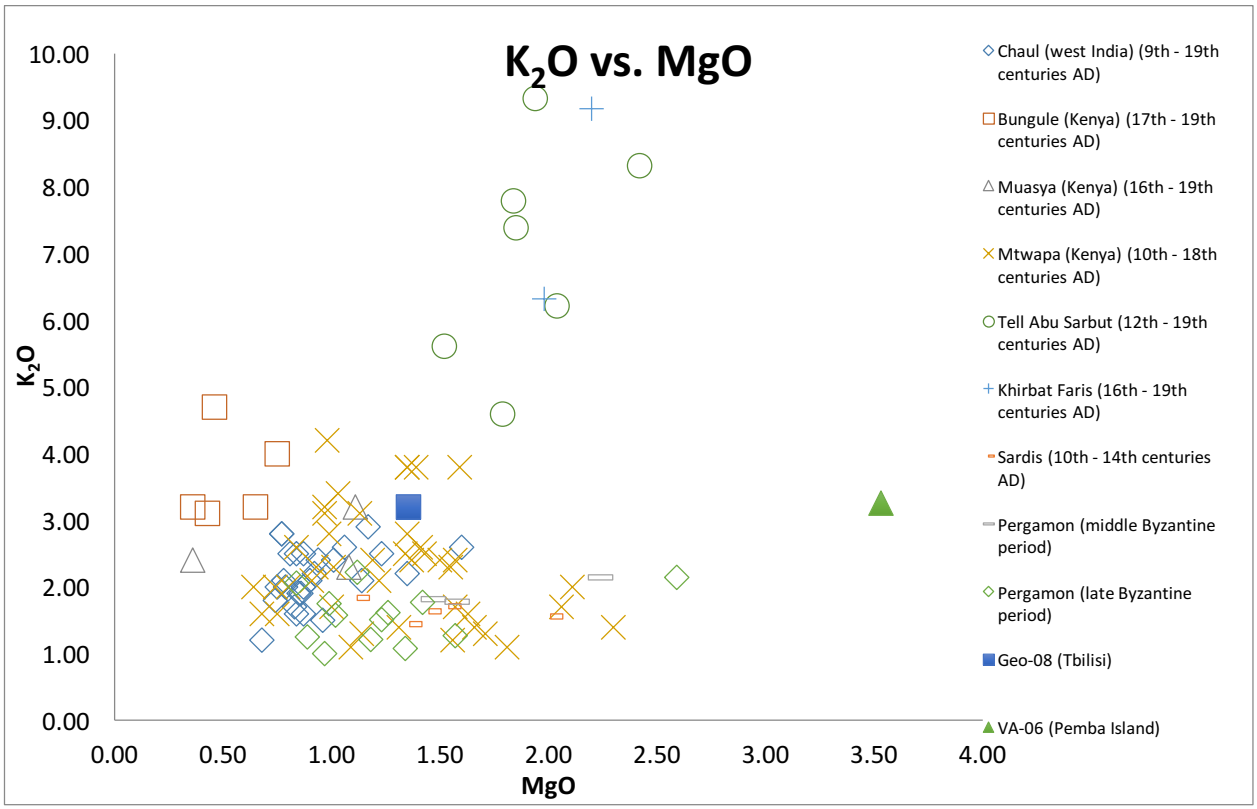


Figure 8.18: A bi-plot of K_2O versus MgO for the high alumina glasses from 10th – 13th centuries AD Tbilisi, Islamic Pemba Island and late 8th – 9th centuries AD al-Raqqa.

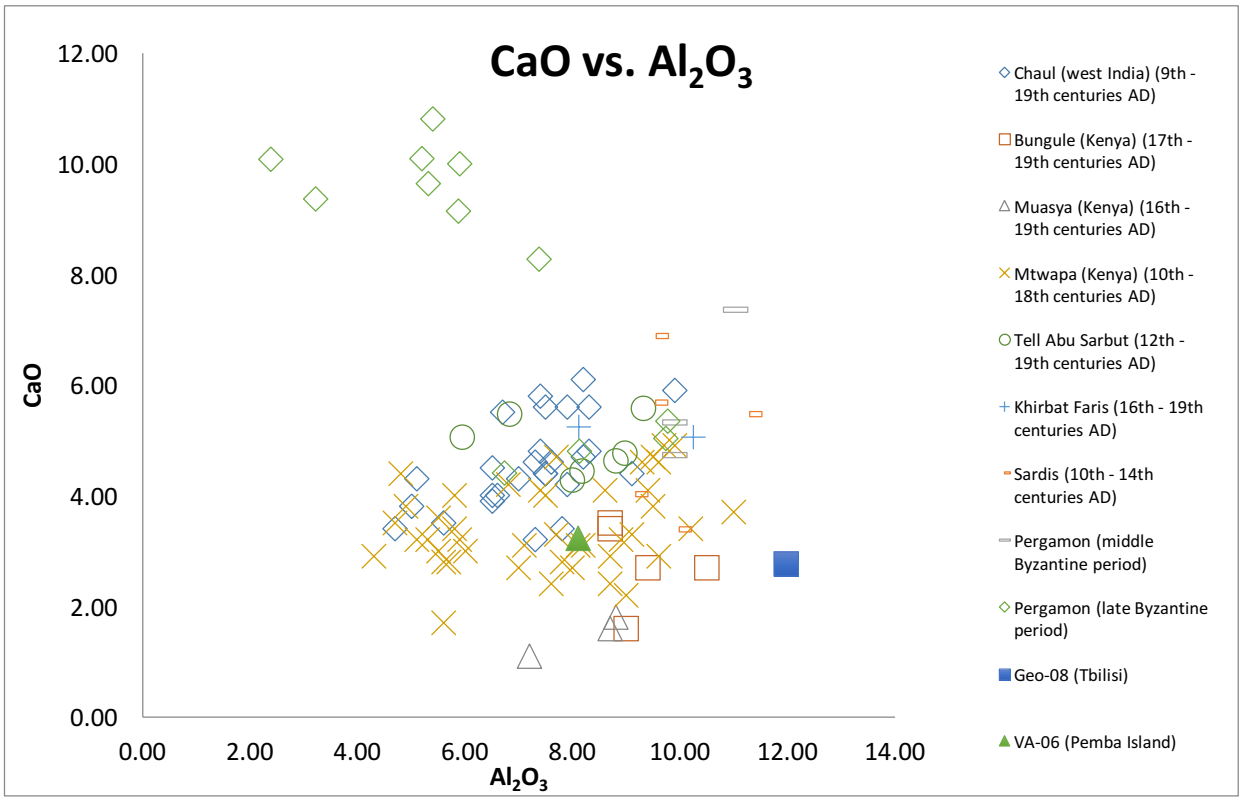


Figure 8.19: A bi-plot of CaO versus Al_2O_3 for the high alumina glasses from 10th – 13th centuries AD Tbilisi, Islamic Pemba Island and late 8th – 9th centuries AD al-Raqqa.

8.4 Evidence of recycling/mixing:

Recycling of glass has great value to ancient glassmakers technologically, socially and economically. Archaeological evidence from shipwrecks such as the 11th century AD Serce Limani, and secondary glass workshops such as Jalame, Bet She'an and Sardis shows that glass cullet was in high demand throughout the antique and medieval periods (Keller 2004, 66-67; Price 1998, 337-338).

Technologically, cullet helps to speed up the melting process of glass and to lower the melting temperature. It is also relatively free of impurities that are usually found in raw materials and it helps to control the levels of major, minor and trace components in the final glasses (Henderson *et al.* 2004, 459; Keller 2004, 65).

The recycling of glass began to increase in the early medieval period. At Crypta Balbi, the majority of the 8th century AD glasses were recycled glasses; at San Vincenzo in Molise the coloured glasses were the result of recycling 1st – 3rd centuries AD mosaic tesserae with cullet (Freestone 2015, 35; Mirti *et al.* 2001, 499; Schibille and Freestone 2013, 8). It is possible to suggest that the supply of fresh raw glasses from the Middle East had decreased substantially during this period (Freestone 2015, 34-35). The reuse of old glasses would be cheaper for glassmakers and would be easier to obtain than imported fresh raw glasses through long distance trade (Keller 2004, 67).

Scientific studies of ancient glasses shows that the key indicators of recycling include contamination by coloured glasses that would incorporate elements such as copper, lead and cobalt into the final glasses. This is because the separation of glass colours in the recycling process was not perfect, which would inevitable incorporate different coloured glasses into the colourless glasses (Al-Bashaireh *et al.* 2016, 7; Freestone 2015, 29-30).

Decolourisers such as manganese and antimony are indicators of recycling if decolourised glasses were incorporated into the naturally coloured glasses. Elevated levels of P_2O_5 and K_2O may also be indicators that recycling occurred due to the increased interaction between the glass and the fuel (Al-Bashaireh *et al.* 2016, 7).

8.4.1 Evidence of recycling/mixing in natron glass:

Eighteen out of thirty-six Type 3 natron glasses from al-Raqqa have elevated levels of MnO between 0.02% and 0.15%. A small number of these also have elevated levels of CoO (~0.02%), PbO (0.02 – 0.04%), MgO (>0.60%) and K_2O (>0.60%) which, according to the threshold set out by Al-Bashaireh *et al.* (2016) on Levantine glasses, were the result of recycled glasses (Al-Bashaireh *et al.* 2016, 8).

Although raw natron glasses were found in the glass workshop from Tell Zujaj, there is no evidence to suggest that they were made in al-Raqqa. But considering that many Levantine I glass production centres ceased to exist after the 7th century AD (e.g. Apollonia and Dor), and the increased dominance of Levantine II glasses in the Levantine region, it is not impossible that old Levantine I glasses were recycled and remelted in Tell Zujaj during the late 8th and 9th centuries AD.

The excavations at HaGolan Street in northeastern Tel Aviv, Israel in 1970 show that no Levantine I glass composition was used to manufacture glass vessels in the workshop (Freestone *et al.* 2015, 52). It is likely that Levantine I glass group in the region was replaced by the Levantine II glass group after the 7th century AD, with Bet Eli'ezer the primary production centre of this new glass group until the 8th century AD.

8.4.2 Evidence of recycling/mixing in plant ash glass – Type 4b:

It is noticeable that al-Raqqa Type 4b shows the characteristics of recycling/mixing. It is likely that Type 4b was the result of glassmakers mixing recycled or reused cullet from the two end members (Types 4a and 4c) with fresh raw glasses. This helps to control the chemical compositions in the final glass melt (Henderson 2000, 85; 2002, 599; 2013, 284; Henderson *et al.* 2004, 457-459). This is why we see a tight cluster of glasses (Type 4b) in between Types 4a and 4c in terms of their levels of CaO, Al_2O_3, Fe_2O_3 and Na_2O (Figures 8.15 – 8.17).

8.4.3 al-Raqqa Type 2 and al-Mina VA-15:

It is possible that al-Raqqa Type 2 and al-Mina VA-15 were the result of recycling and mixing. This was first suggested by Henderson and co-workers (Henderson 1999, 234; 2000, 84; Henderson *et al.* 2004, 460). They have suggested that this type of glass may have been the result of recycling between natron and plant ash glasses, which might not have been glasses from al-Raqqa (Henderson *et al*. 2004, 460). The elevated levels of MnO, Fe_2O_3 and TiO_2 suggest coloured glasses were used to mix in the glass melt (Henderson 1999, 232; 2000, 84). Many of these analysed by Henderson are highly coloured glasses that include translucent emerald green, deep yellow-green and brown (Henderson 1999, 232). The same is observed in this study which found that high coloured glasses such as blue and dark green belong to this group.

If the glass type was the result of mixing natron and plant ash glass cullets, Type 2 would overlap with the natron glasses. However, none of the glasses from Type 2 overlap with the natron glasses (Figures 8.20 – 8.22).

A more likely explanation is that it probably relates to the recycled/mixed plant ash glasses Type 4b and plant ash glasses from Type 1. It is even possible that Type 2 is the direct result of glassmakers mixing a high ratio of Type 4b recycled/mixed glass with a small quantity of glasses from Type 1. Figure 8.20 shows that the concentrations of Al_2O_3 and Fe_2O_3 in Type 2 are in between those of Types 4 and 1. And it only overlaps with the recycled/mixed glasses in Type 4b. None of them are related to the natron glasses from al-Raqqa.

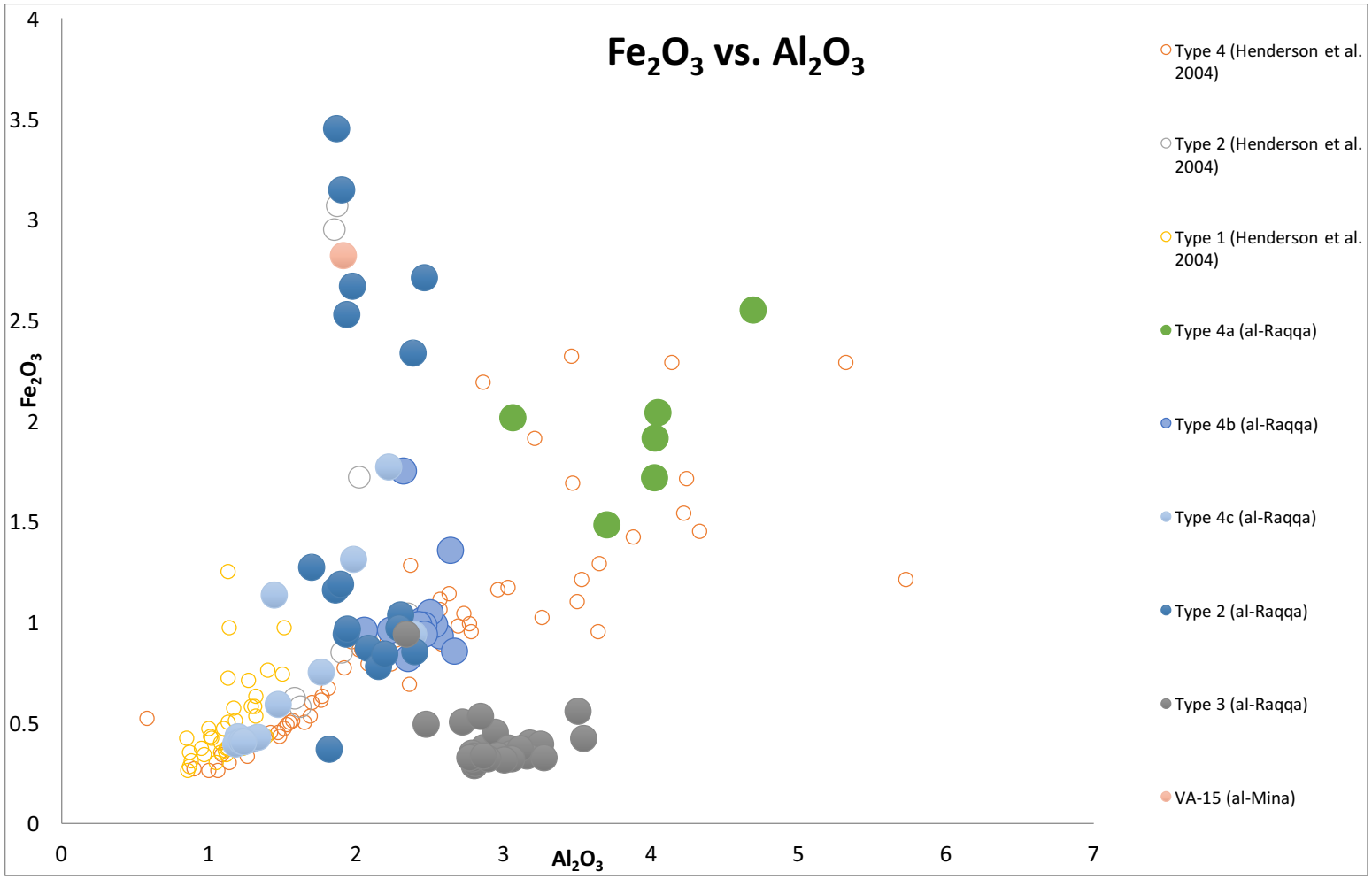


Figure 8.20: A bi-plot of Fe_2O_3 versus Al_2O_3 for Types 4a, 4b, 4c, 2, and 3 from late 8th – 9th centuries AD al-Raqqa and VA-15 from 9th – 10th centuries AD al-Mina. Data for al-Raqqa glasses: Henderson *et al*. (2004).

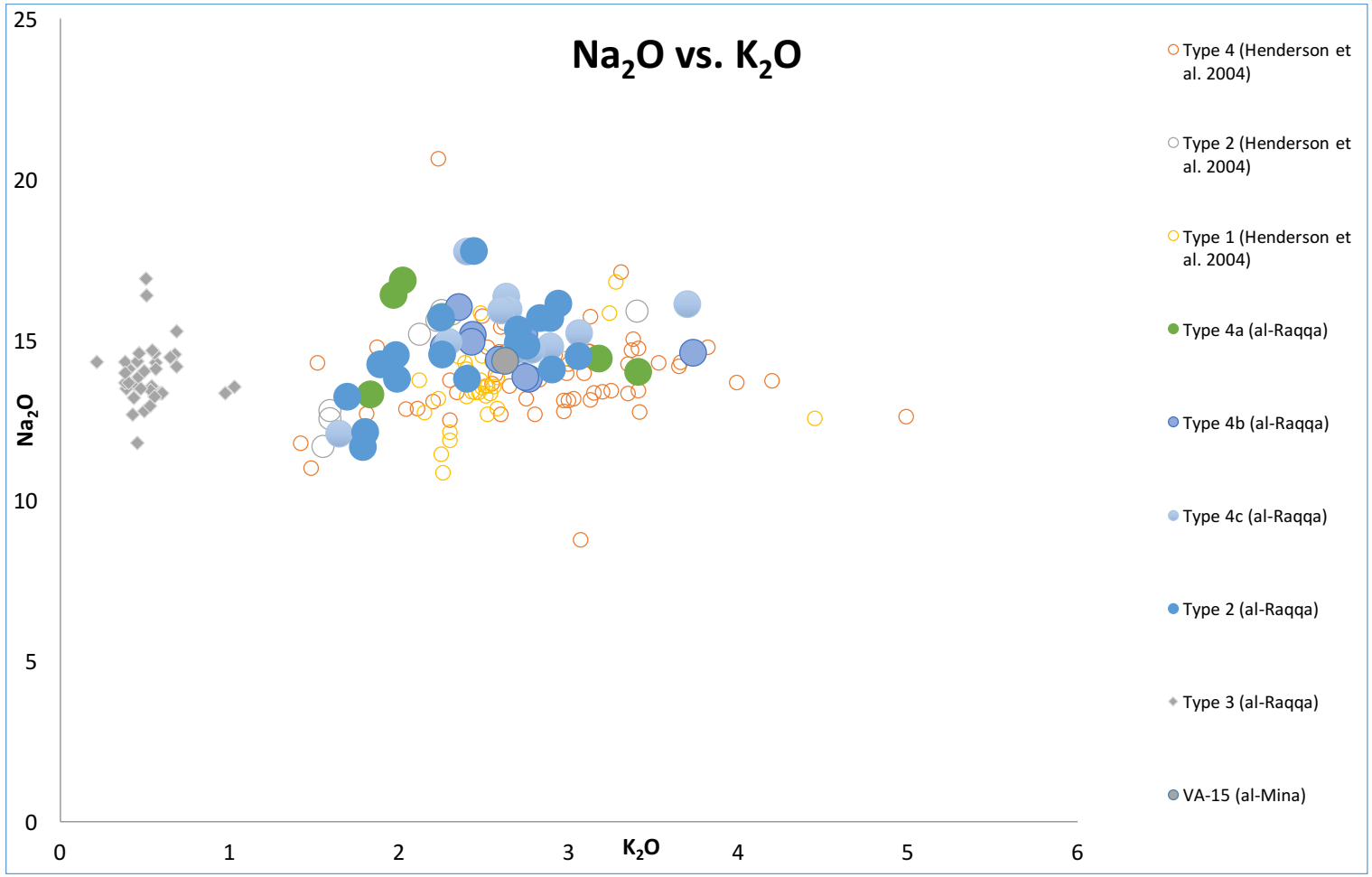


Figure 8.21: A bi-plot of Na_2O versus K_2O for Types 4a, 4b, 4c, 2, and 3 from late 8^{th} – 9^{th} centuries AD al-Raqqa and VA-15 from 9^{th} – 10^{th} centuries AD al-Mina. Data for al-Raqqa glasses: Henderson *et al*. (2004).

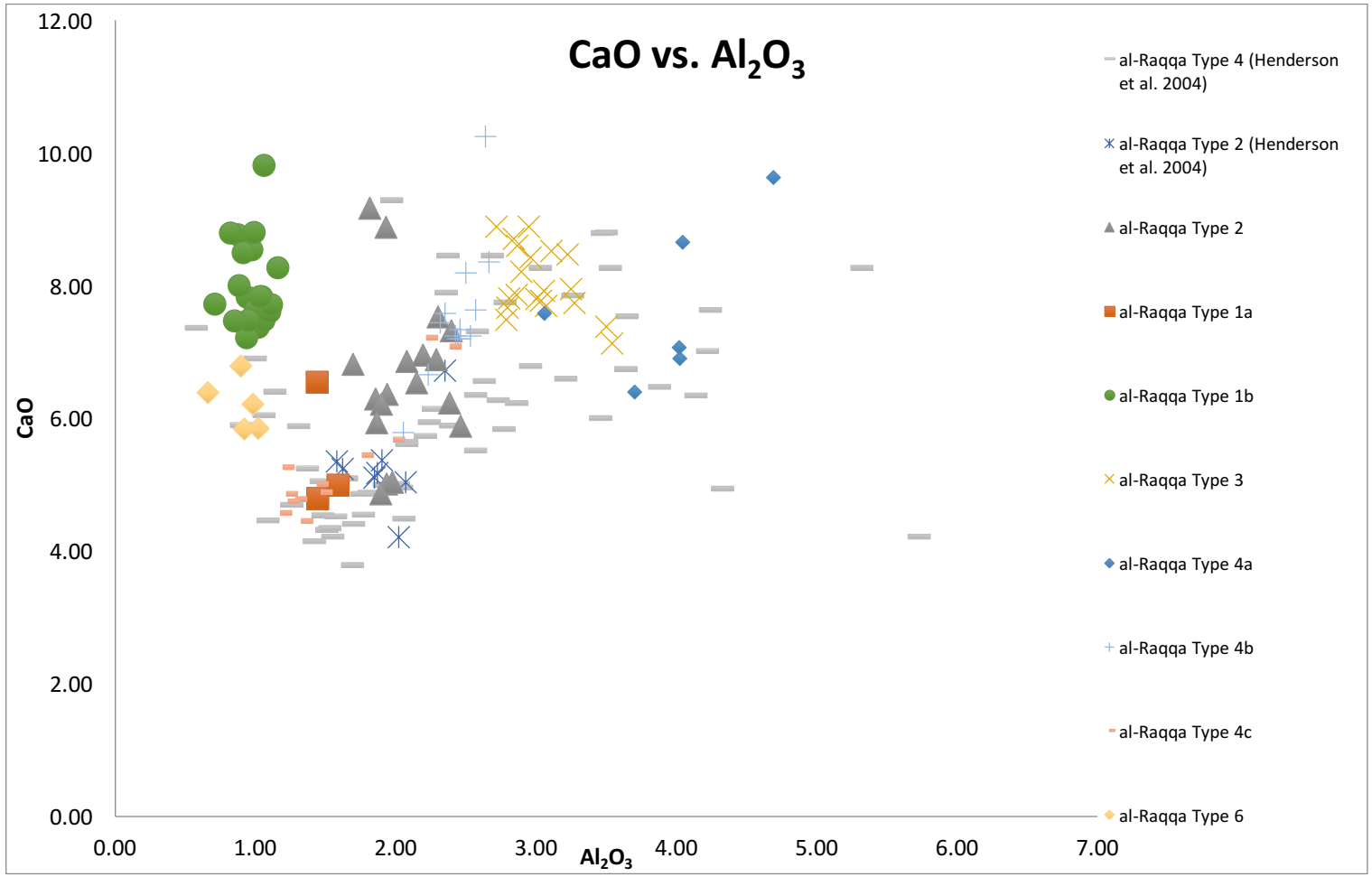


Figure 8.22: A bi-plot of CaO versus Al_2O_3 for Types 4a, 4b, 4c, 2, and 3 from late 8^{th} – 9^{th} centuries AD al-Raqqa and VA-15 from 9^{th} – 10^{th} centuries AD al-Mina. Data for al-Raqqa glasses: Henderson *et al*. (2004).

The same can be observed in the alkali level. Figure 8.21 shows that Type 2 and VA-15 have very similar concentrations of alkalis as found in the recycled/mixed glasses in Type 4b and Type 1. Type 2 positions itself in between Type 4 and Type 1. None of which are related to the natron glasses.

For its lime source, Type 2 also sits in between Types 4b and 1. Some of the glasses in plant ash Type 2 display a positive correlation between Al_2O_3 and CaO like Type 4b, which suggests feldspar rich in Al_2O_3 and CaO was also used to increase the lime content in glasses in Type 2 (Figure 8.22). All these suggest a high ratio of glasses from Type 4b was mixed with glasses from Type 1.

These results therefore suggest that Type 2 is closely related to the recycled/mixed glasses in Type 4b and plant ash glasses in Type 1. None of the glasses from Type 2 relate to the natron group glasses from Raqqa. Neodymium and strontium isotope analysis shows that there is evidence of mixing in Type 1 and 4 glasses, possibly mixed with imported raw glass made from chemically distinct raw materials (Henderson 2013, 340-342).

The al-Raqqa Type 2 and VA-15 will now be compared with Islamic glasses from the 8^{th} – 11^{th} centuries AD. A bi-plot of MgO and Al_2O_3 (Figure 8.23) shows that they are associated with Henderson *et al.*'s (2004) Type 2 from al-Raqqa, almost all of the glasses from the 11^{th} century AD shipwreck Serce Limani and eight fragments of coloured glass from Nishapur. Type 2 and al-Mina VA-15 in this study have similar concentrations of Al_2O_3 as the Serce Limani and Nishapur glasses. The majority of the al-Raqqa glasses have low Fe_2O_3 and this is similar to other glasses. This suggests a relatively pure source of silica was used to produce these glasses and that these glasses are similar to each other geologically.

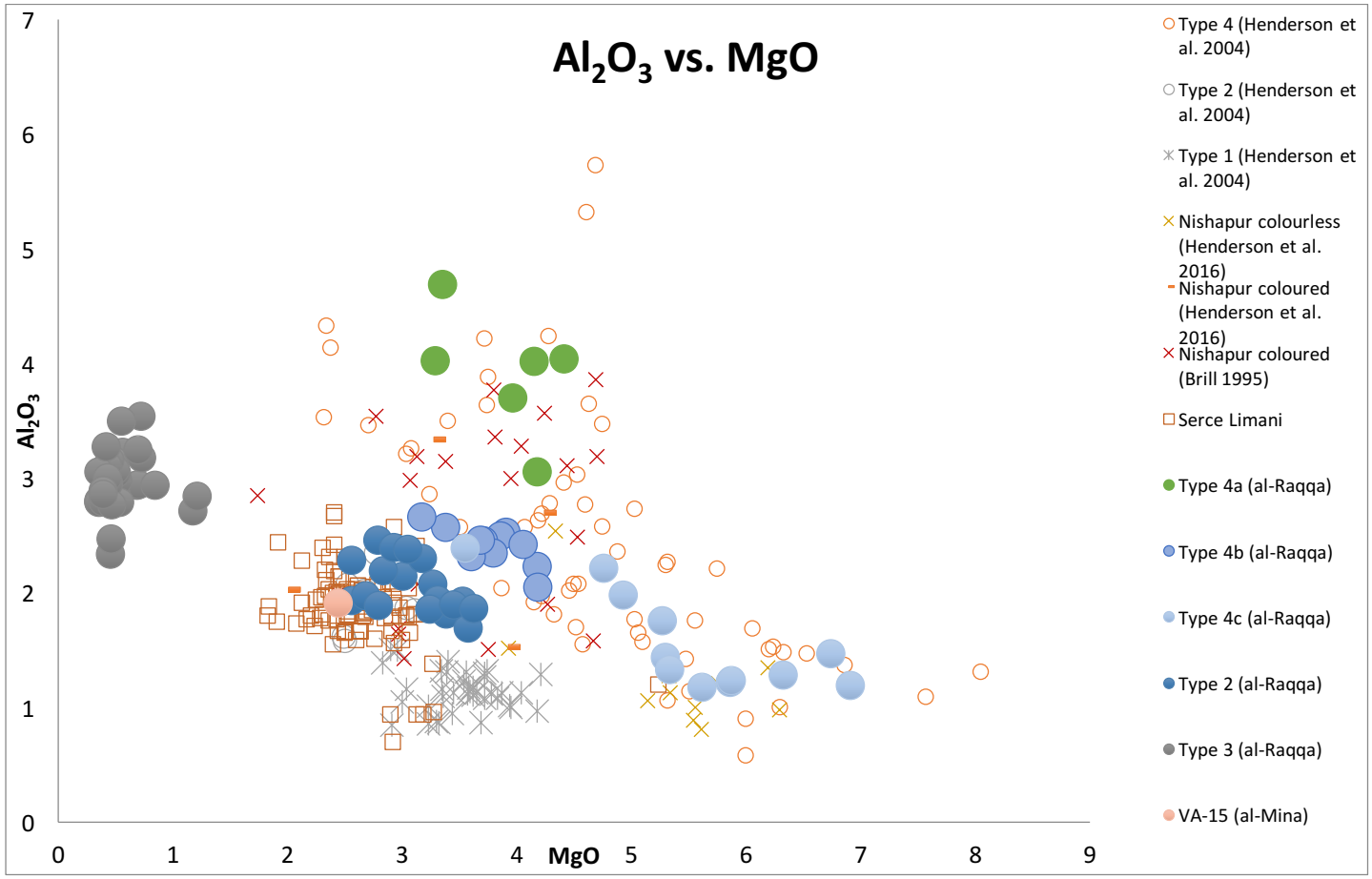


Figure 8.23: A bi-plot of Al_2O_3 versus MgO for Types 4a, 4b, 4c, 2, and 3 glasses from late 8th - 9th century AD al-Raqqa and VA-15 from 9th – 10th centuries AD al-Mina. It is displayed according to composition groups and sites. Data for al-Raqqa glasses: Henderson *et al*. (2004); Nishapur colourless and coloured glasses: Brill (1995) and Henderson *et al*. (2016); Serce Limani glasses: Brill (2009).

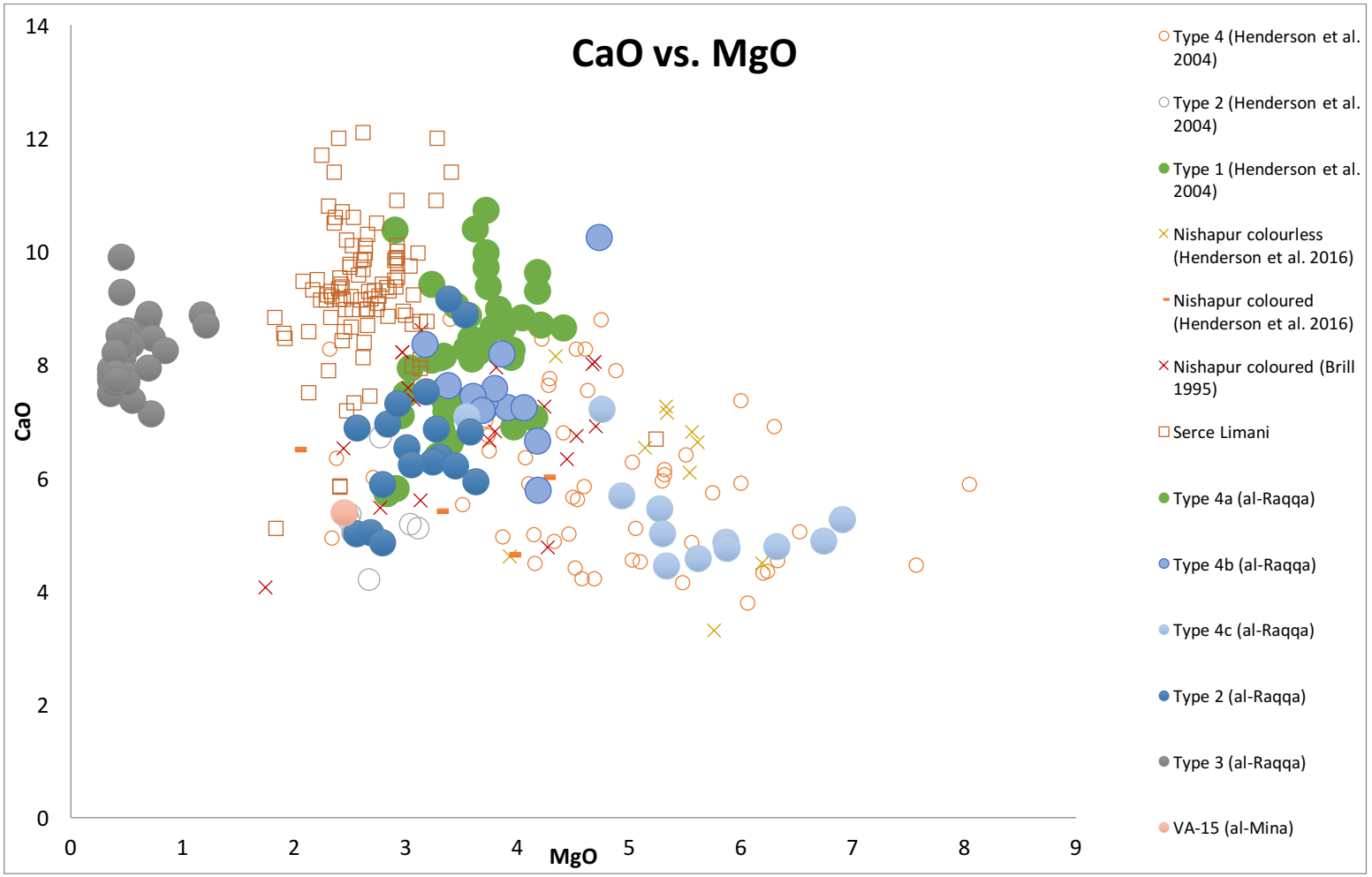


Figure 8.24: A bi-plot of CaO versus MgO for Types 4a, 4b, 4c, 2, and 3 glasses from late 8th - 9th century AD al-Raqqa and VA-15 from 9th – 10th centuries AD al-Mina. It is displayed according to composition groups and sites.

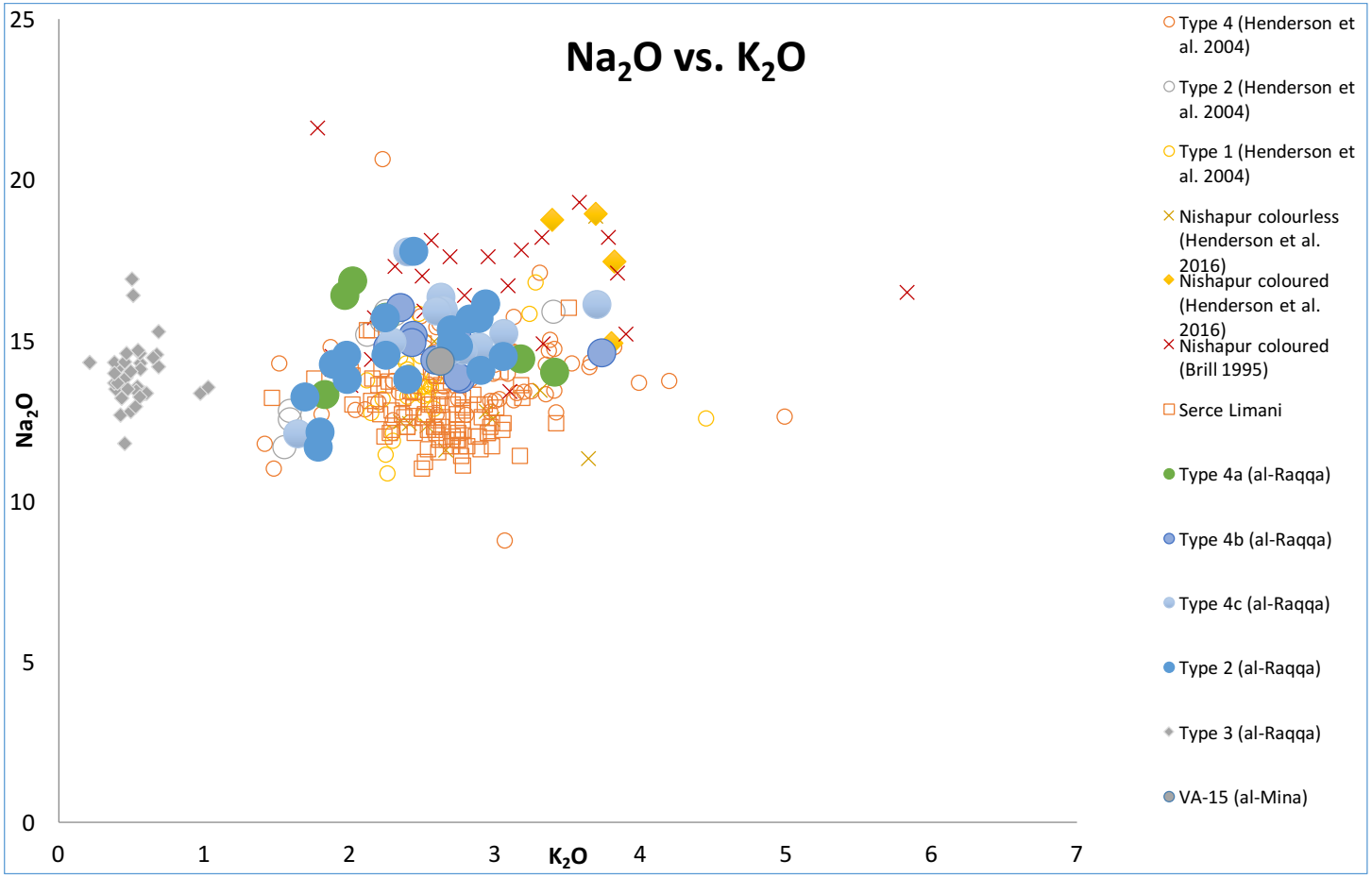


Figure 8.25: A bi-plot of Na_2O versus K_2O for Types 4a, 4b, 4c, 2, and 3 glasses from late 8th - 9th century AD al-Raqqa and VA-15 from 9th – 10th centuries AD al-Mina. It is displayed according to composition groups and sites.

The levels of CaO in al-Raqqa Type 2 and al-Mina VA-15 are very similar to Henderson *et al.*'s (2004) Type 2 glasses and the Nishapur coloured glasses. And they are significantly lower than the Serce Limani glasses (Figure 8.24). It is likely that plant ashes with low level of CaO were used to produce glasses from al-Raqqa, al-Mina and Nishapur.

But the geological origin of the plant ashes used to produce these glasses could be different. As we have mentioned before, al-Raqqa Type 2 has a positive correlation between Al_2O_3 and CaO, which suggests a third source of calcium and alumina, such as feldspar, was used to increase the level of CaO in the glasses from Type 2.

The difference between Type 2, Nishapur and the Serce Limani glasses can also be observed in the alkali levels (Figure 8.25). The al-Raqqa, al-Mina and Nishapur glasses have higher concentrations of Na_2O than the Serce Limani glasses. But the K_2O levels in these glasses vary. Eight glasses from al-Raqqa Type 2 in this study and all of the glasses from Henderson *et al*.'s (2004) Type 2, and the majority of the Nishapur coloured glasses have lower K_2O levels than the Serce Limani glasses. On the other hand, nine glasses from Type 2 in this study, the al-Mina VA-15 and a glass from Nishapur have similar levels of K_2O as the Serce Limani glasses. These reflect the use of plant ashes with different compositions. The similarity between the al-Raqqa, al-Mina and Nishapur glasses in alkali levels suggest a similar composition of plant ashes and/or species were used to produce these glasses, and they were possibly produced from the same production zone.

Raw glasses of this glass group were found previously, which suggests this glass group was probably made in al-Raqqa or imported from somewhere else (Henderson *et al.* 2004, 452, Figure 2).

8.4.4 Evidence of recycling/mixing in plant ash glass – Zeyrek Camii Group 2:

This glass group is rather different from the other two glass groups from Zeyrek Camii. It is similar to the 'vessel glasses' from Zeyrek Camii (Figures 8.14 – 8.16). Interestingly, the majority of the glasses in Zeyrek Camii Group 2 displays a strong positive correlation between Al_2O_3, MgO and CaO. The same is observed in Brill's

'vessel glasses' from Zeyrek Camii (Brill 2005, 228-229). But the correlation between K_2O and MgO in these two glass groups is rather weak. It is possible that the source of CaO came from dolomite or dolomite sandstone rather than plant ashes (Henderson 2000, 29). Their K_2O and MgO levels are relatively low compared to other plant ash glasses from Zeyrek Camii (Figures 8.15 and 8.16).

When we compare these two groups with contemporary glasses from the Byzantine Empire, it is clear that they are associated with the mixed natron-plant ash based glasses rather than the plant ash based glasses. Mixed natron-plant ash glasses are found in the west such as at the Torcello basilica in Italy, Nufaru in Romania, Daphni and Hosios Loukas in Greece (Andreescu-Treadgold and Henderson 2006; Arletti *et al.* 2010; Bugoi *et al.* 2013). The typical value of K_2O in mixed natron-plant ash glasses is usually at below 2.5% (Andreescu-Treadgold and Henderson 2006, 126; Bugoi *et al.* 2013, 2887). All but one glass in Zeyrek Camii Group 2 have K_2O between 1.28% and 2.34%. ZC-06 has high concentrations of MgO (2.52%) and K_2O (4.41%) which suggests plant ash was used to produce this piece of glass (Figures 8.15 and 8.16). Another characteristic of mixed-natron plant ash glasses is their high concentrations of Al_2O_3 and Fe_2O_3, which suggests impure sand or mixed silica sources were used. High concentrations of Al_2O_3 (1.81% - 3.13%) and Fe_2O_3 (0.94% - 2.08%) are found in Zeyrek Camii Group 2 (Figure 8.14) (Adreescu-Treadgold and Henderson 2006, 129; Bugoi *et al.* 2013, 2887).

8.4.5 Evidence of recycling/mixing in plant ash glass – Tbilisi Geo-03 and 05:

Tbilisi Geo-03 and 05 are similar to the mixed-natron plant ash glasses from Zeyrek Camii, Nufaru, Serce Limani and Hosios Loukas. The levels of CaO, Al_2O_3, Na_2O and K_2O in this group are similar to the glasses mentioned above (Figures 8.14 – 8.16). But there are some differences. Tbilisi Geo-03 and 05 have a higher concentration of MgO (4.02% and 3.11%), SO_3 (0.52% and 1.46%) and P_2O_5 (0.42% and 0.85%) than the mixed-natron plant ash glasses. This may suggest locally produced plant ash glasses were mixed with natron glasses. The similarity between the Tbilisi glasses and the mixed-natron plant ash glasses from the Levantine and Byzantine regions suggests they shared a similar glass production technology.

8.5 Glass compositions and colours:

8.5.1 Natron glass:

The majority of the natron glass groups in this study, especially glass groups related to Levantine I and II types, are aqua in colour (n=31). The majority of the raw glasses from Apollonia, Dor and Bet Eli'ezer and glass remains from Ramla are also coloured aqua (Freestone *et al*. 2000, 67; Tal *et al*. 2008, 84-85). This is due to the presence of iron as ferrous (Fe^{2+}) and ferric (Fe^{3+}) ions, which ranges from 0.29% to 0.50%. Even a small concentration of iron can impart a green colour to the glasses. The higher Fe_2O_3 level in RAQ-33 (0.94%) and VA-19 (0.90%) could suggest sands with a higher level of iron-bearing minerals were used to produce the glass.

A small number of natron glasses (n=5) from al-Raqqa Type 3 are nearly colourless. They are not truly colourless but are lightly tinted, greenish and yellowish. A small number of these formed part of Henderson *et al.* (2004)'s study of al-Raqqa glass (Henderson *et al.* 2004, 460). Only traces of MnO and Sb_2O_5 were found in these glasses, which are less than 0.03%. This suggests no decolourisers were intentionally added to the glasses to make them colourless.

The deep brown colour found in VA-27 is unusual and is largely the result of a high concentration of Fe_2O_3 (0.91%) in the form of ferric ion (Fe^{3+}).

As regards the blue glass (Geo-09) from Tbilisi, the blue colour in this sample was the result of the high concentration of CoO (0.09%) in the glass.

8.5.2 Plant ash glass:

The colours of the plant ash glasses are more diverse than the natron glasses. The predominant colours of the low MgO-high Al_2O_3 glasses in this study are various shades of green that include olive green, dark green, emerald green and turquoise. Indeed, many of the coloured glasses from Nishapur in this group are also coloured in various shades of green including dark green, green,yellow-green or bluish-green (Brill 1995, 220-227). Many of these glasses have high concentrations of Fe_2O_3 and are

positively correlated with Al_2O_3 (Figure 45). It is likely that the iron originated from iron-bearing minerals in the silica source such as sands.

On the other hand, many of the high MgO-low Al_2O_3 glasses in this study are coloured in green, yellow-green, cobalt blue, blue and aqua. In contrast with the Nishapur colourless glasses, only two glasses from this group are colourless.

For al-Raqqa Type 6 and Samarra VA-10 and 11, only three fragments of the glasses are colourless (all from Type 6). On the other hand, two fragments of glasses from Type 6 are blue and aqua along with two tank furnace glasses (VA-10 and 11) from Samarra that are coloured mid-green and aqua.

Curiously, the majority of the glasses from al-Raqqa Types 1a and 1b are colourless. A small number of glasses from al-Raqqa, al-Mina Group 1 and Pemba Island (VA-03 and 04) are highly coloured in blue, aqua, green, deep brown, red and yellow-purple.

The colours of Type 2 from al-Raqqa and al-Mina (VA-15) are quite restricted and specialised. Six of them are coloured in blue, six are dark green and five are colourless.

Chemically, the majority of the green glasses of various shades has high concentrations of Fe_2O_3 (0.31% - 3.45%). It is in the form of ferric iron in the glasses and they were melted in an oxidised state to generate various shades of green (Pollard and Heron 2008, 164; Sanderson and Hutchings 1987, 105).

The colourless glasses in these groups are decolourised by manganese. The evidence suggests MnO was introduced in the glass deliberately (Henderson 1985, 283). The use of manganese oxide in plant ash glasses was documented by a 9th century AD chemist, Jabir Ibn Haiyan, who lived in al-Raqqa when the caliph Harun al-Rashid was present (Henderson *et al*. 2004, 461).

However, there are some differences in the concentrations of MnO between different groups. The colourless glasses from al-Raqqa Type 6 have relatively low concentrations of Fe_2O_3 (0.19% - 0.34%) and MnO (0.28% - 0.41%). It is possible that because of the relatively pure source of silica used to make this glass, glassmakers did not need to

introduce large amounts of MnO in the glasses to counteract the green colour produced by Fe_2O_3.

On the other hand, the colourless glasses of al-Raqqa Types 1a and 1b and al-Mina Group 1 have higher concentrations of Fe_2O_3 (0.58% - 1.11%) and MnO (0.87% - 2.10%) than al-Raqqa Type 6. The same is found in the colourless glasses from al-Raqqa Type 4c which have high concentrations of Fe_2O_3 (1.18% - 1.22%) and MnO (1.07% - 1.43%). The colourless glasses from Type 2 have concentrations of Fe_2O_3 (0.37% - 0.96%) and they have the highest concentrations of MnO (0.93% - 3.21%) out of all glass groups. This suggests that a rather impure source of silica with a higher concentration of iron-bearing minerals were used to make these glasses. Therefore, a higher concentration of MnO was introduced in these glasses.

For the window glasses in Zeyrek Camii Group 1, the elevated levels of MnO (0.55% - 1.16%) in the form of divalent ions caused the glasses to be colourless and lilac. But manganese is also responsible for colourisation. In Zeyrek Camii Group 1, the high concentration of MnO (2.21%) in the purple window glass (ZC-10) was in the form of trivalent ion that coloured the glass to purple (Bamford 1977, 50; Brill 1988, 276; Henderson 1985, 283).

Blue glasses are found in al-Raqqa Type 4b and Type 4c (high MgO-low Al_2O_3 type), Type 2, Type 6, Zeyrek Camii Group 2 and Samarra VA-13 (high MgO-low Al_2O_3 type). Figures 8.26 and 8.27 show that these blue glasses can be divided into two types: (1) blue glasses with high concentration of Fe_2O_3 and elevated levels of CoO, CuO and ZnO; (2) blue glasses with low concentration of Fe_2O_3 and traces of CoO, CuO and ZnO.

It is noted that the blue glass (RAQ-01) from al-Raqqa Type 6, 3 out of 6 blue glasses (RAQ-17, 60 and 74) from al-Raqqa Type 2, Samarra VA-13, 2 out of 3 blue glasses (RAQ-27 and 82) from al-Raqqa Type 4b and 1 out of 2 blue glasses (RAQ-23) from al-Raqqa Type 4c have low Fe_2O_3 (0.43% - 1.09%) and only traces of CoO (<0.05%), CuO (<0.05%) and ZnO (0.06%). It is possible that ferrous iron dominates these blue glasses and they were melted in a reducing furnace conditions to produce the blue colour (Brill 1988, 172; Weyl 1976, 106).

On the other hand, blue glasses RAQ-57 from al-Raqqa Type 4b, RAQ-25 from al-Raqqa Type 4c, RAQ-10, 45 and 52 from al-Raqqa Type 2, and ZC-03 and 07 from Zeyrek Camii Group 2 have high concentrations of Fe_2O_3 (1.57% - 2.71%) and elevated levels of CoO (0.10% - 0.19%), CuO (0.17% - 0.56%) and ZnO (0.08% - 0.65%). The high concentration of CoO in these glasses was the direct result of the blue colour. It is possible that cobalt-rich raw materials were used to colourise these glasses in blue. Cobalt was introduced into the base glass in the form of untreated alum or as a cobalt concentrate which was prepared before it was added to the glass (Henderson *et al*. 2004, 462; Rehren 2001, 484, 486; Tite and Shortland 2003, 294).

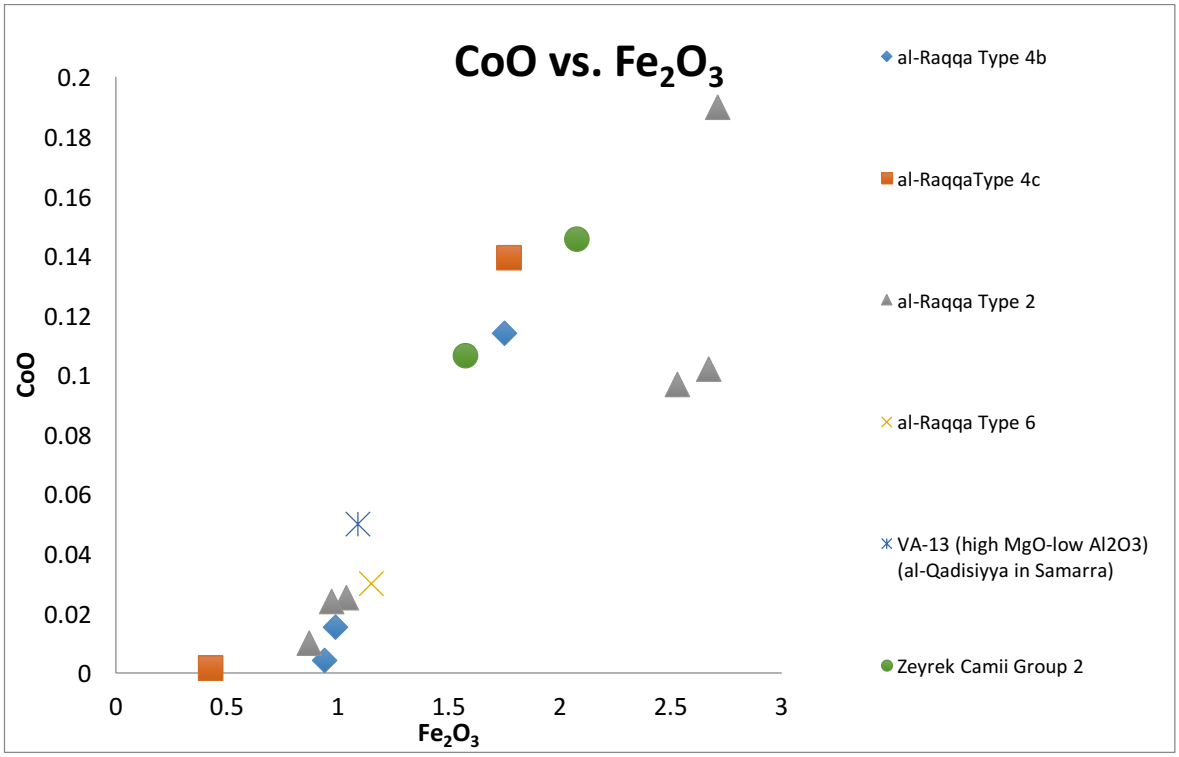


Figure 8.26: A bi-plot of CoO versus Fe_2O_3 for blue glasses from al-Raqqa Types 2, 4b, 4c and 6 from late 8^{th} – 9^{th} centuries AD al-Raqqa, VA-13 from 9^{th} – 10^{th} centuries AD al-Qadisiyya in Samarra and Zeyrek Camii Group 2 from 11^{th} – 12^{th} centuries AD Zeyrek Camii.

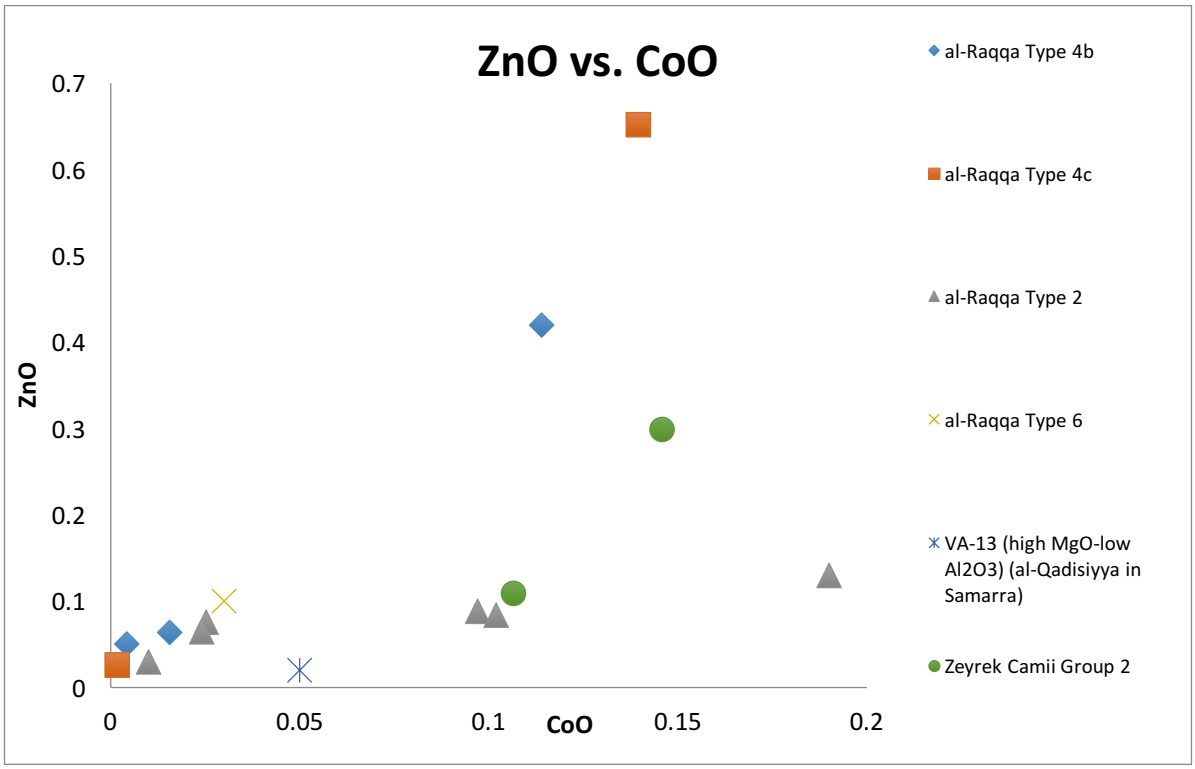


Figure 8.27: A bi-plot of ZnO versus CoO for blue glasses from al-Raqqa Types 2, 4b, 4c and 6 from late 8th – 9th centuries AD al-Raqqa, VA-13 from 9th – 10th centuries AD al-Qadisiyya in Samarra and Zeyrek Camii Group 2 from 11th – 12th centuries AD Zeyrek Camii.

The lustre/enamelled glass (VA-16) from al-Mina Group 1 is coloured deep brown. The deep brown colour may result from the presence of ferric ion (0.29%) in the glass. No elevated level of CuO is found in this piece of glass which suggests CuO was not responsible for the deep brown colour. The high alumina glasses (n=2) from Tbilisi and Pemba Island are coloured green and emerald green.

8.6 Glass compositions and vessel forms:

8.6.1 Natron glass:

All of the al-Raqqa Type 3 glasses in this study are goblets (n=13), bowls (n=7) and bottles (n=10). This suggests that a rather restricted range of glass vessels were produced using the Levantine I glass recipe. The hemispherical goblets (RAQ-64, 72 and 77), cylindrical goblets (RAQ-86 and 87) and a goblet with a small stem (RAQ-13) are all made with Levantine I glass composition. This study also found that Byzantine period bottles such as RAQ-70 and new types of bottles appeared in the Umayyad

period. The cylindrical bottle (RAQ-31) and small/medium bottles with globular or squat body (RAQ 67, 71 and 73) were also produced with Levantine I glass recipe.

On the other hand, decorated vessels such as the lustre-painted bottle (RAQ-04), and two bowl with tonged (VA-19) and scratched (VA-27) decorations belong to al-Raqqa Type 5 (Levantine II) and al-Mina Egypt II respectively. The natron glass from Tbilisi (Foy-2) was a bracelet (Geo-09).

Many lustre-painted glass vessels, such as beakers and bottles, were manufactured with the Levantine II recipe like RAQ-04 from al-Raqqa Type 5. Kato *et al.* (2009) found that all but one lustre-painted beakers belong to Levantine II glass group (Kato *et al.* 2009, 1700). Based on the composition, they have suggested that these lustre-painted beakers were imported to Raya in the south Sinai Peninsula (Kato *et al.* 2009, 1706). Indeed, no natron glasses were produced in Tell Zujaj and only two Levantine II glasses were present on site. It is likely that al-Raqqa Type 5 was imported from Israel. And it is likely that lustre-painted glasses were specifically made using Levantine II composition in Israel.

On the other hand, tonged decorated vessels were found in Egypt, Syria, Israel, Iraq and Iran. We do not have enough information to determine the origin of this decorative technique. The earliest example of tonged decoration was found in Caesarea dated to the Umayyad period (Stratum VIII, before AD 749) and a large group of tonged vessels were found in Bet Shean (Gorin-Rosen 2010, 243; Hadad 2005, 37; Kroger 1995, 95; Pollak 2003, 165). Al-Mina VA-19 has an Egyptian composition (Egypt II) which suggests that this particular vessel was made in an Egyptian workshop and was produced with Egyptian glass recipe. In Raya, tonged decorative glasses were also produced exclusively with Egypt II glass recipe (Group Na2-b) (Kato *et al*. 2009, 1705). These provide strong evidence that Egypt II tonged decorated glass vessels were produced in Egypt and were distributed not only in Egypt, but to northern Syria.

Scratch-decorated natron glasses were thought to have been made at different production sites across the Islamic East, especially Egypt, Syria and Israel in the ‘Abbasid and Fatimid periods (Hadad 2000, 69; Kucharczk 2009, 40). The composition of al-Mina VA-27 and three samples from Raya (all were made with the Egypt II glass

recipe) suggest Egypt was one of the places where scratch-decorated natron glass was produced during the late Umayyad – early ‘Abbasid period. (Kato *et al.* 2009, 1705). The presence of Egypt II scratch-decorated glasses in al-Mina suggests Egyptian scratch-decorated glasses were exported to northern Syria in the late 8^{th} – 9^{th} centuries AD, although in a small quantity.

8.6.2 Plant ash glass:

As regards the low MgO-high Al_2O_3 glass groups, the dominant types of glass vessels in Nishapur, al-Raqqa Type 4a (n=2) and Pemba Island (VA-05) are bottles and flasks. Many of these bottles from Pemba Island and Nishapur are mould-blown. It should be noted that ‘Abbasid period bottles (e.g. RAQ-28 and 58) from al-Raqqa and Nishapur were produced during the late 8^{th} – 10^{th} centuries AD with this composition. But it seems that from the 10^{th} century AD onwards only bracelets were produced with this composition in al-Raqqa (found in 11^{th} century AD Tell Fukhkhar) and Tbilisi in medieval Georgia (Geo-01 and 04).

For the high MgO-low Al_2O_3 glass group, the vessel types are more diverse than the low MgO-high Al_2O_3 glass group. The majority of these glasses are strongly coloured and are closed vessels which include bottles (RAQ-08 and 95), small bottles (RAQ-19) and alchemical vessels (RAQ-95) dated to the ‘Abbasid period. A small number of these are open vessels include goblet and beaker/bowl. A window glass (RAQ-03), bottle (RAQ-28) and a bracelet (RAQ-110) are also coloured.

The beaker/bowl with linear-style decoration (RAQ-89) is of a high MgO-low Al_2O_3 glass type and might have come from Iraq. This confirms that this style was indeed practised in Iraq. The tonged decorations from al-Raqqa (RAQ-88 and 90) and al-Mina (VA-26) might also have come from Iraq according to their compositions, all of which are decorated with circles and lines of dashes.

The majority of the glasses from al-Raqqa Type 6 are colourless and are in the forms of bottles, small bottles (RAQ-18) and lamps (RAQ-22). The composition of the rose water (?) sprinkler (RAQ-40) is interesting. As regards the vessel form, it has a parallel

at Samarra dated to the 9th century AD (Lamm 1928, 19, u.37). The chemical composition suggests this glass might have been imported from Iraq and/or Iran.

Colourless bottles and small bottles are also found in the Raya PA-2 colourless group and at Nishapur. Therefore, it is not impossible that these bottles, along with their contents, were exported to Egypt and northern Syria from Iraq and/or Iran in the late 8th – 9th centuries AD. This suggests that the demand for Iraqi and/or Iranian goods increased in this period.

For al-Raqqa Type 1a, all of the glass forms are dark green bracelets from the 11th century AD Tell Fukhkhar. On the other hand, the majority of 9th – 10th centuries AD plant ash glasses from al-Mina Group 1 and al-Raqqa Type 1b are dominated by beakers/bowls, bottles (include globular bottles) and small bottles. Only a small number of glasses are windows (two from al-Raqqa), bracelet (one from al-Raqqa) and jars (two from al-Raqqa).

As regards decorations, seven out of eight bowls from al-Mina Group 1 have tonged decorations with the stylised birds which appear to be of Syrian origin (Lane 1937, 68, 70). The closest examples which have stylised birds are found on a fragment of a beaker from Fustat and a fragment of a bowl from the Mesopotamian region (Carboni 2001, 285, Cat. 3.54; Scanlon and Pinder-Wilson 2001, 80-81, Pl. 38i). The chemical analysis shows that the tonged decorated glasses from al-Mina were indeed produced with a northern Syrian glass recipe. This suggests they were likely to be produced in northern Syria in the 9th – 10th centuries AD, perhaps in al-Raqqa (?).

The Pemba Island glasses are also decorated with mould-blown twisted ribs and scratched decoration. Both are in the colours of aqua and emerald green. Both of the glasses have a Syrian/Levantine chemical composition. This reinforces the assumption that mould-blown and scratched decorations were also practised in Syira and Israel apart from Egypt, Iraq and Iran. VA-16 from al-Mina is a bottle decorated with lustre/enamel. Its decoration and colour (deep brown) is unusual. There is no parallel found in the Middle East. But its composition suggests it is of northern Syrian origin.

A small number of undecorated beakers/bowls, jars windows and bracelets from al-Raqqa and al-Mina are blue coloured (1 bowl/beaker and 1 jar from al-Raqqa), aqua (1 beaker/bowl from al-Raqqa and 1 bottle from al-Mina), green (2 globular bottles from al-Raqqa), deep brown (1 bottle from al-Mina), red (1 window glass from al-Raqqa) and yellow-purple (1 window glass from al-Raqqa). The lustre/enamelled glass from al-Mina is coloured in deep brown.

All al-Raqqa Type 2 glasses and a glass from al-Mina (VA-15) that are blue colour are bottles (3), bowl (1) and flasks (2). A small number of the Nishapur glasses that are associated with this group are also coloured in blue and they have elevated levels of CoO and CuO (Brill 1995, 220-227). They are in the form of small bottles. On the other hand, three of the colourless glasses are small bottles, one of which is a bowl and another is a bottle. Six of the bracelets are exclusively dark green.

As for the glasses from Zeyrek Camii Group 1, they are cast, painted window glass. Only one sample (ZC-15) is a vessel rim. Two are coloured in lilac (ZC-09) and purple (ZC-10). Four of the window glasses are colourless (ZC-08, 11, 12 and 13). The vessel is also colourless.

The majority of the glasses from Zeyrek Camii Group 2 are in the forms of glass cakes, chunks and vessels. Three glass vessels are a cup (ZC-04), a lamp (ZC-06) and a beaker (ZC-14). Compared with other groups, only two samples are crown glass (ZC-05) and cast window glass (ZC-07). Also, their colours are rather different from those of Zeyrek Camii Groups 1 and 2. Only two samples are colourless (ZC-06 and 14), while the rest are highly coloured that include yellow, blue-green, cobalt blue and green. This corresponds to Brill (2005)'s analysis which shows that the vessel glasses were made with mixed-natron plant ash glass (Brill 2005, 228).

The mixed natron-plant ash glasses from Tbilisi are in the forms of bracelets (Geo-03 and 05). They are coloured in various shades of green. The plant ash glasses from medieval Tbilisi are in the forms of a cup (Geo-02) and a plate (Geo-06).

Curiously, the high alumina glasses from Tbilisi and Pemba Island are in the forms of ring (Geo-08) and mould-blown phial (VA-16). The majority of the high alumina

glasses from south and southeast Asia, west India and Jordan are bracelets and glass beads (Boulogne and Henderson 2009, 63; Dussubieux *et al*. 2008, 803). Only glasses from east Africa such as Kenya are predominantly in the form of glass vessels and glass beads (Dussubieux *et al*. 2010, 1653). The similarities between the Kenyan glasses and Pemba Island in terms of glass composition and vessel types suggest VA-16 comes from Kenya.

8.7 Summary:

The natron glass groups in this study are linked to the groups that have been previously identified by researchers such as Freestone (2005, 197). Al-Raqqa Type 3 is compositionally similar to Levantine I glasses and are mainly consisted of goblets (n=13), bowls (n=7) and bottles (n=10) and are mainly coloued aqua. Al-Raqqa Type 5 is similar to Levantine II glasses and are coloured aqua and consists of a lustre-painted bottle (RAQ-04) and a bottle (RAQ-14). Both Levantine glass groups were produced on the Israeli coast during the 6^{th} – 8^{th} centuries AD. The two glass samples from al-Mina belong to the Egypt II glass groups that were produced in Egypt during the 8^{th} – 9^{th} centuries AD. They consist of a tonged (VA-19) and scratched (VA-27) decorated bowls. The bracelet (Geo-09) from Tbilisi belong to Foy-2 glass group that was produced in Egypt during the 6^{th} – 7^{th} centuries AD.

On the other hand, the plant ash glass groups in the 9^{th} – 10^{th} centuries AD can be divided into four different types: (1) low MgO-high Al_2O_3, (2) high MgO-low Al_2O_3, (3) low Al_2O_3-CaO and (4) low Al_2O_3-MgO-high CaO.

Type 4a from al-Raqqa, VA-08, VA-09 and VA-12 from al-Qadisiyya in Samarra, VA-01 and 02 from Fustat, Geo-01 and 04 from Tbilisi and VA-05 from Pemba Island belong to low MgO-high Al_2O_3 glasses. They are associated with glasses from Iraq (e.g. Ctesiphon) and Iran (e.g. Nishapur). The variations in MgO, CaO, Na_2O, K_2O, SO_3 and Cl suggest they were produced with different raw materials and in different glass production centres in al-Raqqa in Syria, Fustat in Egypt, Samarra in Iraq and Georgia. VA-05 from Pemba Island is likely to be imported from Iraq and/or Iran. They are dominated by bottles and flasks and are coloued in various shades of green.

Al-Raqqa Type 4c, VA-07 from Pemba Island, VA-13 from al-Qadisiyya in Samarra and VA-26 from al-Mina belong to high MgO-low Al_2O_3 glasses. They are likely to be produced in Iraq (e.g. Samarra) and/or Iran (e.g. Nishapur) with high MgO alkali source. These glasses are coloured green, blue and aqua and consist of bottles, small bottles, goblets, beakers and bowls.

Al-Raqqa Type 6 and al-Qadisiyya VA-10 and 11 belong to low Al_2O_3-CaO glass group. The raw glasses from al-Qadisiyya in Samarra suggests this group was probably produced in Samarra in the 9^{th} – 10^{th} centuries AD and imported to al-Raqqa. They are coloured blue, aqua and green and three of them are colourless. They consist of bottles, small bottles and lamps.

Al-Raqqa Types 1a and 1b and al-Mina Group 1 belong to low Al_2O_3-MgO-high CaO glass group and they are compositionally different from the glass groups produced in Lebanon (e.g. Tyre) and Israel (e.g. Khirbat al-Minya and Banias) during the 10^{th} – 13^{th} centuries AD with their low CaO and SiO_2. They consist of bracelets bowls and bottles. The al-Mina glasses are tonged decorated. They majority of al-Raqqa Type 1 are colourless, a small number of this glass type are coloured blue, aqua, green, deep brown, red and yellow-purple.

By the 11^{th} – 12^{th} centuries AD, plant ash glasses also appeared in the Byzantine Empire and Georgia. Zeyrek Camii Group 1 is compositionally similar to glasses from Tyre, Damascus and Banias which suggests they were possibly produced in these regions. They are coloured purple and lilac and colourless. They are mostly window glass. Geo-02, 06 and 07 from Tbilisi were also compositionally similar to glasses from Tyre and Serce Limani, but the high levels of SO_3 and P_2O_5 suggest they were possibly produced in Georgia using a different alkali source. They are all bracelets.

As regards the high alumina glasses, they are compositionally similar to east African glasses from Kenya and Mtwapa. It is likely they originated from east Africa.

Evidence of recycling and mixing is also found in this study in both the natron (al-Raqqa Type 3) and plant ash glasses (al-Raqqa Types 2 and 4b, al-Mina VA-15. There

is evidence that natron glass was mixed with plant ash glasses Zeyrek Camii Group 2 and Tbilisi Geo-03 and 05.

Chapter 9: Discussion – the social and economic aspects of glass in the late 8th – 14th centuries AD

9.1 Introduction:

In this chapter, the social and economic aspects of late 8th – 14th century AD glasses will be discussed. Several questions will be addressed. In terms of natron glass, why did the trade of natron glasses became increasingly localised in the 7th – 9th centuries AD? For plant ash glasses in the late 8th – 10th centuries AD, we will consider why plant ash glasses was adopted in Syria, Israel, Lebanon and Egypt during this period. We will also look at the organisation of the Islamic glass industry in the 9th – 10th centuries AD and the Byzantine glass industry in the 11th – 12th centuries AD. And finally, we shall look at how plant ash glasses were spread to the Byzantine Empire in the 11th – 12th centuries AD and why the Byzantines adopted the use of plant ash glasses. And we will also discuss the economic aspects of medieval Georgian glass and east African glass in Pemba Island.

9.2 Economy of natron glass:

9.2.1 Natron glass in the 7th – 9th centuries AD:

Natron glass was produced and distributed in Israel and Egypt during the 7th – 9th centuries AD. Chemical analyses of natron glasses show that Levantine I glasses were mainly distributed within 100 km radius of the primary glass production centres during the 6th – 7th centuries AD (Freestone *et al*. 2000, 68, Fig. 2). That is from Apollonia and Dor to consumer sites such as Caesarea and Ramla. But it is known that Levantine I glasses continued to be exported to places outside the Levantine region, such as Pergamon and Sardis in Turkey, Butrint in Albania, Maroni Petrea in Cyprus, Aquilia in Italy and Britain (Brill 1999b, 106-107, Table V K; Gallo *et al.* 2014; Rehren *et al.* 2015, 273; Schibille 2011, 2945). But by the 7th and 8th centuries AD, Levantine I glasses ceased to be produced in Israel. The evidence from al-Raqqa suggests Levantine I glasses found there might have been recycled glass from an earlier period.

A new regional glass group called Levantine II appeared and replaced the Levantine I glasses in the 7th – 8th centuries AD. Bet Eli'ezer in Israel was a major production centre of Levantine II in this period. The distribution of Levantine II was very small and mainly localised. This is confirmed in a recent study by Phelps *et al*. (2016) who have analysed early Islamic glasses from Jerusalem, Nahal Shoval, Ramla, Tel Rosh and Ahihud in Israel (Phelps *et al*. 2016, 60-61). It shows that Levantine II glasses were mainly distributed in southern Israel and rarely found in northern Israel or beyond (Phelps *et al*. 2016, 59). The only evidence that the Levantine II glass type was used to produce glass vessels was found at HaGolan Street, Tel Aviv in Israel where Levantine II glass vessels were found to have been produced in a secondary glassworkshop (Freestone *et al*. 2015, 50-51).

In Egypt, the previously popular HIMT glasses were replaced by two regional glass groups, Egypt I (7th – 8th centuries AD) and II (8th – 9th centuries AD). Egypt I was first identified by Gratuze and Barrandon (1990) in their study of Islamic glass weights (Group 1) dated to the Umayyad and early 'Abbasid period (Gratuze and Barrandon 1990, 159-161). And this group was subsequently identified by Kato *et al.* (2009) in Raya (Group N2-a2) which consists of glass weights, a bottle and a beaker (Freestone *et al.* 2000, 72; Kato *et al.* 2009, 1705). Based on the current evidence, this glass group was mainly distributed in Raya, south Sinai in Egypt only (Gratuze and Barrandon 1990, 162, Figure 9; Kato *et al.* 2009, 1700, Table 1). None of this glass group is found in this study.

Evidence for the manufacture of Egypt II glasses was found in the primary and secondary glass workshop at Tell el Ashmunein in Egypt. This glass type appears to have been produced in Egypt in the 8th – 9th centuries AD. Sixty percent of the 500+ glass assemblage in Raya belong to this group (Kato *et al.* 2009, 1705). Many of these glasses were decorated with tonged, scratched, lustre-stained, black-painted, moulded and stamped decorations (Kato *et al.* 2009, 1705). It is possible that the biggest consumer of this glass group was Egypt.

The question is why did the trading of natron glasses became increasingly localised in the 7th – 9th centuries AD? The limited distribution of Levantine I and II, Egypt I and II

glasses in the 7th – 9th centuries AD largely reflects the localised economies in this period.

9.2.2 The Byzantine and Umayyad economy and the natron glass industry in the Middle East:

From the late 6th century AD and at the turn of the 7th century AD, the Byzantines still controlled territories in Turkey, Syro-Palestine and Egypt. However, the Byzantine economy became increasingly regionalised and localised even before the Arab Conquest (Brubaker and Haldon 2011, 495; Haldon 2012, 103; Loseby 2008, 632-633). Ceramic evidence shows that local coarse and kitchen wares dominated the assemblages in several coastal sites in southern and western Turkey (Haldon 2012, 104). For instance, 40% of the ceramic finds from Limyra were coarse wares and some 82% of these were produced locally. Only 7% of which were imported (Vroom 2004, 297). The industrial-scale production of ceramics for export had diminished and was replaced by locally produced and household-produced wares (Haldon 2012, 107).

Numismatic evidence from the Balkans, Asia Minor and Greece shows a similar pattern which indicates the localisation of trade and exchange within the Empire. For instance, excavations at Sarachane in Constantinople had yielded 80 percent of coins minted in the capital and 20 percent from other mints across the empire for the period AD 491 – 641; however, after AD 641, 100 percent of coins from the site came from the local mint. Excavations at the Athenian Agora also shows that 50 percent of coins dated to the late 5th – mid-7th centuries AD came from the Constantinopolitan mint, but it rose to 95 percent in later periods (Brubaker and Haldon 2011, 485; Haldon 2012, 111).

The ceramic and numismatic evidence suggest trade in this period was a series of less extended and overlapping interregional networks, rather than long distance trade that we saw in the Roman period (Haldon 2012, 103).

For glass, regional glass groups rich in boron and alumina became the dominant type of glass from the 6th century AD onwards in western Turkey including Aphrodisias, Sardis and Pergamon (Brill 1968; Dussubieux *et al*. 2010, 1649; Rehren *et al*. 2015, 276-277). Indeed, recent research has suggested that hot springs in western Asia Minor,

Afyon-Gazligol and Urganli, could have been exploited for an alkali mineral to produce mineral high alumina glasses in Pergamon or its surrounding region (Tite *et al.* 2016, 63-64). No such glass groups were found outside this region except for Constantinople in the 11th – 12th centuries AD.

Import of glass, especially Levantine I glasses, became increasingly rare in places such as Pergamon, Butrint, and Aquileia after the 6th century AD (Conte *et al.* 2014, 9; Gallo *et al.* 2014, 13; Rehren *et al.* 2015, 277). It is possible that trading contacts between Byzantine glassworkers and Levantine glassmakers decreased during this period.

The Arab Conquest in the mid-7th century AD further localised the economy. Maritime trade routes to the east were disrupted by the Islamic conquest. Alternative routes, such as the northern route to the east via the western coast of the Black Sea across southern Russia and the Caspian route eastwards, or by sea from Constantinople to Cherson or Trebizond onto the eastern route, were developed (Brubaker and Haldon 2011, 513-514). These alternative routes could be time-consuming and more expensive than maritime trade routes via the Mediterranean Sea.

The Byzantine monetary economy further contracted due to the loss of revenue and resources from rich provinces such as Egypt and subsidies paid to foreign rulers. The state had to find ways to reduce expenditure including the reduction in emissions of gold and the curtailment of bronze coinage. This affected the liquidity of the social elite and their spending of bronze coinage in commercial activity (Brubaker and Haldon 2011, 473, 599).

Consequently, demand for luxury items by the social elites (who now had less income and had to rely on the state for salaries) decreased and this applies to glasswares (which were considered luxury items) (Antonaras 2010, 384). This is reflected in the number of of glasswares found in excavations. For instance, demand for glass in metropolitan cities like Constantinople decreased substantially after the 7th century AD. The number of glass finds dated to the 8th century AD in the Sarachane excavations in Constantinople was sparse. It is not certain whether a glassworkshop existed in Constantinople after the 7th century AD (Hayes 1992, 401). In Sardis, excavations show that the secondary glassworkshop(s) ceased to operate after the Arab Conquest. No

glasses were dated between the 8th and 10th centuries AD. It was not until the late 10th century AD that a glassworkshop began to operate again and glasses only appeared in the forms of bracelets and window glass (von Saldern 1980, 98). In Amorium, no 8th – 9th century AD glasses were found (Gill 2002). It is likely that import of raw glasses from Israel and Egypt had decreased substantially in this period due to the falling demand for glass.

The localised economy, disrupted maritime trade networks, curtailment of bronze coinage and the falling demand for glass in the Byzantine Empire were likely to have a negative effect on the Levantine I glass producers in the east. By the end of the 7th century AD, Levantine I glass largely disappeared outside the Middle East. Some, if not all, Levantine I production workshops, such as Apollonia and Dor, ceased to operate by the end of the 7th century AD (Tal *et al.* 2004, 58). The paucity of Levantine I glass production outside Israel suggests the demand for glass had decreased substantially and its distribution pattern had become increasingly localised in Syria-Palestine, especially in inland regions by the end of the 7th century AD (Phelps *et al*. 2016, 65). Glassworkers recycled old natron glasses rather than importing fresh raw glass for consumption. The continued evidence of Levantine I glasses in al-Raqqa only suggests that glassmakers in the city were reusing old Levantine I glasses for local consumption. In Rome, the majority of the 8th century AD glasses from Crypta Balbi were recycled glasses; at San Vincenzo in Molise glassworkers recycled 1st – 3rd centuries AD mosaic tesserae to produce glass (Mirti *et al*. 2001, 499; Schibille and Freestone 2013, 8). Not only did Levantine I glasses become increasingly localised, but HIMT glasses in Egypt, which previously enjoyed a wide distribution pattern, had also disappeared in this period.

The establishment of the Umayyad Caliphate did not help to re-establish trading contact between glassworkers and glassmakers in the east and west. It appears that new glass groups had replaced the old 'internationalised' glass groups and had quickly adopted the model of local distribution. And this is also linked to the economy of the Umayyad Caliphate.

Although the Umayyads did not interrupt the economy in Syria, Israel and Egypt, the Umayyad's political, fiscal and exchange systems were highly localized (Wickham 2004, 167). The centralisation of the Roman fiscal system and exchange network in the

previous centuries largely disappeared. Although Egypt, Syria and Israel were under the same caliphate, their fiscal systems were largely independent from each other. There was little exchange and commerce between the two regions (Wickham 2004, 167; 2005, 778-779).

This is because the Umayyads sought to rule the caliphate with Syria as its centre without relying economically, culturally and militarily on Iraq or Egypt (Cobb 2010, 226). The authority of the Marwanid dynasty (AD 661 – 750) dominated in the core region of Syria. But it devolved power and taxation to provinces outside Syria. Thus, the Marwanids had little authority in the provinces and their economies, such as Iraq, that were away from Syria (Cobb 2010, 244; Loseby 2008, 635).

Syria, Lebanon and Israel it continued to prosper under the Umayyad Caliphate (Morony 2004, 175). The region became the core economic and military region in AD 661 when the Caliph Mu'awiyah established the capital in Damascus (Walmsley 2000, 269). Ceramic evidence suggests production and exchange were highly localised in the region during the Umayyad period, focusing on small groups of city territories such as Jerusalem, the Decapolis, 'Aqaba and its hinterland (Wickham 2005, 775-776).

The Egyptian economy was also localised even before the Arab Conquest, due to the fertility of its land, easy communication and transport system of the Nile River and its own elaborate fiscal system (Wickham 2005, 767-768).

The same is observed in the glass industry during the Umayyad period. A new, localised Levantine glass group called Levantine II appeared in the Middle East in the 7^{th} – 8^{th} centuries AD. Current evidence suggests it was mainly traded in southern Israel (Phelps *et al*. 2016, 59). The Egyptian glass types, Egypt I and II, were also largely produced and distributed in Egypt. The localised economy in the Middle East in the 7^{th} – 9^{th} centuries AD had dictated the distribution pattern of Levantine II, Egypt I and II glasses, which had become increasingly localised. Glass of specific compositional groups were mainly found to have been distributed and consumed locally, not internationally. This shows that there is a link between the economic context and the production, trade and distribution of glasses.

But all of this does not mean trade between regions stopped completely during the 7th – 9th centuries AD. It is likely that it continued but on a smaller scale than the previous centuries and varied between regions (Morony 2004, 179).

From the natron glasses analysed in this study, there is evidence that a very small number of Levantine II glasses (al-Raqqa Type 5) were imported from Israel to al-Raqqa during the late 8th and 9th centuries AD. RAQ-04 is a lustre-painted bottle and RAQ-14 is an undecorated bottle. Three fragments of glass from the 8th – 9th centuries AD Bijan Island in Iraq also belong to the Levantine II glass group. These suggest there was limited glass trading contact between Israel, northern Syria and Iraq in the 8th – 9th centuries AD (Daszkiewicz and Raabe 1996, 225).

In contrast, a large group of Levantine II glasses that are lustre-painted, threaded or pinched decorated were also imported to Raya in Egypt during the 8th century AD (Kato *et al.* 2009, 1703-1704). It appears that Israeli products were popular in Egypt during this period. The same is true for the Egyptian products. Egypt II was by far the most abundant glass type found outside Egypt and the biggest consumer of Egypt II outside Egypt was Israel. A large quantity of Egypt II glass vessels was found at Ramla, Ha-Bonim, Ahihud and Ashdod-Yam in Israel and some of them are decorated with tonged, applied, pinched and mould-blown decorations (Phelps *et al.* 2016, 66, 69). A small number of Egypt II glasses were even exported as raw glass to the glassworkshop at HaGolan Street, Tel Aviv in Israel to be worked into glass vessels (Freestone *et al.* 2015, 51).

Only a small quantity of Egyptian glasses was exported to northern Syria. Two pieces of glass from al-Mina belong to Egypt II glass group and were likely imported from Egypt. VA-18 and VA-27 are bowls and are decorated with tonged and scratched decorations respectively. Therefore, the chemical analyses suggest glass trade between regions continued during the Umayyad period, but the scale varied between regions. There was a greater contact between Israel and Egypt than with northern Syria during this period. It is possible that many of these Egyptian and Israeli glasses and their contents are luxury goods and were favoured by well-off consumers in Israel and Egypt.

9.3 Economic and social aspects of plant ash glass (late 8th – 10th centuries AD):

9.3.1 Previous explanations on the rise of the plant ash industry:

The previous chapter shows that by the late 8th and 9th centuries AD, plant ash glass was (re-) introduced in Syria, Lebanon, Israel and Egypt. There are a number of explanations for why plant ashes were adopted as the main alkali source for glass production in Syro-Palestine and Egypt during this period.

Whitehouse (2002) and Shortland *et al.* (2006) have proposed that political events in Egypt played a role in this technological change. Civil wars and foreign invasions in the 7th – 9th centuries AD had ravaged the Wadi Natrun and the trading port of Alexandria. This may have seriously affected the supply of natron to glassmakers outside Egypt and can explain why glassmakers began to search for a new alkali source during this period (Shortland *et al*. 2006, 527-528; Whitehouse 2002, 194). It has been demonstrated that the trade in natron to glass production centres outside Egypt was highly organised and extensive throughout the Roman period (Jackson *et al*. 2016). Therefore, any disruption in the natron trade would be keenly felt by glassmakers that did not have their own natron supply and would eventually lead to the shortage of glass supply.

However, we should bear in mind that other places such as Lake Van in Turkey, Fezzan in Libya, Sebket al Melah in Tunisia and Lake Pikrolimni in Macedonia were also possible sources of natron for glassmaking in antiquity (Devulder and Degryse 2014, 89). If the supply of natron from Egypt was disrupted, glassmakers in the east could have turned to other places for natron to ensure the natron glass industry continued uninterrupted.

Recent boron isotopic study on the sources of natron has shown that the δ^{11} B values of natron from al Barnuj and the Wadi Natrin in Egypt, Fezzan in Libya and Sebket al Melah in Algeria are between +25% and +35% δ^{11} B (Devulder and Degryse 2014, 91). And these δ^{11} B values match the δ^{11} B values of natron glasses dated to the 1st – 8th centuries AD including glasses from 1st – 7th centuries AD Sagalassos, 6th – 8th centuries

AD Bet Eli'ezer, 6th – 7th centuries Apollonia and 8th – 9th centuries AD Tell el-Ashmunein (Devulder and Degryse 2014, 92-94). This shows that at least one or more sources of natron was exploited for glass production between the 1st – 8th centuries AD. And it is possible that there are other possible sources of natron yet to be discovered in the eastern Mediterranean, especially north Africa (Devulder and Degryse 2014, 94).

Another explanation for the decline of the natron glass industry was put forward by Foy and Nenna (2001), who suggest that the increased rainfall in the 8th century AD in the regions of the Sahara desert could have affected the natron supply in the region (Foy and Nenna 2001, 26). It has been demonstrated that the amount of natron produced is dependent on the climate. But so far there is no evidence to suggest that there was a severe climatic change in the Mediterranean during the 8th and 9th centuries AD that could have affected the formation of natron in Egypt (Shortland *et al.* 2006, 527). Therefore, we cannot place too much emphasis on this factor until we have concrete evidence that climatic change occurred in the region during this period.

More recently, Henderson (2013) has proposed that the demise of the natron glass industry and the re-introduction of plant ash were a result of the 'Abbasid caliphate's justification of Islamic rule (Henderson 2013, 266). They used arts and crafts, which formed an innate part of every aspect of life under the 'Abbasids, as mediums to create a sense of belong to Islamic society (Henderson 2013, 266). As the caliphate became more centralised under the Caliphs Harun al-Rashid and al-Ma'mum, this became more pronounced and it is not surprising that this revolution in the glass industry occurred in major political centres such as Baghdad, Samarra and al-Raqqa where the centres of government were located (Henderson 2013, 266).

Although these factors could have contributed to the collapse of the natron glass industry and the rise of the plant ash industry in the east, they seem unsatisfactory. They were mainly focused on the shortages of natron in the Middle East during the 7th – 9th centuries AD. Only Henderson (2013) has considered the political and cultural impacts of Islamic rules on glass production in the Middle East (Henderson 2013, 266).

One factor has been overlooked by archaeologist and archaeological scientists. It is the economic integration in the east under the 'Abbasid rule. This did not only increase

trade between provinces, but it also encouraged technological and cultural interactions between Iraq, Syria, Israel, Lebanon and Egypt, which could lead to the introduction of plant ash glasses and its domination in the region.

9.3.2 'Abbasid economic integration and the (re-) introduction of the plant ash glass in northern Syria:

In the Umayyad period, the fiscal, exchange and administrative systems in Syria and Egypt were localised (discussed at 9.2.2). Under the rule of the 'Abbasid Caliphate, we see an increased level of centralisation in terms of the fiscal system and administration. The 'Abbasids had transferred the centre of power and economy from Umayyad Syria to Iraq and began to integrate the provinces in the caliphate to Iraq (Whitehouse 1988, 68; Wickham 2004, 168). This is reflected in the numismatic evidence: silver coinage mints were shifted to Madinat al-Sham and to Rayy after the founding of Baghdad and the establishment of the heir apparent in Rayy in AD 765 – 767 (Heidemann 2010, 657).

Economically, the centralisation of the state helped to integrate provinces into the Iraqi economy and focused it on Baghdad (Wickham 2004, 168). Income was coming directly from provincial taxation to the military and political centre of Baghdad in Iraq. This was made possible with the presence of the loyal and experienced Khurasan army in every province (Bennison 2009, 28).

The increased tax revenue in Iraq from provinces and the foundation of Baghdad and other cities in the region helped to stimulate the commercial economy in Iraq and it helped to facilitate trade within the Caliphate (Milwright 2010, 159; Walmsley 2000, 343). There is evidence that the trade focus had shifted from the Mediterranean to the Mesopotamian region (Loseby 2008, 635; Wickham 2004, 168). Iraq had become the central focus of the 'Abbasid economy (El-Hibri 2010, 272, 276; Milwright 2010, 47; Wickham 2010, 361-362). The 'Abbasid capital, Baghdad, became a commercial and industrial metropolis (Bennison 2009, 71). Glass was one of the products that were readily available for the population in and outside Baghdad. Historical sources mentioned that the Qadisiyya quarter of Baghdad was a glass production area in this period (Henderson 2013, 267).

The ‘Abbasids were able to join existing Byzantine and Sassanian commercial zones, Iraq/Iran, Syria, Israel, Lebanon and Egypt, and created a new interconnected commercial area in the Middle East (Bennison 2009, 137). Inter-regional trade between Iraq and other provinces flourished under the ‘Abbasid rule. This is especially pronounced between northern Syria and Iraq. Major land and river routes within the Caliphate served as important trade and communication routes. For instance, the Tariq al-Barid (the great ‘Post Road’), which was constructed during the Umayyad period, remained in use and connected towns in northern Syria such as al-Raqqa and Aleppo with Baghdad in Iraq during the ‘Abbasid period (Walmsley 2000, 299-300).

This route was a strategically important route for the whole region and it also determined the local economic activity. Many fairs (held annually either in spring or summer and autumn), such as those in Aleppo, Manbij, al-Raqqa, Rahba and Ana, were located on the Tariq al-Barid and the Euphrates that connected them to Baghdad (Binggeli 2012, 290, 295; Haldon 2010, 21). The presence of fairs along this route reflected the development and importance of the Euphrates network to the economy of Baghdad and northern Syria (Binggeli 2012, 296).

There is no doubt that these commercial and communication networks facilitated the exchange of goods between regions. The presence of different fairs in different cities encouraged competition between fairs and would have attracted merchants and visitors from farther afield (Binggeli 2012, 291).

The economic integration of northern Syria to Iraq did not only increase communication and trade between provinces, it also encouraged the movement of people and goods. As a result, technological innovation, ideas and culture were freely travelled across the Caliphate along these commercial and communication routes. People in northern Syria were increasingly exposed to Iraqi culture, technology and ideas which were heavily promoted and produced in Iraq, especially in Baghdad during the late 8th and 9th centuries AD.

But at the same time, local cultures continued to play an important part in the provinces. This resulted an interaction of cultures between Iraq and Syria and Palestine. This did not only benefit producers and merchants economically, but as Walmsley (2000)

pointed out, it also 'opened their region to new and universally preferred cultural values' (Walmsley 2000, 331).

The increase of trade and commerce, the movement of craftsmen and the mixing of local and foreign cultures had a significant influence on the material culture in northern Syria. The best evidence of this influence is found in al-Raqqa.

Al-Raqqa was founded in AD 771 and briefly became the capital of the Caliphate under Harun al-Rashid. It was located strategically near the Byzantine frontier. From al-Raqqa Harun could launch military operations in Byzantine territories, thus committing himself to the Byzantine *jihad* (Humphreys 2010, 529). Economically, it was located on the Tariq al-Barid that connected it to Baghdad, but at the same time it acted as a crossroads for Iraq and Israel and Lebanon. An inland harbour was built which provided rapid communication with Baghdad and shipping for food, goods and raw materials in and out of the city (Heidemann 2006, 37).

A new industrial zone was constructed between al-Rafika and al-Raqqa to serve everyday pottery, glass and luxury products for the palatial quarter north of the cities of al-Rafika and al-Raqqa (Challis *et al.* 2004, 146; Heidemann 2006, 40; Henderson *et al.* 2005, 133). At Tell Aswad, fourteen ceramic kilns (possibly more as a number of fragmentary structures were found) were built and operated after AD 771. And these kilns produced at least three types of pottery in al-Raqqa dating to the late 8th and 9th centuries AD (Challis *et al.* 2004, 146; Heidemann 2006, 40; Henderson *et al.* 2005, 139; Milwright 2010, 147).

Alkali-glazed wares were produced in the Mesopotamian region since the Parthian and Sassanian periods. After the second half of the 8th century AD various glazed wares were produced in Iraq and eventually spread to Syria and Egypt and around the Islamic world (Taxel 2014, 119, 123).

Chemical analysis of lustre and lead-alkali with stonepaste wares from Tell Aswad shows that Iraqi influence on pottery production technique was found in al-Raqqa. It has been suggested that potters from Basra in Iraq might have overseen the production of these wares (Borregaard 2008, 13). Lustre decoration on glazed pottery was probably

produced in Iraq during the reign of Harun al-Rashid in AD 766 – 809. Stonepaste was also developed and used in Iraq (Mason and Tite 1994, 35; Pradell *et al.* 2008, 1201). Heidemann (2006) has suggested that Harun might have transferred the whole pottery workshops from Iraq to al-Raqqa in order to provide everyday and luxury wares for the inhabitants of the palace quarter (Heidemann 2006, 40; Milwright 2010, 147). So, it is not impossible that Iraqi potters were present in al-Raqqa to supervise the production of glazed pottery for the Caliph and his retinues.

This influence was not restricted to pottery production. Indeed, the late 8th - 9th centuries AD glassworkshop at Tell Zujaj and the glass furnace at Tell Abu Ali produced the earliest evidence of Iraqi influence on glass production in northern Syria.

Glass production in the Mesopotamian region in the early Islamic period was heavily influenced by the Sasanian tradition (Carboni 2001, 15). Low MgO-high Al_2O_3 glasses and high MgO-low Al_2O_3 glasses were possibly made in Iraq and/or Iran since the Sassanian period. This is attested in the 3rd - 7th centuries AD glass finds from Ctesiphon and Veh Ardasir in Iraq. The typical values of MgO in Sassanian glasses are 3.20% - 8.40% and they have various levels of Al_2O_3 between 1.40% and 3% (Brill 1999a, 83; 2005, 80-91, Table 2; Henderson *et al*. 2016, 144; Mirti *et al.* 2008, 438-440). This suggests that plant ashes were used as a flux and impure sand was used as the silica source. Trace element analysis of two 7th century AD glasses from Ctesiphon shows that they have high Cr/La ratios that are similar to the Sassanian plant ash glasses from Veh Ardasir (Henderson *et al*. 2016, 139, 147; Mirti *et al*. 2009, 1064). This indicates low MgO-high Al_2O_3 and high MgO-low Al_2O_3 glasses were made in Iraq and/or Iran.

These two Sassanian glass types were used to produce early Islamic glasses from Iraq/Iran, such as Ctesiphon, Nishapur and al-Qadisiyya in Samarra. It is likely that the 'Abbasid glassmakers in the region had adopted the Sassanian glass production technique, using impure sands as a silica source and plant ashes as an alkali source. At al-Qadisiyya in Samarra, there is evidence that a glass kiln (excavation area N9) existed in the village as early as the Sassanian period. Numerous glassworks dated to the Sassanian – 13th century AD were also found in al-Qadisiyya (Northledge and Kennet 2015, 497-498). Therefore, it is not impossible that glassmakers in Samarra had adopted

Sassanian glass production technique to manufacture glass in the mid-9th century AD when Samarra was founded as a capital.

The study of al-Qadisiyya raw glasses and glass wastes and the data from the Ctesiphon and Nishapur glasses shows that at least three different types of plant ash glasses were produced in Iraq and Iran in the 9th – 10th centuries AD: low MgO-high Al_2O_3, high MgO-low Al_2O_3, and low Al_2O_3-CaO glasses. In the late 8th and early 9th centuries AD, all of these glass types were present in the glass workshop at al-Raqqa.

This study and previous study by Henderson *et al.* (2004) have shown that the low MgO-high Al_2O_3 glasses (Type 4a) from al-Raqqa were manufactured in the glass workshop at Tell Zujaj. This type of glass (low MgO- high Al_2O_3) was also found in al-Qadisiyya in Samarra, Iraq, Ctesiphon in Iraq and Nishapur in Iran. But the differences in CaO, MgO, Na_2O and K_2O between these glass assemblages suggest they were produced in different production zones. Two raw glasses (VA-08 and 12) from al-Qadisiyya in Samarra are similar to the Ctesiphon glasses which suggests they were made using similar raw materials and possibly within the same production zone. However, these two Samarra glasses are compositionally different from al-Raqqa Type 4a. The analysis in the previous chapter suggests that plant ashes from different geological bedrocks, which determine the level of CaO in plant ashes, were used to produce the al-Raqqa, Ctesiphon and Samarra glasses.

Further strontium isotope analysis of some plant ash glasses (raw glass and vessel fragments) from al-Raqqa and plant ashes from the surroundings of the city shows that they have the same range of strontium isotope values (Henderson *et al.* 2005, 670; Henderson *et al.* 2009, 418-419). This strongly suggests local raw materials were used to produce low MgO-high Al_2O_3 glasses in al-Raqqa and Samarra. But the similarity between the al-Raqqa and Samarra glasses further supports the idea that al-Raqqa glassmakers were influenced by Iraqi glassmaking technology and attempted to imitate Iraqi glass by using similar raw materials.

This study shows not only that the al-Raqqa low MgO-high Al_2O_3 glass relates compositionally to the Iraqi and Iranian glass, but that they were also very similar in terms of glass colours and vessel forms. As the author has mentioned in the previous

chapter, various shades of green including olive green, dark green, emerald green and turquoise were found in the al-Raqqa, Samarra and Nishapur glass assemblages. And this glass type was used specifically to make bottles and flasks. Many of which are present in the al-Raqqa and Nishapur assemblages.

Based on this evidence, it is likely that the production of low MgO-high Al_2O_3 glasses in al-Raqqa was influenced by glassmakers in Iraq and/or Iran. Glassmakers in al-Raqqa began to produce this type of glass using local raw materials in an attempt to imitate the Iraqi product. It is not impossible that glassmakers from Iraq were present in al-Raqqa to oversee the production of these glasses, given that potters from Basra might also have been present in al-Raqqa to supervise the production of glazed pottery. Perhaps these Iraqi glassmakers came from Basra as well. Historical sources indicate that craftsmen from Basra were highly regarded by the 'Abbasid caliphs because when Samarra was founded in AD 836, glassmakers and glassworkers from Basra were recruited to work in the city (Northledge 2005, 236).

Some may argue that the glasses from Samarra with low MgO-high Al_2O_3 composition are dated to a later period in the 9^{th} – 10^{th} centuries AD, making it possible that this technology originated in northern Syria (al-Raqqa) and was subsequently exported to Samarra and as far as Nishapur. However, this is not possible because chemical analysis of Sassanian glasses from Iraq has shown that low MgO-high Al_2O_3 glasses originated from Iraq and/or Iran as early as the Sassanian period (Brill 2005, 80-91, Table 2; Henderson *et al*. 2016, 139, 147; Mirti *et al*. 2009, 1064). Historical sources mention that glassmakers and glassworkers from Basra (who had probably produced similar types of glasses in Basra) were recruited by the caliph al-Mu'tasim to work in Samarra when he founded the city in AD 836 (Northledge 2005, 236). There is no mention that glassmakers and glassworkers from al-Raqqa were recruited to work in Samarra. Moreover, the presence of a Sassanian glass kiln and glassworks dated to the Sassanian-13^{th} century AD in Samarra further proves that glassmaking in Samarra were influenced by Iraqi and Iranian glass production technique during the 'Abbasid period, with the Iraqi glassmakers from Basra and local glassmakers and glassworkers from al-Qadisiyya overseeing the glass production in the city.

Despite al-Raqqa glassmakers' ability to produce Iraqi/Iranian-influenced glasses, glasses from the east continued to be imported to al-Raqqa. Its strategic position on the Euphrates ensured the city continued to receive fresh glasses from Iraq and Iran. The high MgO-low Al_2O_3 glasses (Type 4c) from al-Raqqa, and a small group of low Al_2O_3-CaO glass (al-Raqqa Type 6) appear to have come from Iraq and/or Iran. No raw glasses with these two compositions were found in al-Raqqa. The precise origin of the high MgO-low Al_2O_3 glass type is unclear. The analysis of Sassanian glasses from Veh Ardašir in Iraq have similar calcium, magnesium and alkali sources as these two types of glasses from Nishapur in Iran and Samarra in Iraq. Given Samarra was a major glass production centre in the 9^{th} – 10^{th} centuries AD (Henderson *et al*. 2016, 142), it is very likely that high MgO-low Al_2O_3 and low Al_2O_3-CaO glasses originated in Iraq, and Samarra was one of the glasswork production centres to have produced these two compositional groups.

The glass vessels forms from these two compositional groups in al-Raqqa are also very similar to those found in Nishapur and Samarra, which further supports the theory that high MgO-low Al_2O_3 and low Al_2O_3-CaO glasses were imported from Iraq/Iran. Closed vessels such as bottles and small bottles and open vessels such as beaker/bowl were the dominant types of vessel with these compositions. They are mainly colourless but various shades of green and blue colours are also present. They are mainly decorated with cut, tonged, stamped and threaded decorations. Cut decoration practised in the Mesopotamian region since the Sassanian period and continued to be practised in the region in the early Islamic period. Evidence of this is found in Nishapur and Samarra (Carboni 2001, 76-79; Henderson *et al*. 2016, 136; Kroger 1995, 96-99; Whitehouse 2010, 14). A linear- styled decorated beaker/bowl (RAQ-89) and tonged decorated beakers/bowls (RAQ-88 and 90, VA-26) from al-Raqqa and al-Mina are thought to have come from Iraq based on the decorative styles and chemical compositions. Although a different glass cutting tradition was present in Egypt, many cut vessels from Iraq and/or Iran continued to be imported to Egypt such as Raya and Fustat (Brill 1999b, 168-170; Henderson *et al*. 2016, 142; Kato *et al.* 2010, 1392).

A possible reason why this type of glass was not produced in al-Raqqa is due to the lack of plant ashes with high MgO up to 8% or more in northern Syria. Chemical analysis of ashed plants in Iraq and Iran shows that they have higher concentrations of

MgO (8% - 13.8%) than ashed plants from *Salsola* and *Suaeda* plant ashes from Syria, which have MgO up to 4% (Barkoudah and Henderson 2006, 306-307; Tite *et al.* 2006, 1287). None of these would have provided high levels of MgO in the glasses after plant ashes were ashed and treated.

Plant ashes with high MgO are likely to be grown in the magnesium-rich alluvium of the Euphrates and Tigris Rivers, which might have been more readily available in Iraq and/or Iran than in Syria and were likely used to produce high MgO-low Al_2O_3 and low Al_2O_3-CaO glasses (Kato *et al.* 2010, 1392). It is possible that the lack of high MgO plant ashes in Syria had constrained glassmakers' ability to produce high MgO-low Al_2O_3 glasses.

While it is certain that Iraqi technology and culture had a great influence on the production and consumption of glass and ceramics in al-Raqqa, we should not assume that local/regional traditions disappeared and ceased to contribute to the local economy and society.

For instance, the production of high lead tin-opacified glazes was influenced by the Mediterranean (perhaps the Levantine) potters, not Iraqi potters (Borregaard 2008, 14). The presence of Levantine I glasses suggests these natron glasses might have been made by glassmakers from Israel. Specific vessel types, such as Byzantine goblets, were made with natron glass. It is possible that these glassmakers either travelled from Israel through the coastal road or Damascus, or they were local inhabitants in Syria.

Moreover, there is evidence that technological exchange occurred between Levantine glassmakers and Iraqi glassmakers. The use of sands from the Israeli coast to increase CaO in al-Raqqa Type 4 glasses could be the result of Levantine glassmakers sharing their knowledge on local raw materials with Iraqi glassmakers in the production of plant ash glasses. The exchange of technology and ideas occurred when Syria, Israel and Lebanon were integrated with the Iraqi economy, which facilitated the movement of people and ideas between regions through the new trade networks.

The presence of Iraqi styles of glasses and ceramics is also a sign that consumer taste had changed in northern Syria. As Walmsley (2000) had pointed out, such a shift from

local tradition to new exotic styles in the region indicates 'a ready acceptance of new cultural attitudes from outside Bilad al-Sham, and the shift of the political centre from the region to Iraq was obvious to the inhabitants' (Walmsley 2000, 330-331). The demand for plant ash glasses had increased substantially. It is estimated that about 68% of the analysed al-Raqqa glasses were made with plant ashes in the late 8^{th} – 9^{th} centuries AD.

The interaction between local and foreign glassmakers, and the changing consumer taste offered new economic opportunity to glassmakers to revive the glass industry in Israel and Syria. This might have encouraged glassmakers to develop new types of glass. There is evidence from al-Raqqa that local glassmakers were experimenting with new raw materials to produce a new type of plant ash glass that is different from the Iraqi ones. Glassmakers in al-Raqqa might have been trying to balance the amount of silica and alkali sources against each other in varied proportions. This is reflected in the mixed/recycled glasses (Type 4b) from al-Raqqa Type 4 which were the result of mixing various proportions of raw glasses containing the maximum and minimum contents of silica and alkali sources (Henderson 2013, 284; Henderson *et al.* 2004, 456-457). The final product of this possible experiment is al-Raqqa Type 1 which is relatively more homogenous than al-Raqqa Type 4.

9.3.3 Plant ash glasses in Egypt, Lebanon and Israel:

At the same time, long-distance trade with Egypt and the Levantine region also intensified during the 9^{th} – 10^{th} centuries AD. Road networks such as the coastal road had linked northern Syria with cities on the Mediterranean coast. This road began from al-Raqqa and it extended westward to Aleppo where it followed the coast down to Atrabulus, Bayrut, Sidon, Tyre, Akka, Qaysariyah, Arsuf, Asqalan and Ghazzah (Walmsley 2000, 301). Its economic importance is reflected in the establishment of fairs in Jerusalem, Asqalan, al-Ramla and al-Urdunn. All of which were located on this route (Binggeli 2012, 294). Arabic sources suggested that these annual fairs were already present in the late antique period and continued to operate in the 'Abbasid period. These fairs focused trade and commerce in the east during this 'Abbasid period rather than the Mediterranean (Binggeli 2012, 294). Another route linking southern inland Greater Syria to Iraq via 'Amman and the Jordan Steppe was first extended by

the Umayyads (Bessard 2013, 395). It is possible that this route continued to be used and maintained during the ‘Abbasid period.

Markets (*suq*) in cities and towns in Israel, Jordan and Lebanon also helped to facilitate the trading of goods, ideas and technology. Markets were built when town-based commerce emerged in cities and towns in the 7th and 8th century AD and continued into the ‘Abbasid period (Walmsley 2000, 280). For instance, in Palmyra, the main colonnaded street north west of the tetrapylon was built with a long line of shops to produce a market centre in the late 7th and 8th centuries AD and continued to function in the ‘Abbasid period; at Baysan, Jarash and Bayt Ras shops and small manufacturing units occupied a central place within the towns and cities (Walmsley 2000, 276-279). New Islamic cities such as Ramla and Ayla also featured shop-lined streets with tetrapylon-style monuments at the main crossroads (Walmsley 2000, 283). This suggests market towns and cities played a central role in commerce during the 8th – 9th centuries AD. These market towns and cities were connected by extensive road networks which greatly facilitated the trading of goods and ideas and for visitors to interact with people from different cultural backgrounds (Bennison 2009, 86; Walmsley 2000, 304; 2009, 461).

This is reflected in the material evidence. Ceramic evidence in Israel, Jordan and Lebanon show that new types of pottery were produced in the region which are essentially ‘Islamic’. The Islamic Cream Ware is a domestic ware that comprised of jars, jugs, flasks and bowls in a soft, aerated, off-white to pale yellow or very light brown ware. Those that were present in Jordan and Israel showed a clear influence from fine wares of early ‘Abbasid Iraq and Samarra. This shows a break from the previous tradition employed in the area in the previous centuries (Walmsley 2000, 329-330).

The Opaque White-Glazed Ware is another ware that was unique in its decoration and was influenced by the Chinese porcelaneous white wares which were imported to western Asia at around the middle of the 8th century AD. Its glazing technology was influenced by the Parthians and the Sassanians. This type of pottery and its technology spread to Iran and eventually to the Levant and Egypt (Taxel 2014, 126). Also, lustre ware began to be used on pottery in the first half of the 9th century and continued into the late 10th century AD. It first appeared in southern Iraq such as at Basra. This

technique spread from Iraq to Egypt and Syria (Ettinghausen *et al.* 2001, 68-69; Watson 2004, 38). This technique inspired the production of Egyptian lustre wares during the late 10th – late 12th centuries AD (Taxel 2014, 129).

Other types of glazed wares include splashed polychrome, thick turquoise and 'Coptic glazed' wares which were produced in Egypt and introduced to southern Levant (Jordan) during the 8th – 10th centuries AD. They may have inspired local imitations of this ware in the region (Taxel 2014, 124; Walmsley 2000, 330; Wickham 2004, 168).

All the aforementioned wares had replaced the previous Fine Byzantine Ware and Red Painted Ware in the early 9th century. This shows that interactions between Iraq, Egypt Israel, Lebanon and Jordan helped to facilitate trade between these regions in the 'Abbasid period and consumer taste began to change from Byzantine-inspired products to Iraqi-inspired products. Such influence shows that the prosperity of the Levantine region (Israel, Lebanona and Jordan) was not because of trade and contact with the Mediterranean, but it was owed to the east (Wickham 2004, 168; 2010, 360). These new local fine wares also suggested that the less wealthy were able to acquire local-produced luxury items, which were relatively cheaper than those of imported luxury wares, in quantities in an affordable price (Watson 2004, 46). This stimulated the local production of luxury wares and local industries in the regions flourished without solely relying on imports.

The consumer's desire for plant ash glasses also increased substantially. It is possible that plant ash glasses from the east and northern Syria became available in markets and fairs in Israel, Lebanona and Jordan and Egypt. Seeing a new economic opportunity, it is possible that glassmakers in Egypt, Israel and Lebanona began to adopt and experiment with the use of local plant ashes in the early 9th century AD.

There is evidence that Iraqi-influenced glassmaking occurred in Egypt. The analysis of the raw glass and frit from Fustat shows that they belong to the low MgO-high Al_2O_3 glasses. These glasses are compositionally different from the al-Raqqa and Samarra glasses. It is likely that they were produced with a different composition of plant ashes with high concentration of Cl that was possibly grown in Egypt. This is shown in the chemical analysis of plant ashes from Egypt, such as *Salsola* from Wadi Natrun, *Suaeda*

from Barnug and Taposiris Magna and *Anabasis articulata* from Taposiris Magna. All of the Egyptian plant ashes have high level of Cl (13.7% - 34.9%) compared to plant ashes from Syria and the Levant (2.00% - 15%), Iraq (2% - 6.1%) and Iran (9% - 11.40%) (Tite *et al*. 2006, 1286-1287).

Curiously, a group of seven glasses from Fustat (AD 750 – 850) analysed by Brill (1999) also belongs to this group. Therefore, it is possible that the raw glass and the frit from Fustat might have been used to produce glass vessels in Fustat. However, Egyptian low MgO-high Al_2O_3 glass is relatively rare compared with high MgO-low Al_2O_3 glasses, which were found in large quantity in Fustat and Raya (PA-2 colourless glasses), and is likely to have been imported from Iraq and/or Iran (Brill 1999b, 168-170; Kato *et al.* 2010, 1383).

The presence of locally produced low MgO-high Al_2O_3 glasses suggests plant ash glass production in Egypt was probably initially influenced by Iraqi glassmaking technology in the 8^{th} – 9^{th} centuries AD. And it was subsequently refined and a unique composition of Egyptian plant ash glass was produced. Recent trace element analysis of Egyptian plant ash glasses in the 8^{th} – 15^{th} centuries AD shows that Egyptian glass was characterised by low Li/K ratios and high Cs/K ratios (Henderson *et al*. 2016, 139-140). But in the absence of a glass workshop in Fustat, further research on the Fustat glass assemblage on a much larger scale is needed to determine whether the low MgO-high Al_2O_3 glass type was widely produced in Fustat.

In Israel, at Bet She'arim, there is evidence that glassmakers were experimenting with the use of plant ash in the early 9^{th} century AD (Freestone and Gorin-Rosen 1999, 116). The glass slab was considered a failed experiment as the CaO level in the glass slab was far too high (15.9%) due to the combination of lime-rich shell-bearing sand and lime-rich plant ashes. As a result, the glass devitrified, about 35% of calcium silicate crystals formed during the melting process (Freestone and Gorin-Rosen 1999, 112, 115).

The continued influx of plant ash glasses and the increased demand for plant ash glass in these two regions had ensured that, by the 10^{th} century AD, plant ash glasses had dominated the market in Israel, Lebanon and Egypt. The number of local primary glass production centres in Israel and Lebanon (such as Tyre and Banias) that produced plant

ash glasses also increased throughout the 9th – 13th centuries AD to satisfy the rising demand for plant ash glasses. Strontium analysis of glasses from the primary production site of Tyre shows that local raw materials were being exploited for the production of these raw glasses (Henderson *et al.* 2009, 419; Leslie *et al.* 2006, 262). Plant ashes that came from the Cretaceous rocks context shared by Tyre and al-Raqqa were used to produce glasses in Tyre (Henderson 2013, 337; Henderson *et al.* 2009, 419). On the other hand, the glasses from the secondary production site in Banias suggest plants that were grown in the Cenezoic basaltic area in southeast Damascus were used (Henderson 2013, 337-338; Henderson *et al.* 2009, 419).

But one question remains unanswered, did this influence on glassmaking in the Levant come directly from Iraq? The chemical analysis of glass from the Levantine region, such as Khirbat al-Minya, al-Mina, Tyre and Banias suggests that they display similar characteristics as al-Raqqa Type 1 and subtype 1 glasses. As we have discussed in Chapter 8, it is even possible that the glasses from al-Mina might have been produced with similar sources of raw materials as the al-Raqqa glasses.

Current research suggests that the glass workshop at al-Raqqa was the earliest place to have produced this type of glasses (low Al_2O_3-MgO-high CaO) and as far as the author is aware this type of glass was not found in Iraq and/or Iran. It is not impossible that this new plant ash glass type (and its production technique) was spread from al-Raqqa directly, not from Iraq, to Israel and Lebanon thanks to the coastal road leading to the Mediterranean coast and the road from Aleppo to Damascus and onto Egypt (Binggeli 2012, 293). In the case of al-Mina, considering it was a river port that was near to Aleppo and was connected with al-Raqqa, it is not impossible that this new plant ash glass type and its production technique was spread from al-Raqqa to al-Mina via Aleppo.

From the 10th century AD onwards, the primary glass production centres in Israel and Lebanon began to produce a regional composition of plant ash glass that is influenced by the Syrian products. And it is unlikely that the Byzantine reconquest of parts of northern Syria in the late 9th - 10th centuries AD had interrupted the spread of plant ash glasses to Israel and Lebanon.

Moreover, unlike Egypt, current research shows that no low MgO-high Al_2O_3 and high MgO-low Al_2O_3 glasses were found in Israel and Lebanon. The absence of these compositional groups reinforces the idea that the use of plant ash technology in Israel and Lebanon was probably influenced by northern Syrian glassmakers.

But it should be noted that the earliest evidence of plant ash glasses in Israel and Lebanon is from Khirbat al-Minya where 8th century AD glasses of Levantine composition was found (Henderson *et al*. 2016, 136). But without any evidence of glass production in the city or its surrounding region dated to the 8th century AD, and the fact that glassmakers at Bet Shean were still experimenting the use of plant ashes as the alkali source for glass production in the early 9th century AD, it is therefore still possible that the production of plant ash glasses in Israel and Lebanon was influenced by northern Syrian glassmakers and/or plant ash glassmaking technology.

The integration of the economy and the commercial networks within the Caliphate had facilitated significant demands for different types of Iraqi and/or Iranian-inspired glass vessels from the inhabitants in the Levantine region. This in turn had facilitated the growth of plant ash production centres in the Levant in the 9th and 10th centuries AD.

The above discussion shows that economic integration and orientation, aided by the trade networks, facilitated the trade of plant ash glasses. Moreover, it also facilitated the movement of people which had a great impact on the adoption of plant ash as the main alkali flux for glassmaking and the development of the plant ash glass industry in the Middle East.

9.4 Plant ash glass in East Africa:

Apart from the Middle East, Iraqi/Iranian glasses were traded to as far as Pemba Island in East Africa. VA-05 and 07 belong to the low MgO-high Al_2O_3 and high MgO-low Al_2O_3 glasses respectively. These two pieces of glass are mould-blown glasses. VA-05 is decorated with a concentric lozenge and VA-07 is decorated with vertical ribs. They are not uncommon in the Iranian region (Carboni 2001, 221; Kroger 1995, 87). The fact that VA-05 is also compositionally related to the Nishapur coloured glass suggests this piece of glass could have come from Iran. On the other hand, the composition of VA-

07 does not match those from Nishapur but it is similar to the glasses from al-Raqqa and Raya. At this stage it is not possible to suggest the exact origin of this piece of glass, but the evidence points to Iraq as high MgO-low Al_2O_3 glasses were produced in Iraq.

Nonetheless, the presence of Mesopotamian glasses (more specifically Iranian glasses) in East Africa suggests there were commercial contact between Iran and East Africa. There is increasing evidence to suggest that trade between the two regions increased during the 'Abbasid period. Archaeological excavations from Shanga in Kenya and Chibuene in Mozambique have produced Mesopotamian pottery such as jars with barbotine decoration and blue-green glaze and white tin glazed vessels of the Samarra horizon (Whitehouse 1988, 67).

At the same time, high alumina glasses from Kenya in east Africa were also found in Pemba Island (VA-16). This type of glass was circulated between the east coast of Africa and Madagascar and the west coast of India. This suggests south and southeast Asian and east African glasses were traded to Pemba Island from the 9th century AD onwards and continued into the 19th century AD (Dussubieux *et al*. 2008, 817).

9.5 Organisation of glass production in the Islamic East and east Africa:

Using scientific analysis and archaeological evidence, this study shows that the centralised glass production of natron glass was replaced with a regional glass production model as proposed by Henderson *et al*. (2016, 142). It shows that plant ash glasses were produced in different regional production zones in inland regions using local resources. Regional compositions of glass were used to supply local glassworkshops within the same regions as the primary glass production centres. Archaeologically, the presence of Sassanian glass kiln and glassworks (including the raw glasses from al-Qadisiyya) dated to the Sassanian – 13th century AD suggests Samarra was a primary glass production centre in Iraq. Using major and minor elements analysis, it is possible to show that in the late 8th – 9th centuries AD low MgO-high Al_2O_3, high MgO-low Al_2O_3 and low Al_2O_3-CaO glasses were specifically produced in Iraq and/or Iran as early as the Sassanian period and continued to be produced in the 'Abbasid period. And Nishapur was another primary glass production centre in Iran that specialised in the production of these glasses (Henderson *et al*. 2016, 142).

Even when the al-Raqqa and Fustat glassmakers began to produce low MgO-high Al_2O_3 glasses, they used local raw materials to manufacture this type of glass which have a specific chemical fingerprint characteristic of Syrian and Egyptian glasses.

By the 9th – 10th centuries AD, northern Syria (namely al-Raqqa) and the Levantine region (Tyre) had produced a specific type of plant ash glasses such as al-Raqqa Type 1 and subtype 1, and plant ash glasses from Tyre and Banias. They are characterised by low Al_2O_3 (usually below 1.50%) and MgO (up to 4%) and high CaO (up to 12%).

Vessel types also support the regional glass production model. For example, colourless glasses decorated with cut (RAQ-89) and tonged decorations (e.g. RAQ-88 and 90, VA-26) have an Iraqi and/or Iranian chemical compositions. Colourless bottles and small bottles were also typical Iraqi and/or Iranian products with an eastern composition (e.g. glasses from al-Raqqa Type 6). In al-Mina, a large quantity of tonged decorated bowls from al-Mina Group 1 has a northern Syrian composition.

At present it is not possible to say if a glass industry existed in Pemba Island due to the lack of archaeological discovery of glassworkshops and glass in the island. Further study of glasses from east Africa, both chemically and archaeologically, can help us to understand more about the organisation of the glass industry in Pemba Island.

9.6 Plant ash glass in the Byzantine Empire:

From the 10th century AD, there is evidence that plant ash glasses began to appear beyond the Islamic Middle East and be used in the Byzantine Empire. There is ample evidence to suggest that demand for glasses had increased within the Byzantine empire, especially in what is now Turkey.

In Sardis, excavations show that its secondary glass workshop(s) began to produce glass bracelets and windows in the late 10th century AD and continued to operate until the 14th century AD (von Saldern 1980, 98). In Amorium, glasswares began to reappear in the 10th and 11th centuries AD and a large quantity of glasses were recovered in excavations. Some glass types were influenced by Islamic styles (such as the Blue Coil Ware with tonged decorations) (Lightfoot 2005, 178).

The miracle collection of St. Photeine (written in the 11th or 12th century AD) has mentioned that a glassworkshop existed in Constantinople during the middle Byzantine period. It referred to a glassworkshop that caught fire in Constantinople (Mango 2000, 202; Talbot 2005, 141). The text is contemporary with the mounts, if not the carved glass vessels that are now in the Treasury of San Marco (Henderson and Mango, 1995, 346).

However, the scale of operation in these glassworkshops were largely restricted to the production of architectural decorations such as window glass (cast and painted) and mosaics. Many of which were found in Byzantine churches. For instance, in Amorium, fragments of window glasses in the colours of bluish green, green, olive, colourless, yellow and brown are found in the 10th – 11th centuries contexts associated with domestic buildings in the Upper City and the Lower City Church (Gill 2002, 225-228).

In Istanbul, two groups of stained window glass were found in the Pantocrator Church (Zeyrek Camii) and in the Chora Church (Kariye Camii) (Henderson and Mango 1995, 346). The Zeyrek Camii glasses were found with H-shaped lead cames. Their colours are strong blue (24%), colourless (24%), amber-yellow (18%), emerald green (16%), purple-red (13%) and pink (5%) (Megaw 1963, 349). They were painted in opaque enamel paint on its interior surface, and nine life-size human figures banded by geometric motifs were painted (Henderson and Mango 1995, 346; Megaw 1963, 351-360).

A small quantity of stained window glass associated with lead cames was found in Kariye Camii. They are in the colours of blue, purple-red, light and dark green, colourless, pink, red and amber-yellow (Megaw 1963, 365). Life-size human figures were also painted on these glasses. Megaw (1963) has suggested that these two groups of glasses came from two contemporary workshops (Megaw 1963, 365).

Also, personal ornaments such as bracelets, beads and gems were the common types of glasses in this period (von Saldern 1980, 101). But everyday and luxury glass vessels such as lamps, tablewares and containers were also found in a number of sites such as Amorium and Istanbul. For instance, lamps with handles decorated with blue threads, goblet lamps, the Blue Coil Ware, gilded glass and Red Streak Ware (Antonaras 2010,

395, 402; Davidson 1952, 112; Gill 2002, 38, 44-46, 56, 133-134, 136, 140-141, 163; Gorin-Rosen and Winter 2010, 170, 174; Hayes 1992, 405; Lightfoot 1999, 341-342; 2005, 175-178; Olcay 2001, 86). But they were produced in small numbers (Antonaras 2009, 83).

Current research shows that by the 11th century AD plant ash glass was the dominant type of glass in the Middle East (Arletti *et al.* 2010, 808; Freestone 2002, 70-71; Henderson *et al.* 2004, 455; Kato *et al.* 2010, 1382). It shows that plant ash glasses were used as architectural decorations, such as windows (cast and painted) and mosaics in Byzantine churches.

In the monastery of Hosios Loukas in Greece glass tesserae from mosaics were made with plant ashes (Arletti *et al.* 2010, 809). Plant ash-based glass tesserae were also found in the mosaics of the 11th century AD Torcello basilica (Andreescu-Treadgold and Henderson 2006, 121; 2009, 408).

This study shows that cast and painted window glasses from Zeyrek Camii were made with plant ashes glasses. Brill (2005) has also found another type of plant ash glass that contain elevated level of B_2O_3, which was not found in this study (Brill 2005, 217). And in Kariye Camii window glasses were also made with plant ash glasses (Brill 2005, 218-219; Mango and Henderson 1995, 351).

Personal adornments such as glass bracelets were made with plant ashes and became the dominant type of glass in middle Byzantine assemblages in Sardis and Sagalassos in Turkey (Lauwers *et al.* 2010, 145-146).

But at the same time, there is ample evidence to suggest that natron glasses continued to be used in the Byzantine Empire and the Islamic East during this period. Recycling and mixing of natron glass with plant ash glass occurred extensively, especially on everyday glass objects and mosaic tesserae. For instance, the presence of mixed-natron plant ash glass cakes and chunks in Zeyrek Camii suggests recycling and mixing of glasses occurred probably in Constantinople. The analysis of vessel glasses from Zeyrek Camii in this study and Brill (2005) shows that they were made with the mixed-natron plant ash glass recipe.

At Nufaru and Isaccea in Romania many 10th – 13th centuries AD bracelets (all 16 fragments from Nufaru and 62 out of 78 bracelets from Isaccea) were mixed-natron plant ash glasses (Bugoi *et al.* 2013, 2887; 2016, 1029). At the monasteries of Daphni and Hosios Loukas in Greece and the Torcello basilica in Italy a number of glass tesserae belong to the mixed-natron plant ash glass type (Andreescu-Treadgold and Henderson 2006, 126; Arletti *et al*. 2010, 808-809). Only a very small number of window glasses (2 out of 8 cast window glass and crown glass from Zeyrek Camii) was made with this recipe.

There is also evidence that a significant amount of mixed-natron plant ash cullets was produced in the Islamic east and were shipped to the Byzantine territories. About three matric tons of glass cullet, in which two tons were raw glass and two-thirds of the other ton were cullets that were misshapen or cracked before they were broken into pieces for transport, were found in the 11th century AD Serce Limani shipwreck (Bass 1984, 65; van Doorninck Jr. 1990, 58-59; van Doorninck Jr. 2009, 4).

Chemical analysis of the glasses shows that a significant number of the glasses were made of mixed-natron plant ash glasses and they overlapped with the mixed-natron plant ash glasses from Zeyrek Camii (Arletti *et al.* 2010, 808; Brill 2009, 468-469). The origin of the glasses could have come from some glassworkshops along the Fatimid Syrian coast. It has been suggested that the glasses may have been from Tyre as it was a famous glass production centre during this period (Bass 2009b, 503).

9.6.1 The social and religious reasons of why plant ash glass was used in Byzantine churches:

Plant ash glass from the east had been described as ‘high quality glasses’ in the medieval period. Jewish manuscripts (11th – 13th centuries AD) in the Cairo Geniza has explicitly mentioned that the glasses from Tyre and Beirut were of high quality (Goitein 1996, 110). And according to the 12th century AD Jewish traveller Benjamin of Tudela, Jews in Tyre manufactured the famous Tyrian glass. Also in Antioch, Benjamin of Tudela noted that there were about ten glassmakers present in the city in the 12th century AD (Boas 1999, 151). The similarity between the Zeyrek Camii window glasses and

glasses from Lebanon (e.g. Tyre), Israel (e.g. Banias) and Syria (e.g. Damascus) suggests the source of glass for the Zeyrek Camii windows was in these regions.

One question remains unanswered, why most of the recycled glass was used to produce everyday objects (such as glass vessels and bracelets) and tesserae, while 'high quality plant ash glasses' were only used to produce window glasses for churches?

One possible reason is the important role glass windows, like glass lamps and precious metals, played in churches. The window glasses found in Zeyrek Camii were not only made for aesthetic reason, but also reflects the wealth and power of the patrons (the Komnenois) who had commissioned the windows for the church in the 11th - 12th centuries AD (Dell'Acqua 2004, 73).

Indeed, it has been suggested by some scholars that power and legitimacy were reflected in the *opus sectile* floor in the south church of the Zeyrek Camii. Its decorations represented the glory of the Byzantine past, the Komnenian ideology and its association to the house of Constantine. For instance, the bands of fishes and animals at the east and west ends represent the 'earth and ocean' that was a popular theme in early Christian floor mosaics; the wild and mythological creatures of the central floor were symbols of rulership and power; the zodiac represented the Komnenoi's interest in astrology; and the depiction of the life of Samson could be viewed as an antetype for a valiant emperor (Ousterhout 2001, 142, 145-147, 150). Together they sent a powerful message that the Komnenian emperors were the new Samsons and new Constantines, and there is no question about the Komnenoi's legitimacy to the throne (Ousterhout 2001, 150).

Another possible reason is because window glasses played an important role in church lighting which shaped the experience of the worshippers within churches in relation with their understanding of faith and society (Nesbitt 2012, 140; 2013, 207). Light played a crucial role for the worshippers to experience the divine in Byzantine churches (Nesbitt 2012, 145). The sanctuary and nave in Byzantine churches were symbols of Heaven and Earth respectively (Dell'Acqua 2006, 307). And the sanctuary itself was regarded as the sacred space where 'the throne of God and His dwelling place are said to be' (Dell'Acqua 2006, 308). Therefore, patrons and/or architects would use various

devices to illuminate certain parts of churches to enhance the importance of different sacred spaces (Nesbitt 2012, 159). Window glass (especially natural coloured glasses in blue or green) was used to create a mystic atmosphere in sacred spaces in churches (Dell'Acqua 2006, 303).

And stained glass windows also played an important role in creating and enhancing the sacred space in Byzantine churches (Dell'Acqua 2006, 316). Many of them were found in Zeyrek Camii. Some of the painted glasses were analysed in this study and by Brill (2005, 226-228). Dell'Acqua (2006) has suggested that painted and figurative window glasses were used for icon devotion and to highlight the most significant areas of the church. They were designed to compete with or detract from other iconographic mediums (e.g. mosaics and paint) in the church (Nesbitt 2013, 214). This is referred to as the hierarchy of glazing (Dell'Acqua 2006, 306).

Through this practice, the most important area in the church would become the focal point of the church (Nesbitt 2013, 214). Indeed, the coloured painted window glasses analysed in this study belonged to the 'high quality' plant ash-based compositional group, along with two groups of painted window glasses analysed by Brill (2005) (Brill 2005, 226, 228). This shows that a part(s) of Zeyrek Camii was probably the most significant part of the building where high quality painted window glasses were used and to create a mystic atmosphere in this part(s) of the church.

On the other hand, colourless glasses (including crown glass discs in this study) were used to filter natural light which is soft. These glass discs were installed in small roundels that pierced a solid panel. They became popular by the middle Byzantine period (Nesbitt 2012, 150). Unlike stained glass it does not create strong rays or colourful effects on the sacred space or church decorations. These glasses were used in Byzantine churches to enhance wall mosaics (Dell'Acqua 2004, 74; 2006, 316-318). The mosaic tesserae are often angled to catch the light at an obtuse or acute angle so that the light can enhance the colours in the image (Nesbitt 2012, 143). Chemical analyses of tesserae found that PbO was used to enhance the brilliance of the glass. Ten of the mosaic glasses from Dalphni were found to have contained PbO (Arletti *et al.* 2010, 805). The combinations of the position and chemical property of glass mosaics and light were intended to enhance the importance of a specific mosaic (possibly of

icons) to worshippers, transforming the icons to lifelike figures (Dell'Acqua 2006, 310; Nesbitt 2012, 156). At the same time, the reflective light from the mosaics contributed to the brightness of the space, thus enhancing its sacredness (Dell'Acqua 2006, 313).

The majority of the crown glasses from Zeyrek Camii Group 1 were colourless and were produced with plant ash glasses. The use of colourless window glasses in other parts of Zeyrek Camii was to avoid overshadowing the figured windows glasses in the building (Nesbitt 2013, 214). This clearly shows that the hierarchy of glazing played an important role in the use of different types of window glasses.

The importance of window glasses in shaping the spiritual experience of the worshippers in Byzantine churches, and the important status of Zeyrek Camii as a symbol of imperial power ensured that high quality glasses were used to decorate the church. Therefore, it is not impossible that high quality plant ash glasses from Syria, Israel and Lebanon were used to decorate the windows of Zeyrek Camii and lesser quality of glass was used to produce glass vessels and personal adornments.

9.6.2 Trading of plant ash glass in the 11th – 12th centuries AD:

The appearance of plant ash glasses in the Byzantine Empire during the 10th – 12th centuries AD is significant. It is no coincidence that the appearance of plant ash glasses outside the Islamic East is related to the political and economic climates in this period. By the 10th century AD, the 'Abbasid caliphate was weakened by internal conflicts and its government had no real power by this time. The Byzantines took advantage of this and began to launch military campaigns against the Muslims. Throughout the 10th centuries AD, with the encouragement from the great military landowning families of eastern Turkey, the Empire had recovered territories in the east, namely Melitene in AD 934, Martyropolis, Amida, Daras and Edessa in AD 934 – 944 by the general John Kourkouas; under the soldier emperor Nikephoros II Phokas (AD 963 – 969) Cilicia, Taurus, Cyprus and Antioch were reclaimed, and Emperor John Tzimiskes (AD 969 – 976) had taken Aleppo in Syria and Nisibis in Mesopotamia in AD 972. By the reign of Basil II (AD 976 – 1025) all of Turkey, parts of Syria, Mesopotamia and the Caucasus (Armenia and Georgia), southern Italy and the entire Balkan Peninsula

belonged to the Byzantines (Laiou 2002a, 17-18; Laiou and Morrisson 2007, 44; Shepard 2009, 520-526, 534-535; Wickham 2010, 308-309).

At the same time, the Byzantine economy began to improve and its elites, primarily in Constantinople, were increasingly prosperous. These led to an increased in the demand for luxury items, such as silks and glass (relatively expensive for ordinary people) from foreign countries (Jacoby 2000, 31). It is not coincidence that the glassworkshop in Constantinople was recorded operating in the capital during this period. The demand for foreign made glasses (possibly from Syria, Israel and Lebanon) increased as a result of the successful military operation in the Middle East and recovery of the Byzantine economy.

The rise of the Fatimids and the conquest of Egypt, Israel and part of Syria (included Dasmascus) from the Turks had brought the region into contacts with the Byzantines (Kennedy 2004, 322). In the last decade of the 10th century AD, the Fatimids' attempt to conquer the rest of Syria including Aleppo and Homs had resulted open conflict between the Byzantines and the Fatimids. Neither side gained much from this conflict (Lev 1995, 202).

But this conflict did not damage the economies of the two great powers. Instead it had a positive impact on trade between the two states. The Fatimids strived to maintain good relations with the Byzantines throughout the 11th and the beginning of the 12th centuries AD. Embassies were maintained between the two empires (Thomson 2008, 54). For the Byzantines (especially the Constantinopolitan elites), to establish diplomatic relation with the Fatimids would prove beneficial politically and economically: the Fatimids were wealthy and they controlled the southern Mediterranean coast with important trade routes (Thomson 2008, 53). Both sides realised that coastal cities were important for commercial and naval activities. And Syrian coastal cities such as Tripoli, Tyre, Sidon, Ascalon and Gaza became important. Together they controlled the major trading routes in the Mediterranean (Thomson 2008, 54). This continued into the 11th and 12th centuries AD and had greatly increased commercial activities through the sea in the region (Lev 1995, 203; Kennedy 2004, 325-326).

Medieval manuscripts in the Cairo Geniza had shown that in the 11th and 12th centuries AD the Muslims had traded extensively with the Byzantines and the Italians. They were regarded as 'first-rate customers' in Syria, Egypt, Tunisia and Sicily (Goitein 1996, 211). Tunisia and Sicily were important trading hubs in the Mediterranean during the 10th and the early 11th centuries AD. Their ports were regularly used for trading goods between the east and the west (Goitein 1996, 212).

The manuscripts in the Cairo Geniza also mentioned that ports and coastal cities along the Syro-Palestine coast, such as Ascalon, Antioch, Acre, Tyre and Tripoli were important trading centres for short and long distance trades for Syrian and Egyptian traders (Goitein 1996, 212). The manuscripts mentioned that Egypt was trading with ports that were located on southern Asia Minor, namely Tarsus, Seleucia and Antalya (Goitein 1996, 214). The Geniza records show that the Muslims were willing to trade with the Byzantines and the West during this period. There were letters, such as one sent from Alexandria to Fustat in the later years of the 11th century, that mention goods such as spices were to be kept for the Byzantines (Goitein 1996, 44; Jacoby 2000, 44).

Their presence in the local Islamic markets had greatly influenced the prices of goods being sold there. There are letters which described how the demand for spices such as pepper by the Byzantines had pushed up their prices (Goitein 1996, 44-45). Also, we find evidence that goods from the Byzantine Empire were exported to the Islamic lands. These include timber (which was scarce in the Middle East) cheese, corals, silks and pharmaceutical products (Goitein 1996, 46-47; Jacoby 2000, 40; Laiou 2002b, 746).

Trade between the Byzantines and the Fatimids continued into the 12th century AD despite the crusades. A Genizah letter from Old Cairo dated to January 1133 indicates that Byzantine merchants were present in Old Cairo. The Arab chronicler Ibn al-Athir reports that 'Franks' (Westerners) and 'Rum' (Byzantines) were trading in Acre before Saladin captured the city in AD 1187 (Jacoby 2000, 63). And there is evidence from contemporary sources that a residential and commercial facility for Muslim merchants (*mitaton*) existed in Constantinople during this time (Jacoby 2000, 64). This shows the importance of Muslim merchants to the Byzantines.

Archaeology shows that Byzantine glazed wares found their way into the Middle East through land and sea routes. At the same time, Islamic glazed potteries such as glazed bowls were exported from Fatimid Egypt, Syria and North Africa (such as Tunisia) to Italian cities such as Pisa which has the largest group of glazed bowls (600+ items). They were used for architectural decorations (Milwright 2010, 165). The Serce Limani shipwreck and its cargoes show that the scale of trade between the Byzantines and the Fatimids was sophisticated by the 11th century AD. The shipwreck and this study also shows the importance of glass production centres in Syria, Israel and Lebanon to the Byzantine glass industry in supplying fresh raw glass and recycled cullets to the Byzantines. They used plant ash glasses from the east to decorate their churches and to produce everyday glass vessels and personal adornments for consumption.

All this shows that during the 11th and 12th centuries, trade between the east and the west continued to be conducted despite the war between the Byzantines and the Fatimids. The Geniza documents suggest that the Muslims were eager to trade with the Byzantines, and maritime trade had become much more important in both the Byzantine Empire and the Islamic East. Coastal cities in these two regions flourished as a result. So, it is not unreasonable to suggest that the glass industry in Syria, Israel and Lebanon during these two centuries also flourished with the Byzantine Empire as a result of increased trade and demands. Once again, the glassmaking industry in Syria, Israel and Lebanon used maritime trade to export their goods to the west. There is evidence from the Serce Limani shipwreck that maritime transport of raw and recycled glasses between ports, which occurred in large scale throughout the Roman period, was revived in the 11th – 12th centuries AD. And ports regained their importance as hubs in the supply networks for the glass industry in the Byzantine Empire and the Islamic East (Wilson *et al*. 2012, 375-377).

9.7 Organisation of glass production in the Byzantine Empire:

This study shows that the Byzantines had their own regional glass production in western Turkey during this period. Regional high alumina-boron glasses were produced with a high boron mineral from hot springs in Afyon-Gazligol and Urganli in western Turkey (Tite *et al*. 2016, 63-64). As far as the author is aware, this type of glass was largely distributed in town and cities such as Pergamon, Aphrodisias and Sardis in western

Turkey. Another type of plant ash glass with elevated level of boron was also found in Zeyrek Camii in Constantinople. It is notably different from the high alumina-boron glasses from western Turkey. It may represent a regional glass group that utilised high boron plant ashes from regions such as western Turkey and they were exported in limited quantity within the Byzantine Empire (Brill 2005, 217). But at the same time, Byzantine glassmakers also made use of plant ash glasses that were possibly made in Syria, Israel and Lebanon. Many of them were exported to Constantinople and other cities in the Byzantine Empire to be worked into glass vessels.

9.8 Medieval Georgian glass industry:

The presence of Mesopotamian- and Levantine-recipes of glassmaking in Tbilisi in Georgia suggests there was some sort of glass trading contact between Georgia, Iraq/Iran, Israel, Syria, Lebanon and the Byzantine Empire during the 10^{th} – 14^{th} centuries AD. The results from this study show that during the 10^{th} – 14^{th} centuries AD the medieval Georgia glass industry was influenced by early Islamic glass technology in Iraq/Iran, Israel, Syria and Lebanon as well as middle Byzantine glass technology. This is represented by the presence of two glass groups in medieval Tbilisi: (1) low MgO-high Al_2O glasses; (2) mixed natron-plant ash glasses. The former was a glass production technology that originated in Iraq/Iran and the latter was extensively practised in the Byzantine Empire during the 10^{th} – 12^{th} centuries AD. The high levels of SO_3 in the Georgian glasses may suggest local plant ashes were used to produce these glasses. And this may suggest the medieval Georgian glass industry represents a regional glass production centre in south Caucasus with links to the glass production centres in Iraq/Iran, the Levantine region and the Byzantine Empire during this period.

The finding of east African high alumina glass (Geo-08) in Tbilisi suggests long-distance trade between south Caucasus and east Africa existed in the 10^{th} – 14^{th} centuries AD. However, research on medieval Georgian glass and ceramics is lacking at the moment. Therefore, more research is needed to determine the extent of the impact Islamic and middle Byzantine glass technology had on medieval Georgian glass production and glass trade between south Caucasus and east Africa.

9.9: Summary:

This chapter shows the importance of the economy to the glass industry and trading of glass in the Middle East and the Byzantine Empire during the late 8th – 12th centuries AD. The disintegration of a unified economy in the 6th – 8th centuries AD had regionalised the glass industry and reduced the demand for glass outside Israel and Egypt. This caused the demise of the Levantine I and HIMT glasses, which enjoyed international consumption during the Roman period. What replaced these two types of glasses are regional glass groups such as the Levantine II in Israel and Egypt I and II in Egypt. Glass trade between regions was limited in this period, mainly between Israel and Egypt.

This continued well into the late 8th century AD when the 'Abbasids came into power and were able to integrate different regional economies in Syria, Israel, Lebanon and Egypt into the Iraqi economy. Trade and commerce, previously fragmented and dominated by local and regional trades, were able to flourish and spread across the 'Abbasid Caliphate. This was aided by road networks and economic institutions such as markets and fairs.

Plant ash glass, previously a regional glass type in Iraq and Iran, was able to flourish and spread first into northern Syria, and from there to Lebanon, Israel and Egypt via trade and commercial networks and economic institutions, and became the dominant type of glass in the Middle East. Plant ash glasses were prized by the Byzantines in the 11th – 12th centuries AD and were imported in large quantity to the Byzantine heartland, such as Constantinople for the decoration of churches, such as the Komenian Pantokrator Church (Zeyrek Camii) and Chora Church (Kariye Camii) in Istanbul. Again, thanks to the flourishing economy in the Byzantine Empire and the Fatimid Syria, Israel, Lebanon and Egypt and the regained importance of harbours and coastal cities in trade, plant ash glasses were able to spread westward. It was traded as far as Pemba Island in east Africa and Tbilisi in Georgia in the medieval period.

But this does not mean plant ash glass production was not regionalised in the late 8th – 12th centuries AD. Chemical and archaeological evidence show that each region was producing its own unique chemical groups of plant ash glasses. Each region also

specialised in the production of different type of glass vessels, such as cut and facet cut decorations were practised in Iraq and Iran and scratched decorations were practised in Syria, Egypt and Iraq and/Iran and tonged decorations in Egypt and Iraq/Iran and to some extent northern Syria. Despite this, we see a greater exchange of glass and glassmaking technology between regions in the late 8^{th} – 12^{th} centuries because of an integrated and interconnected economy and trading networks.

Chapter 10: Conclusion and further research

In the study of ancient glass, it is typical to study this material using either an art-historical (i.e. typological analysis) approach or scientific (e.g. chemical analysis) approach. Each approach has its own merits. Typological analysis helps us to investigate the evolution of different types of glass vessels in different periods and the social and political effects on glass types evolution. It also helps us to understand the distribution patterns of different glass vessel forms across space and time, and to potentially identify production zones and production centres of different vessel forms. A scientific approach helps us to investigate the technological process of glass production, such as the types of raw materials used to produce glass, the decisions made by glassmakers/glassworkers to use different raw materials (such as environmental constraints and physical properties of the raw materials), possible production zones and the provenance of glass.

However, by combining these two approaches together, along with other disciplines such as environmental studies (e.g. using existing chemical data on plant ashes, natron and sands), pottery and numismatic studies, archaeological evidence of glass production centres (primary and secondary) and historical documents, we can begin to recreate the glass industry in the eastern Mediterranean, south Caucasus and east Africa during the late 8^{th} – 14^{th} centuries AD. This study demonstrates that we can use an interdisciplinary approach to investigate the social, economic and technological aspects of glass production in this period.

At the outset of this study, the author set a series of research questions which the author hopes to answer using typological, archaeological and scientific approaches. We shall discuss this briefly in the following sections.

10.1 Chemical compositions of glasses, raw materials and production zones in the late 8th – 14th centuries AD:

The results of this study have shown that it is possible to identify different compositional groups of glasses in the Middle East, Turkey, south Caucasus and east Africa according to chronology using their major and minor elements. In Syria, Israel and Egypt, natron glasses continued to be used during the late 8th – 10th centuries AD. In al-Raqqa and al-Mina in northern Syria, Levantine I and II and Egypt II glasses continued to be used during this period. The evidence suggests the glassworkshop (Tell Zujaj) at al-Raqqa either imported or reused Levantine I glasses to manufacture Levantine I glass vessels. On the other hand, Levantine II and Egypt II glasses in al-Raqqa and al-Mina are likely to be import from glassworkshops in Israel and Egypt respectively. There is no evidence to suggest the glass workshop at al-Raqqa was manufacturing these types of natron glasses. A piece of glass (Geo-09 bracelet) from Tbilisi in Georgia belongs to the Egyptian Foy-2 glass type. This study shows that Foy-2 glasses were distributed as far north as the south Caucasus. Recent analysis of a group of Byzantine glass weights with Foy-2 composition suggests this glass group is dated to the 5th – 7th centuries AD (Schibille *et al*. 2016, 9). Therefore, it is likely that Geo-09 was made with recycled glass of Foy-2 composition.

At the same time, plant ash glasses began to appear and take hold in the former heartland of natron glass production. Using major and minor elements, three types of plant ash glasses appeared and produced in northern Syria, Egypt, Iraq and Iran dated to the late 8th – 9th centuries AD: (1) low MgO-Al_2O_3 glasses; (2) High MgO-low Al_2O_3 glasses; (3) low Al_2O_3-CaO glasses. These three compositional groups may have originated in Iraq dated as early as the Sassanian period (3rd – 7th centuries AD), based on the date and chemical compositions of glasses from 3rd - 7th century AD Ctesiphon and Veh Ardasir in Iraq.

Based on the current evidence, these compositional groups first appeared in al-Raqqa and Egypt in the late 8th – 9th centuries AD. Environmental studies of plant ashes from al-Raqqa in northern Syria, Wadi Natrun Barnug and Taposiris Magna in Egypt and chemical analysis of glasses from al-Raqqa and Fustat show that low MgO-Al_2O_3 glasses were likely produced using their own local plant ashes. There is evidence from

Georgia that low MgO-high Al_2O_3 glasses continued to be produced in the southern Caucasus in the 10^{th} – 14^{th} centuries AD and are likely to be influenced by northern Syrian and Iranian glassmaking technology. Chemical analysis of the Georgian glasses suggests local plant ash with high SO_3 was used in Georgia. Thus, we are seeing at least four production zones producing variants of low MgO-high Al_2O_3 glasses.

On the other hand, high MgO-low Al_2O_3 glasses and low Al_2O_3-CaO glasses appear to be produced in Iraq (e.g. Ctesiphon and Samarra) and Iran (e.g. Nishapur) and were exported to northern Syria and Egypt during this period. It is likely that the lack of high MgO plant ashes in northern Syria and Egypt constrained the glassmakers' ability to produce high MgO plant ash glasses in these regions.

By the 9^{th} – 10^{th} centuries AD, a 'new' type of plant ash glass appeared in northern Syria Israel and Lebanon and had replaced natron glass in the regions. It is characterised by low Al_2O_3-MgO-high CaO. The earliest example of this type of glass was found in al-Raqqa (al-Raqqa Type 1) in the late 8^{th} – 9^{th} centuries AD. It was then spread to other places in northern Syria such as al-Mina (al-Mina Group 1) and as far as Pemba Island in east Africa (Pemba Island VA-03 and 04). It has been tentatively suggested by the author that the production technique of this type of glass was spread from northern Syria to the Levantine region in the 9^{th} – 10^{th} centuries AD (Chapter 9, section 9.4) via road and trade networks and economic institutions such as markets and fairs in towns and cities. Chemical data from 10^{th} – 11^{th} centuries AD Tyre in Lebanon and 11^{th} – 13^{th} centuries AD Banias in Israel show similarities between Levantine and northern Syrian glasses. Therefore, it is not impossible that this type of glass originated in northern Syria.

By the 11^{th} – 12^{th} centuries AD, plant ash glasses spread from the Middle East to the Byzantine heartland of Turkey. Plant ash glasses, possibly from Tyre, Damascus or Banias, were sought after by the Byzantines and were exported to Istanbul in Turkey for the adornment of the Pantokrator Church (Zeyrek Camii) in the 11^{th} – 12^{th} centuries AD.

At the same time, high alumina glasses, which were widely produced, used and distributed in India, east Africa, Sri Lanka Bangladesh and Thailand, appeared in Tbilisi

in Georgia in the 10th – 13th centuries AD and Pemba Island in east Africa. This is the first time high alumina glasses from east Africa, south and southeast Asia were found in medieval Georgia. The alkali source *reh* was likely to be used to produce Tbilisi Geo-08 (a glass ring), and Pemba Island VA-06 (a phial) was produced with a mixture of high alumina glasses from east Africa (likely from Kenya) and plant ash glasses from the Middle East.

The use of scientific analysis and archaeological evidence also supports the notion that the centralised natron glass production in the Middle East was replaced with a series of regional glass production zones in inland regions using local resources to supply secondary glass production centres with glass in this period.

10.2 Evidence of recycling/mixing of glass during the late 8th – 14th centuries AD:

This practice was documented in historical documents and was widespread during this period. It is also attested in archaeological evidence of shipwrecks such as the 11th century AD Serce Limani (Keller 2004, 66-67; Price 1998, 337-338). Using chemical analysis, we are able to identify glass recycling and mixing in this period and to investigate the economic and technological aspects of glass recycling and mixing. This study has successfully identified recycling and mixing in al-Raqqa glasses, Zeyrek Camii glasses and Tbilisi glasses.

In terms of the al-Raqqa glasses, Type 4b, which is likely the result of glassmakers mixing and recycling cullet from two end members (al-Raqqa Types 4a and 4c) with fresh raw glasses. It is possible that the reason behind this is because glassmakers were experimenting with different raw materials and attempted to control the final chemical compositions of the glass. And we have also found that al-Raqqa Type 2 are likely the result of recycling and mixing glasses from al-Raqqa Type 4b and Type 1.

On the other hand, the chemical results also show that natron continued to be used within the Byzantine Empire and medieval Georgia and natron glass was mixed with plant ash glasses in the 11th – 14th centuries AD. Zeyrek Camii Group 2 and Tbilisi Geo-03 and 05 were identified as mixed natron-plant ash glasses. The glass cakes and chunks from Zeyrek Camii Group 2 may suggest this type of glass was mixed and

produced in the form of raw glasses (possibly in primary glass production centres). They were then exported to secondary glassworkshops to produce glass vessels. Indeed, this practice was widespread in the Byzantine Empire and probably in the Middle East. We have found archaeological evidence that this type of glass was mixed and exported to the Byzantine Empire from the Middle East (e.g. glasses from the Serce Limani shipwreck) and were used on mosaic in churches (e.g. Torcello basilica in Italy, Hosios Loukas and Daphni in Greece) and personal adornment (e.g. bracelets from Nufaru and Isaccea in Romania).

10.3 The relationship between composition and glass vessel types:

Typological analysis has been useful in identifying the vessel forms, their evolution through time and space, their distribution patterns and possible production centres. Combined with chemical analysis, this study has shown that there was a link between composition and glass vessel type and it shows a greater precision in identifying the production centres of specific vessel types. For instance, we are able to identify that Egypt was one of the production centres for tonged decorated vessels in the late 8^{th} – 9^{th} centuries AD when natron glass was still produced and used in the region. And at the same time, tonged decorated glasses were also made in Iraq with high MgO-low Al_2O_3 composition. The typology of the tonged decorated glasses (with stylised birds) from al-Mina and their chemical compositions suggest they were likely made in northern Syria. We can also link linear cut decorated glasses with the high MgO-low Al_2O_3 composition group, which suggest this type of glass was specifically made in Iraq in the late 8^{th} - 9^{th} centuries AD.

The investigation of why the majority of the glass windows from Zeyrek Camii was produced with plant ash glasses while mixed natron-plant ash glasses were used to produce vessels and adornments (e.g. bracelets) is an example of using a multi-disciplinary approach (art historical, architectural and chemical approaches) to study glass and its social and religious meanings. It shows that different compositional groups of plant ash glasses were used to reinforce the political and religious significance of window glasses in Byzantine churches in the 11^{th} – 12^{th} centuries AD.

10.4 The social and economic aspects of natron and plant ash glasses:

Using the scientific (chemical and environmental analyses), archaeological (pottery and numismatic evidence) and historical approaches, we can investigate the social and economic aspects of glass in the late 8^{th} – 14^{th} centuries AD. We are able to show that the glass industry in the Middle East was affected by the state of the economy and political climate in the region in this period. The fragmentation of the natron glass industry in the Middle East into regional production centres was due to the localisation of the Byzantine and Umayyad economies. And the localised economy, disrupted maritime trade networks after the Arab Conquest, curtailment of bronze coinage which led to the falling revenue of the state and elites had caused a fall in the demand of luxury wares such as glass. All these had contributed to the decline of the natron glass industry in the east.

Another question that has been left unanswered is why plant ash glasses were (re-) introduced to Syria, Israel, Lebanon and Egypt in this period. This study combined various approaches to argue that greater economic integration between Syria, Israel, Lebanon, Jordan, Egypt, Iraq and Iran under the 'Abbasid Caliphate, changing consumer tastes, cultural interaction between people via trade networks helped to (re-) introduce plant ashes to the heartlands of natron glass production. And the greater economic cooperation between the Byzantines and the Fatimids and the regained importance of coastal cities as trading centres in the 11^{th} – 12^{th} centuries AD helped to spread plant ashes to the west.

10.5 Further work:

This study has highlighted the usefulness of using major and minor elements (electron microprobe analysis) in the study of Islamic, Byzantine, medieval Georgian and east African glasses when combined with other disciplines. As we have seen in Chapters 7 and 8, major and minor elements, especially MgO and CaO, can only provide us with broad compositional groups. It is difficult to separate, for instance, northern Syrian low MgO-high Al_2O_3 glasses from Iranian (e.g. Nishapur) and Iraqi (e.g. Samarra and Ctesiphon) glasses of the same glass type. And it has proved difficult to identify the geological zones of raw materials such as plant ashes.

It has become clear that more sensitive techniques need to be used in future for a wide range of elements that can provide us with more information regarding the study of ancient glass. For instance, the use of trace element analysis has proved to be better at discriminating between plant ash glass production zones than major and minor elements. For instance, it has been shown in a recent study that heavy elements such as chromium (Cr), caesium (Cs) and lanthanum (La) are very useful in discriminating between glass production zones (Henderson *et al*. 2016, 142). Another useful technique is isotopic analyses such as strontium and neodymium isotopic analyses. They have been proved useful in identifying the types of raw materials used and the geological zones the raw materials derived from, and to provide more information on glass recycling and mixing (Henderson 2013, 328, 340-342).

Also, there are still questions that are not addressed in this study: (1) the extent of influence of Sassanian glass production technique on Islamic glass production; (2) the genera of plant ashes used to produce Georgian, Egyptian, Iraqi and Iranian glasses; (3) how widespread were plant ash glasses in Turkey during the middle Byzantine period; (4) the organisation of the glass industry in Byzantine Turkey, medieval Georgia and east Africa; (5) the influence of glassmaking technology in the Middle East on glassmaking in Central Asia and the Far East.

Therefore, the next logical step for future study of glass dated to the 8^{th} – 14^{th} centuries AD would be:

(1) to analyse Sassanian glass from Iraq and Iran, so that we can understand Sassanian plant ash glass production technology and its influence on Islamic glassmaking in the 8^{th} – 9^{th} centuries AD.

(2) to use an environmental approach and scientific analysis (major and minor elements, trace element and isotopic analyses) to study different genera of plants in Iraq and Iraq, the Levantine region, Egypt and Georgia. It will help us to identify the possible genera of plants that were used to produce plant ash glasses in these regions and to understand more about the technology of plant ash glassmaking.

(3) In order to better understand the glassmaking technology and the organisation of the glass industry in Turkey, Georgia and east Africa, it will be beneficial to analyse glasses dated to the 8th – 14th centuries AD from these regions.

(4) We should start investigating the extent of influence eastern Mediterranean glassmaking technology had on glassmaking in Central Asia and the Far East (e.g. China and Japan) by analysing glasses from Central Asia and the Far East. There is increasing evidence that Middle Eastern glasses were exported to China during the 8th – 10th centuries AD (Li *et al*. 2016, 157-178).

(5) Trace element analysis and isotopic analysis should be used in future to investigate glass in the 8th – 14th centuries AD.

It is hopeful that by investigating these themes we can understand more about the global glass industry in the 8th – 14th centuries AD and the social, economic and political aspects of this material.

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Appendix

Samples	SO_3	P_2O_5	V_2O_5	As_2O_5	Sb_2O_5	SiO_2	TiO_2	SnO_2	Al_2O_3	Cr_2O_3	Fe_2O_3	MgO	CaO	MnO	CoO	CuO	ZnO	BaO	PbO	Na_2O	K_2O	Ag_2O	Cl	Glass Types
RAQ-01	0.23	0.14	0.02	0.07	0.04	71.67	0.05	0.03	1.02	0.01	1.15	4.58	5.85	0.45	0.03	0.19	0.10	0.01	0.07	12.59	2.26	0.00	0.68	Type 6
RAQ-02	0.11	0.29	0.02	0.25	0.00	70.24	0.08	0.02	1.02	0.02	0.38	2.94	7.37	1.56	0.00	0.01	0.02	0.02	0.01	14.55	1.93	0.01	0.72	Type 1b
RAQ-03	0.31	0.14	0.02	0.35	0.03	65.52	0.09	0.05	1.47	0.01	0.59	6.74	4.89	0.81	0.02	0.02	0.01	0.02	0.01	17.75	2.40	0.02	0.58	Type 4c
RAQ-04	0.07	0.10	0.01	0.22	0.02	74.48	0.09	0.03	3.54	0.01	0.42	0.72	7.13	0.01	0.01	0.00	0.02	0.04	0.00	13.55	0.54	0.00	0.91	Type 5
RAQ-05	0.21	0.32	0.00	0.05	0.02	67.98	0.06	0.04	0.71	0.00	0.32	3.50	7.72	0.61	0.01	0.00	0.02	0.05	0.00	14.59	3.52	0.01	0.85	Type 1b
RAQ-06	0.27	0.33	0.02	0.05	0.01	66.03	0.08	0.02	1.06	0.00	0.75	3.37	7.48	0.84	0.04	0.06	0.00	0.04	0.00	16.12	2.49	0.00	0.84	Type 1b
RAQ-07	0.21	0.33	0.03	0.22	0.00	66.50	0.15	0.01	1.93	0.02	0.94	3.53	8.88	1.34	0.00	0.01	0.02	0.01	0.02	13.79	2.40	0.00	0.73	Type 2
RAQ-08	0.22	0.20	0.00	0.21	0.02	64.89	0.12	0.03	1.76	0.00	0.75	5.27	5.45	1.99	0.00	0.02	0.00	0.06	0.03	14.79	2.89	0.01	0.52	Type 4c
RAQ-09	0.30	0.30	0.01	0.24	0.01	63.22	0.18	0.03	2.57	0.02	0.93	3.38	7.63	2.67	0.01	0.03	0.02	0.09	0.05	16.02	2.35	0.02	0.72	Type 4b
RAQ-10	0.16	0.28	0.01	0.13	0.02	67.23	0.16	0.01	2.46	0.02	2.71	2.79	5.88	0.20	0.19	0.54	0.13	0.03	0.01	14.92	2.70	0.02	0.62	Type 2
RAQ-11	0.08	0.09	0.01	0.02	0.00	72.07	0.07	0.01	2.94	0.01	0.39	0.68	8.79	0.04	0.01	0.03	0.00	0.04	0.06	14.29	0.56	0.03	0.53	Type 3
RAQ-12	0.22	0.31	0.01	0.05	0.02	66.25	0.06	0.01	1.81	0.01	0.37	3.39	9.16	0.93	0.01	0.04	0.00	0.04	0.02	14.50	3.06	0.00	0.76	Type 2
RAQ-13	0.07	0.10	0.01	0.16	0.02	71.81	0.09	0.00	2.95	0.01	0.42	0.70	8.89	0.04	0.00	0.03	0.01	0.01	0.05	14.10	0.56	0.02	0.55	Type 3
RAQ-14	0.05	0.06	0.02	0.05	0.02	75.22	0.10	0.00	3.50	0.00	0.56	0.55	7.38	0.02	0.01	0.01	0.01	0.06	0.01	11.79	0.45	0.01	0.65	Type 5
RAQ-15	0.32	0.14	0.01	0.01	0.00	66.63	0.08	0.01	1.29	0.00	0.42	6.32	4.79	0.75	0.01	0.03	0.01	0.03	0.01	16.34	2.63	0.01	0.56	Type 4c
RAQ-16	0.07	0.14	0.00	0.40	0.00	73.05	0.06	0.01	2.93	0.01	0.33	0.46	7.74	0.03	0.00	0.04	0.00	0.01	0.01	14.10	0.41	0.03	0.77	Type 3
RAQ-17	0.37	0.26	0.02	0.13	0.00	63.38	0.14	0.00	2.08	0.01	0.87	3.27	6.86	2.95	0.01	0.04	0.03	0.06	0.01	14.81	2.75	0.02	0.59	Type 2
RAQ-18	0.33	0.15	0.00	0.17	0.02	70.76	0.05	0.01	0.98	0.01	0.34	4.87	6.21	0.41	0.00	0.04	0.01	0.05	0.01	11.78	2.09	0.01	0.50	Type 6
RAQ-19	0.18	0.16	0.00	0.06	0.01	66.10	0.11	0.01	1.44	0.03	1.14	5.30	5.01	1.13	0.06	0.13	0.05	0.05	0.03	14.69	2.78	0.02	0.55	Type 4c
RAQ-20	0.07	0.18	0.02	0.20	0.00	67.51	0.10	0.01	2.15	0.02	0.78	3.01	6.54	1.37	0.02	0.07	0.03	0.04	0.02	14.53	1.98	0.02	0.64	Type 2
RAQ-21	0.26	0.24	0.01	0.14	0.00	64.40	0.16	0.04	2.44	0.01	1.01	3.69	7.20	1.03	0.03	0.08	0.08	0.05	0.01	14.69	2.74	0.01	0.62	Type 4b
RAQ-22	0.28	0.09	0.01	0.17	0.01	68.66	0.03	0.02	0.66	0.01	0.19	5.07	6.39	0.28	0.01	0.05	0.02	0.02	0.01	13.50	3.06	0.00	0.63	Type 6

RAQ-23	0.30	0.08	0.01	0.16	0.04	68.38	0.08	0.01	1.33	0.02	0.43	5.33	4.45	1.04	0.00	0.02	0.03	0.02	0.00	14.95	2.29	0.02	0.56	Type 4c
RAQ-24	0.12	0.31	0.01	0.12	0.02	68.52	0.10	0.00	0.94	0.04	0.37	2.80	7.21	1.61	0.01	0.02	0.01	0.01	0.01	13.39	2.14	0.01	0.93	Type 1b
RAQ-25	0.30	0.29	0.01	0.06	0.02	63.17	0.15	0.03	2.22	0.00	1.77	4.76	7.21	0.96	0.14	0.20	0.65	0.04	0.02	14.92	2.70	0.00	0.59	Type 4c
RAQ-26	0.22	0.39	0.01	0.30	0.01	65.84	0.16	0.00	2.23	0.03	0.96	4.18	6.65	2.30	0.01	0.02	0.02	0.05	0.12	13.80	2.77	0.00	0.59	Type 4b
RAQ-27	0.23	0.34	0.03	0.37	0.03	63.01	0.16	0.00	2.53	0.01	0.99	3.91	7.24	0.94	0.02	0.02	0.06	0.03	0.01	14.78	2.72	0.02	0.64	Type 4b
RAQ-28	0.13	0.42	0.01	0.11	0.00	62.79	0.25	0.02	4.02	0.01	1.91	3.96	6.90	0.22	0.00	0.00	0.00	0.02	0.01	14.41	3.18	0.01	0.57	Type 4a
RAQ-29	0.18	0.05	0.01	0.00	0.01	68.29	0.07	0.02	3.23	0.01	0.34	0.56	8.47	0.01	0.00	0.00	0.01	0.05	0.00	16.91	0.51	0.00	0.90	Type 3
RAQ-30	0.15	0.26	0.02	0.21	0.03	65.48	0.16	0.01	2.50	0.01	1.05	3.86	8.19	0.68	0.01	0.09	0.04	0.03	0.22	13.85	2.74	0.00	0.53	Type 4b
RAQ-31	0.25	0.17	0.01	0.08	0.01	72.32	0.06	0.01	2.86	0.01	0.38	0.51	8.60	0.03	0.01	0.03	0.02	0.04	0.04	13.34	0.59	0.02	0.61	Type 3
RAQ-32	0.12	0.28	0.01	0.11	0.05	69.35	0.06	0.05	0.94	0.00	0.35	2.80	7.82	1.89	0.01	0.01	0.02	0.02	0.02	13.23	2.41	0.01	0.88	Type 1b
RAQ-33	0.17	0.02	0.00	0.18	0.03	70.82	0.26	0.01	2.34	0.01	0.94	0.46	9.28	0.01	0.00	0.01	0.03	0.04	0.06	14.30	0.22	0.02	1.09	Type 3
RAQ-34	0.27	0.29	0.01	0.09	0.02	66.89	0.19	0.00	2.05	0.03	0.96	4.19	5.79	0.25	0.00	0.01	0.01	0.02	0.02	14.60	3.73	0.01	0.57	Type 4b
RAQ-35	0.06	0.20	0.01	0.22	0.04	69.81	0.07	0.01	1.00	0.01	0.39	2.67	7.64	2.10	0.01	0.03	0.01	0.05	0.05	11.87	2.36	0.00	0.87	Type 1b
RAQ-36	0.14	0.26	0.02	0.09	0.03	69.02	0.09	0.01	0.95	0.01	0.40	3.23	7.48	1.13	0.00	0.02	0.00	0.04	0.03	13.34	2.31	0.03	0.85	Type 1b
RAQ-37	0.23	0.36	0.01	0.06	0.00	64.88	0.08	0.00	0.97	0.01	0.43	3.83	8.54	0.87	0.01	0.03	0.02	0.03	0.01	14.77	2.82	0.02	0.86	Type 1b
RAQ-38	0.16	0.09	0.00	0.28	0.05	71.18	0.07	0.02	3.15	0.03	0.37	0.49	8.50	0.01	0.01	0.04	0.01	0.03	0.01	13.63	0.44	0.02	0.90	Type 3
RAQ-39	0.14	0.22	0.01	0.22	0.00	69.93	0.06	0.07	1.10	0.01	0.42	3.09	7.60	1.25	0.00	0.04	0.00	0.03	0.02	12.48	2.04	0.03	0.82	Type 1b
RAQ-40	0.33	0.08	0.02	0.17	0.01	70.46	0.05	0.01	0.89	0.02	0.28	4.84	6.78	0.30	0.01	0.01	0.00	0.01	0.02	12.54	2.43	0.01	0.56	Type 6
RAQ-41	0.14	0.25	0.02	0.17	0.04	66.51	0.08	0.01	0.88	0.00	0.34	3.51	8.77	1.19	0.01	0.03	0.02	0.02	0.02	13.20	2.55	0.02	0.89	Type 1b
RAQ-42	0.07	0.14	0.01	0.22	0.01	69.90	0.08	0.02	2.72	0.02	0.50	1.18	8.88	0.14	0.00	0.01	0.01	0.03	0.02	13.34	0.97	0.03	0.67	Type 3
RAQ-43	0.21	0.31	0.02	0.17	0.02	67.25	0.06	0.00	0.85	0.01	0.34	3.08	7.47	1.45	0.01	0.02	0.01	0.04	0.02	14.56	2.24	0.01	0.83	Type 1b
RAQ-44	0.02	0.02	0.03	0.11	0.02	69.62	0.12	0.02	16.52	0.00	2.00	0.24	6.65	0.01	0.01	0.01	0.01	0.03	0.05	3.05	1.04	0.02	0.03	Outlier
RAQ-45	0.07	0.19	0.02	0.16	0.03	71.08	0.12	0.01	1.93	0.02	2.53	2.56	5.01	0.84	0.10	0.56	0.09	0.07	0.03	11.67	1.79	0.00	0.85	Type 2
RAQ-46	0.13	0.24	0.02	0.15	0.02	67.84	0.10	0.00	1.05	0.02	0.34	3.23	7.84	1.35	0.00	0.02	0.01	0.04	0.04	13.31	2.40	0.01	0.95	Type 1b
RAQ-47	0.30	0.26	0.01	0.05	0.01	64.56	0.17	0.03	2.46	0.01	0.98	3.71	7.34	1.08	0.03	0.05	0.07	0.02	0.04	14.39	2.59	0.01	0.59	Type 4b

RAQ-48	0.06	0.11	0.01	0.16	0.00	72.38	0.07	0.01	2.98	0.02	0.38	0.47	8.53	0.01	0.01	0.00	0.02	0.06	0.01	13.84	0.46	0.01	0.85	Type 3
RAQ-49	0.15	0.24	0.02	0.00	0.01	66.44	0.13	0.01	2.67	0.01	0.86	3.17	8.36	0.60	0.00	0.02	0.05	0.03	0.02	14.80	2.26	0.01	0.52	Type 4b
RAQ-50	0.22	0.25	0.02	0.23	0.02	65.33	0.16	0.01	2.35	0.02	0.82	3.79	7.58	0.91	0.01	0.01	0.03	0.03	0.03	15.15	2.43	0.01	0.58	Type 4b
RAQ-51	0.09	0.25	0.02	0.00	0.00	68.69	0.09	0.01	1.11	0.01	0.46	2.76	7.71	2.01	0.01	0.00	0.00	0.07	0.01	12.03	2.39	0.00	0.82	Type 1b
RAQ-52	0.03	0.20	0.02	0.02	0.02	69.96	0.14	0.00	1.97	0.01	2.67	2.68	5.03	0.85	0.10	0.56	0.08	0.06	0.02	12.14	1.80	0.01	0.84	Type 2
RAQ-53	0.17	0.09	0.00	0.02	0.00	71.59	0.06	0.01	3.18	0.00	0.40	0.73	8.47	0.02	0.01	0.00	0.01	0.04	0.04	13.43	0.53	0.02	0.76	Type 3
RAQ-54	0.29	0.40	0.02	0.15	0.04	62.16	0.15	0.02	2.19	0.00	0.84	2.84	6.96	2.82	0.00	0.00	0.05	0.08	0.02	15.68	2.89	0.02	0.77	Type 2
RAQ-55	0.23	0.34	0.02	0.00	0.01	64.57	0.14	0.00	2.40	0.00	0.85	2.93	7.32	3.21	0.02	0.01	0.01	0.07	0.01	14.54	2.25	0.00	0.77	Type 2
RAQ-56	0.13	0.12	0.01	0.05	0.00	71.42	0.08	0.03	2.98	0.01	0.34	0.52	8.39	0.03	0.00	0.01	0.01	0.02	0.03	14.58	0.56	0.03	0.81	Type 3
RAQ-57	0.23	0.31	0.03	0.13	0.01	63.57	0.17	0.02	2.32	0.00	1.75	3.60	7.44	1.92	0.11	0.17	0.42	0.06	0.01	14.74	2.76	0.00	0.61	Type 4b
RAQ-58	0.22	0.39	0.04	0.32	0.00	65.82	0.24	0.01	3.70	0.03	1.48	3.29	6.40	0.36	0.02	0.02	0.03	0.01	0.00	14.00	3.41	0.01	0.49	Type 4a
RAQ-59	0.20	0.34	0.01	0.06	0.02	68.21	0.07	0.00	0.82	0.01	0.38	3.25	8.79	0.90	0.01	0.00	0.00	0.02	0.00	13.64	2.70	0.01	0.82	Type 1b
RAQ-60	0.29	0.28	0.01	0.36	0.00	64.35	0.17	0.04	2.30	0.00	1.04	3.18	7.52	1.90	0.03	0.06	0.08	0.02	0.00	15.67	2.83	0.01	0.72	Type 2
RAQ-61	0.20	0.38	0.03	0.13	0.00	67.34	0.07	0.03	1.03	0.01	0.40	3.09	7.83	1.74	0.01	0.01	0.02	0.04	0.02	15.14	1.95	0.01	0.95	Type 1b
RAQ-62	0.20	0.10	0.01	0.13	0.01	72.95	0.08	0.00	2.79	0.00	0.34	0.54	8.35	0.01	0.01	0.01	0.00	0.03	0.00	14.02	0.50	0.02	0.67	Type 3
RAQ-63	0.03	0.09	0.02	0.09	0.00	71.37	0.11	0.04	2.47	0.01	0.49	0.46	8.12	0.03	0.00	0.01	0.00	0.05	0.01	14.31	0.38	0.02	0.92	Type 3
RAQ-64	0.14	0.11	0.00	0.10	0.01	68.41	0.06	0.01	2.94	0.01	0.45	0.84	8.26	0.02	0.02	0.05	0.04	0.00	0.00	15.26	0.69	0.02	0.91	Type 3
RAQ-65	0.08	0.01	0.03	0.12	0.02	71.04	0.06	0.00	3.04	0.01	0.37	0.46	7.77	0.00	0.00	0.00	0.00	0.05	0.04	14.17	0.69	0.00	0.82	Type 3
RAQ-66	0.06	0.20	0.02	0.09	0.00	70.42	0.10	0.01	2.79	0.01	0.35	0.45	9.90	0.02	0.01	0.00	0.00	0.03	0.01	12.68	0.43	0.04	0.77	Type 3
RAQ-67	0.07	0.07	0.01	0.07	0.00	73.42	0.07	0.02	2.80	0.01	0.29	0.35	7.73	0.00	0.01	0.01	0.02	0.04	0.02	13.49	0.39	0.01	0.81	Type 3
RAQ-68	0.06	0.10	0.00	0.39	0.09	72.47	0.06	0.00	2.81	0.00	0.30	0.35	7.81	0.03	0.01	0.01	0.04	0.04	0.01	13.67	0.38	0.01	0.84	Type 3
RAQ-69	0.09	0.05	0.02	0.36	0.00	70.72	0.05	0.01	3.05	0.01	0.35	0.51	7.81	0.02	0.01	0.02	0.00	0.07	0.02	14.55	0.68	0.02	0.86	Type 3
RAQ-70	0.04	0.13	0.02	0.09	0.01	72.57	0.04	0.01	2.79	0.01	0.32	0.36	7.49	0.01	0.00	0.00	0.01	0.04	0.02	13.67	0.40	0.03	0.84	Type 3
RAQ-71	0.04	0.04	0.02	0.04	0.00	72.08	0.07	0.01	3.25	0.02	0.39	0.70	7.95	0.02	0.01	0.01	0.01	0.01	0.01	13.34	0.60	0.01	0.89	Type 3
RAQ-72	0.07	0.09	0.01	0.02	0.01	71.31	0.07	0.03	3.07	0.02	0.33	0.50	7.70	0.01	0.00	0.00	0.00	0.05	0.04	14.46	0.65	0.01	0.87	Type 3

RAQ-73	0.16	0.08	0.00	0.08	0.01	69.86	0.07	0.01	2.80	0.01	0.33	0.39	7.66	0.01	0.00	0.02	0.00	0.02	0.01	16.39	0.51	0.01	0.87	Type 3
RAQ-74	0.30	0.37	0.01	0.05	0.00	63.40	0.17	0.01	2.29	0.01	0.97	2.56	6.88	2.51	0.02	0.04	0.06	0.05	0.03	16.13	2.94	0.01	0.80	Type 2
RAQ-75	0.27	0.32	0.02	0.26	0.02	64.31	0.12	0.00	2.42	0.01	0.99	4.06	7.24	1.04	0.01	0.03	0.04	0.02	0.03	15.17	2.74	0.01	0.60	Type 4b
RAQ-76	0.20	0.34	0.01	0.32	0.01	64.85	0.08	0.00	0.88	0.02	0.44	3.29	8.00	2.19	0.00	0.00	0.01	0.08	0.01	15.49	2.45	0.01	0.99	Type 1b
RAQ-77	0.08	0.09	0.02	0.00	0.00	71.26	0.05	0.02	2.96	0.01	0.34	0.44	8.42	0.01	0.01	0.01	0.01	0.05	0.03	14.68	0.54	0.00	0.87	Type 3
RAQ-78	0.32	0.17	0.01	0.11	0.02	64.43	0.11	0.01	1.20	0.01	0.43	6.91	5.26	0.05	0.00	0.01	0.02	0.02	0.01	16.11	3.70	0.00	0.51	Type 4c
RAQ-79	0.14	0.14	0.01	0.25	0.00	69.67	0.05	0.00	3.16	0.02	0.33	0.45	8.35	0.03	0.00	0.02	0.01	0.02	0.06	14.33	0.45	0.02	0.85	Type 3
RAQ-80	0.11	0.08	0.01	0.00	0.00	71.84	0.04	0.00	2.77	0.01	0.33	0.47	8.35	0.02	0.01	0.01	0.01	0.02	0.00	13.48	0.48	0.00	0.86	Type 3
RAQ-81	0.17	0.16	0.03	0.18	0.02	71.14	0.08	0.00	3.11	0.01	0.37	0.43	8.52	0.01	0.01	0.01	0.02	0.06	0.04	14.58	0.47	0.00	0.70	Type 3
RAQ-82	0.27	0.32	0.01	0.08	0.00	64.18	0.14	0.00	2.46	0.01	0.94	3.68	7.19	0.89	0.00	0.05	0.05	0.06	0.03	14.97	2.71	0.01	0.62	Type 4b
RAQ-83	0.07	0.18	0.01	0.16	0.02	69.94	0.11	0.01	2.84	0.00	0.53	1.21	8.70	0.15	0.02	0.02	0.00	0.02	0.01	13.55	1.03	0.00	0.63	Type 3
RAQ-84	0.16	0.36	0.01	0.12	0.04	68.15	0.07	0.01	0.91	0.01	0.39	2.95	8.50	1.24	0.01	0.02	0.05	0.04	0.00	12.71	2.56	0.00	0.81	Type 1b
RAQ-85	0.22	0.10	0.01	0.11	0.00	71.16	0.04	0.03	0.92	0.00	0.38	4.34	5.84	0.40	0.01	0.03	0.02	0.04	0.02	12.42	2.28	0.02	0.74	Type 6
RAQ-86	0.05	0.06	0.01	0.20	0.00	73.55	0.07	0.00	3.05	0.01	0.32	0.35	7.92	0.01	0.02	0.00	0.00	0.02	0.00	13.19	0.44	0.02	0.78	Type 3
RAQ-87	0.08	0.05	0.01	0.16	0.00	71.71	0.07	0.01	3.00	0.01	0.31	0.43	7.80	0.01	0.01	0.02	0.01	0.03	0.02	13.97	0.39	0.02	0.85	Type 3
RAQ-88	0.24	0.08	0.03	0.00	0.02	67.12	0.08	0.06	1.18	0.02	0.39	5.62	4.57	1.43	0.01	0.00	0.01	0.03	0.01	15.22	3.06	0.00	0.59	Type 4c
RAQ-89	0.34	0.11	0.01	0.04	0.01	67.99	0.07	0.01	1.22	0.00	0.41	5.86	4.87	1.07	0.01	0.00	0.01	0.02	0.01	15.95	2.64	0.01	0.53	Type 4c
RAQ-90	0.33	0.07	0.01	0.13	0.01	68.76	0.10	0.02	1.24	0.02	0.40	5.87	4.75	1.03	0.01	0.02	0.02	0.02	0.01	15.91	2.60	0.03	0.52	Type 4c
RAQ-91	0.30	0.31	0.03	0.09	0.01	65.82	0.13	0.01	1.94	0.01	0.96	3.31	6.36	2.01	0.02	0.01	0.02	0.08	0.01	15.33	2.70	0.01	0.57	Type 2
RAQ-92	0.08	0.13	0.01	0.13	0.00	72.85	0.08	0.00	2.89	0.00	0.32	0.39	8.21	0.02	0.01	0.07	0.01	0.02	0.01	12.79	0.49	0.03	0.75	Type 3
RAQ-93	0.11	0.14	0.02	0.27	0.03	72.69	0.05	0.00	2.86	0.01	0.33	0.39	7.86	0.01	0.01	0.09	0.02	0.03	0.00	12.94	0.53	0.00	0.80	Type 3
RAQ-94	0.08	0.06	0.02	0.26	0.00	72.59	0.06	0.02	3.27	0.01	0.33	0.42	7.74	0.00	0.00	0.07	0.01	0.05	0.01	13.23	0.56	0.01	0.86	Type 3
RAQ-95	0.24	0.31	0.01	0.02	0.00	64.76	0.15	0.00	2.39	0.02	0.94	3.55	7.08	0.95	0.03	0.10	0.06	0.04	0.03	14.67	2.69	0.01	0.64	Type 4c
RAQ-96	0.21	0.52	0.03	0.32	0.00	59.92	0.27	0.01	4.04	0.01	2.04	4.41	8.65	0.22	0.00	0.05	0.03	0.04	0.00	15.71	2.25	0.01	0.95	Type 4a
RAQ-97	0.22	0.50	0.01	0.25	0.02	67.50	0.09	0.01	1.44	0.02	0.83	2.71	4.79	0.02	0.01	0.04	0.00	0.01	0.01	17.80	2.91	0.01	0.99	Type 1a

RAQ-98	0.16	0.37	0.00	0.06	0.04	68.33	0.11	0.03	1.44	0.01	1.13	3.28	6.54	0.06	0.00	0.04	0.01	0.01	0.02	15.32	1.86	0.01	0.89	Type 1a
RAQ-99	0.23	0.32	0.01	0.17	0.00	67.66	0.13	0.04	1.59	0.01	2.47	3.06	4.99	0.16	0.00	0.02	0.01	0.07	0.03	16.57	1.74	0.00	0.78	Type 1a
RAQ-100	0.15	0.55	0.01	0.20	0.01	67.55	0.16	0.02	1.86	0.00	1.16	3.24	6.29	0.15	0.01	0.02	0.00	0.02	0.05	14.07	2.90	0.01	0.74	Type 2
RAQ-101	0.18	0.39	0.04	0.31	0.00	57.59	0.40	0.03	5.75	0.04	2.94	4.26	8.95	0.05	0.01	0.03	0.04	0.01	0.05	16.25	2.07	0.01	0.58	Type 3
RAQ-102	0.31	0.46	0.04	0.16	0.03	62.28	0.27	0.01	4.02	0.02	1.72	4.15	7.07	0.07	0.00	0.03	0.01	0.00	0.04	16.86	2.02	0.01	0.83	Type 4a
RAQ-103	0.17	0.52	0.02	0.04	0.02	65.70	0.20	0.01	2.38	0.01	2.34	3.05	6.23	0.09	0.02	0.02	0.00	0.04	0.03	15.70	2.25	0.00	0.82	Type 2
RAQ-104	0.08	0.44	0.01	0.25	0.00	66.79	0.24	0.04	3.06	0.02	2.02	3.35	7.58	0.04	0.01	0.02	0.01	0.04	0.06	13.30	1.83	0.03	0.84	Type 4a
RAQ-105	0.10	0.50	0.00	0.16	0.04	67.28	0.13	0.01	1.70	0.01	1.27	3.58	6.81	0.17	0.00	0.01	0.02	0.03	0.03	14.25	1.89	0.03	1.03	Type 2
RAQ-106	0.09	0.40	0.02	0.13	0.01	66.85	0.23	0.02	1.90	0.02	3.15	3.45	6.22	0.07	0.00	0.02	0.02	0.02	0.03	13.78	1.99	0.00	0.99	Type 2
RAQ-107	0.05	0.39	0.01	0.22	0.01	68.01	0.23	0.01	1.87	0.01	3.45	3.63	5.94	0.08	0.01	0.02	0.03	0.02	0.04	13.23	1.69	0.02	0.96	Type 2
RAQ-108	0.15	0.54	0.02	0.18	0.01	61.10	0.19	0.02	2.64	0.01	1.36	4.73	10.25	0.38	0.01	0.01	0.00	0.05	0.06	14.93	2.43	0.01	0.95	Type 4b
RAQ-109	0.21	0.44	0.03	0.22	0.00	58.30	0.34	0.00	4.69	0.02	2.55	4.18	9.63	0.08	0.00	0.03	0.02	0.01	0.01	16.40	1.97	0.03	0.56	Type 4a
RAQ-110	0.04	0.93	0.02	0.34	0.00	69.28	0.11	0.01	1.98	0.01	1.31	4.93	5.68	0.07	0.01	0.01	0.01	0.03	0.02	12.08	1.64	0.02	0.90	Type 4c
RAQ-111	0.17	0.33	0.02	0.00	0.04	67.39	0.07	0.00	0.99	0.00	0.33	3.02	8.80	0.90	0.01	0.03	0.02	0.02	0.01	12.64	2.87	0.01	0.80	Type 1b
RAQ-112	0.36	0.37	0.04	0.15	0.03	66.50	0.15	0.01	1.89	0.01	1.19	2.79	4.86	0.03	0.01	0.03	0.01	0.03	0.00	17.77	2.44	0.01	0.83	Type 2
RAQ-113	0.20	0.29	0.01	0.17	0.01	66.69	0.09	0.01	1.06	0.00	0.46	3.08	9.81	1.17	0.01	0.02	0.01	0.00	0.00	12.28	2.30	0.02	0.75	Type 1b

Appendix Table 1: EPMA results for glass from al-Raqqa, northern Syria. Results are presented in weight percent oxide/element.

Samples	SO_3	P_2O_5	V_2O_5	As_2O_5	Sb_2O_5	SiO_2	TiO_2	SnO_2	Al_2O_3	Cr_2O_3	Fe_2O_3	MgO	CaO	MnO	CoO	CuO	ZnO	BaO	PbO	Na_2O	K_2O	Ag_2O	Cl	Glass Types
GEO-01	0.51	0.36	0.02	0.28	0.00	60.98	0.20	0.00	4.07	0.01	1.96	2.63	6.18	1.96	0.01	0.05	0.03	0.03	0.00	18.13	1.75	0.01	0.52	Low MgO-high Al_2O_3
GEO-02	0.33	0.69	0.02	0.00	0.00	61.41	0.16	0.01	2.94	0.01	1.42	1.95	10.14	0.29	0.02	0.05	0.01	0.06	0.02	16.01	2.68	0.00	0.64	Mixed natron-plant ash
GEO-03	0.52	0.42	0.02	0.52	0.00	61.46	0.14	0.02	3.21	0.02	1.56	4.02	8.32	0.91	0.01	0.04	0.04	0.05	0.02	14.99	2.34	0.03	0.15	Mixed natron-plant ash
GEO-04	0.48	0.67	0.02	0.19	0.04	58.69	0.25	0.02	5.36	0.01	1.69	3.93	8.66	0.32	0.01	0.03	0.02	0.03	0.01	16.29	2.12	0.02	0.98	Low MgO-high Al_2O_3
GEO-05	1.46	0.85	0.01	0.19	0.01	60.23	0.12	0.02	2.98	0.00	0.93	3.11	8.32	0.10	0.01	0.04	0.01	0.01	0.02	18.96	2.05	0.02	1.37	Mixed natron-plant ash
GEO-06	0.20	1.64	0.00	0.04	0.02	62.20	0.13	0.00	2.47	0.01	1.17	2.36	10.94	0.07	0.01	0.04	0.02	0.02	0.01	12.88	4.00	0.03	0.74	Mixed natron-plant ash
GEO-07	0.22	1.48	0.02	0.12	0.03	61.43	0.15	0.01	2.49	0.02	1.23	2.46	11.08	0.07	0.01	0.05	0.02	0.05	0.01	12.80	3.97	0.03	0.72	Mixed natron-plant ash
GEO-08	0.30	0.14	0.02	0.09	0.01	57.95	0.15	0.01	11.98	0.02	1.51	1.35	2.76	0.22	0.00	0.03	0.01	0.06	0.01	18.57	3.20	0.03	0.72	High alumina
GEO-09	0.66	0.21	0.01	0.35	0.01	66.92	0.11	0.02	2.37	0.01	1.32	1.16	6.53	0.44	0.09	0.08	0.02	0.02	0.03	17.75	0.88	0.03	0.49	HIMT

Appendix Table 2: EPMA results for glass from Tbilisi, Georgia. Results are presented in weight percent oxide/element.

Samples	SO_3	P_2O_5	V_2O_5	As_2O_5	Sb_2O_5	SiO_2	TiO_2	SnO_2	Al_2O_3	Cr_2O_3	Fe_2O_3	MgO	CaO	MnO	CoO	CuO	ZnO	BaO	PbO	Na_2O	K_2O	Ag_2O	Cl	Glass Types
ZC-01	0.11	0.33	0.01	0.12	0.00	68.96	0.29	0.01	2.97	0.01	1.19	1.44	6.91	1.34	0.01	0.07	0.02	0.04	0.00	12.93	2.21	0.01	1.11	Zeyrek Camii Group 2
ZC-02	0.14	0.26	0.02	0.18	0.04	66.61	0.15	0.04	2.31	0.01	1.16	2.09	7.74	0.69	0.00	0.16	0.03	0.03	0.15	14.47	1.79	0.01	0.72	Zeyrek Camii Group 2
ZC-03	0.16	0.30	0.01	0.24	0.03	67.58	0.19	0.00	3.13	0.02	2.08	1.58	6.66	0.50	0.15	0.32	0.30	0.03	0.18	13.14	1.89	0.00	0.80	Zeyrek Camii Group 2
ZC-04	0.23	0.18	0.02	0.00	0.00	66.17	0.12	0.02	1.93	0.01	0.98	1.89	8.73	0.74	0.00	0.16	0.01	0.01	0.38	15.32	1.36	0.01	0.62	Zeyrek Camii Group 2
ZC-05	0.22	0.13	0.00	0.55	0.00	66.06	0.12	0.01	1.96	0.00	1.07	1.99	8.26	0.70	0.00	0.25	0.00	0.10	0.27	14.66	1.51	0.00	0.62	Zeyrek Camii Group 2
ZC-06	0.16	0.57	0.02	0.16	0.06	65.25	0.14	0.06	2.73	0.00	0.94	2.52	7.50	0.72	0.00	0.17	0.02	0.08	0.13	13.12	4.41	0.01	0.80	Zeyrek Camii Group 2
ZC-07	0.29	0.25	0.02	0.34	0.02	66.05	0.11	0.04	1.81	0.02	1.57	1.85	7.77	0.88	0.11	0.28	0.11	0.06	0.18	16.22	1.28	0.00	0.80	Zeyrek Camii Group 2
ZC-08	0.19	0.28	0.03	0.04	0.01	66.27	0.08	0.02	0.90	0.01	0.44	3.87	10.15	0.87	0.00	0.10	0.02	0.02	0.04	13.36	2.31	0.02	0.92	Zeyrek Camii Group 1
ZC-09	0.20	0.29	0.01	0.07	0.00	68.89	0.07	0.03	1.37	0.02	0.31	2.82	8.04	0.96	0.02	0.08	0.01	0.04	0.00	14.07	2.38	0.01	0.91	Zeyrek Camii Group 1
ZC-10	0.20	0.25	0.00	0.36	0.00	66.92	0.08	0.01	1.41	0.00	0.48	3.00	8.44	2.21	0.01	0.04	0.03	0.18	0.02	13.51	2.24	0.03	0.74	Zeyrek Camii Group 1
ZC-11	0.18	0.26	0.01	0.22	0.02	69.16	0.09	0.03	1.42	0.01	0.39	2.99	8.28	0.96	0.00	0.02	0.01	0.08	0.03	13.60	2.25	0.01	0.56	Zeyrek Camii Group 1
ZC-12	0.20	0.35	0.01	0.16	0.00	66.85	0.08	0.04	0.90	0.00	0.35	3.44	9.70	0.55	0.01	0.04	0.02	0.03	0.01	14.18	2.20	0.01	0.89	Zeyrek Camii Group 1
ZC-13	0.25	0.31	0.01	0.08	0.00	69.38	0.07	0.04	1.10	0.02	0.54	3.39	9.12	1.06	0.01	0.04	0.01	0.05	0.10	11.38	2.34	0.01	0.79	Zeyrek Camii Group 1
ZC-14	0.25	0.29	0.03	0.04	0.01	64.79	0.17	0.03	2.74	0.01	1.02	2.87	8.21	0.99	0.01	0.12	0.01	0.02	0.16	14.49	2.34	0.00	0.76	Zeyrek Camii Group 2
ZC-15	0.26	0.27	0.02	0.22	0.02	65.01	0.09	0.14	1.30	0.00	0.74	3.45	9.65	1.16	0.00	0.04	0.02	0.05	0.16	13.60	2.64	0.02	0.80	Zeyrek Camii Group 1

Appendix Table 3: EPMA results for glass from Zeyrek Camii in Istanbul, Turkey. Results are presented in weight percent oxide/element.

Samples	SO_3	P_2O_5	V_2O_5	As_2O_5	Sb_2O_5	SiO_2	TiO_2	SnO_2	Al_2O_3	Cr_2O_3	Fe_2O_3	MgO	CaO	MnO	CoO	CuO	ZnO	BaO	PbO	Na_2O	K_2O	Ag_2O	Cl	Glass Types
VA-01	0.11	0.39	0.03	0.18	0.01	66.86	0.71	0.01	3.62	0.01	2.00	2.91	5.29	0.04	0.00	0.01	0.01	0.05	0.02	14.57	1.95	0.01	0.98	Low MgO-high Al_2O_3
VA-02	0.05	0.32	0.02	0.05	0.01	70.58	0.62	0.00	3.31	0.01	1.90	2.32	5.67	0.03	0.00	0.01	0.01	0.02	0.01	12.26	1.36	0.00	0.94	Low MgO-high Al_2O_3

Appendix Table 4: EPMA results for glass from Fustat, Egypt. Results are presented in weight percent oxide/element.

Samples	SO_3	P_2O_5	V_2O_5	As_2O_5	Sb_2O_5	SiO_2	TiO_2	SnO_2	Al_2O_3	Cr_2O_3	Fe_2O_3	MgO	CaO	MnO	CoO	CuO	ZnO	BaO	PbO	Na_2O	K_2O	Ag_2O	Cl	Glass Types
VA-03	0.27	0.20	0.01	0.03	0.01	64.77	0.08	0.00	1.71	0.01	1.18	3.51	7.52	0.12	0.00	0.02	0.03	0.05	0.02	16.83	2.83	0.00	0.91	Type 1
VA-04	0.26	0.21	0.02	0.08	0.01	64.95	0.07	0.02	1.66	0.01	1.18	3.50	7.48	0.12	0.01	0.02	0.03	0.01	0.02	16.82	2.77	0.01	0.91	Type 1
VA-05	0.22	0.46	0.01	0.25	0.02	60.73	0.20	0.05	5.21	0.00	1.33	4.39	5.83	0.10	0.02	0.13	0.02	0.06	0.34	17.20	2.95	0.01	0.80	Low MgO-high Al_2O_3
VA-06	0.17	0.45	0.02	0.18	0.00	59.73	0.27	0.01	8.10	0.00	1.95	3.53	3.23	0.13	0.00	0.01	0.03	0.04	0.01	18.88	3.26	0.01	0.90	High alumina
VA-07	0.28	0.15	0.01	0.25	0.02	67.38	0.08	0.01	2.78	0.02	0.48	4.82	5.09	0.11	0.02	0.01	0.01	0.00	0.03	14.79	3.22	0.01	0.60	High MgO-low Al_2O_3

Appendix Table 5: EPMA results for glass from Pemba Island in Zanzibar. Results are presented in weight percent oxide/element.

Samples	SO_3	P_2O_5	V_2O_5	As_2O_5	Sb_2O_5	SiO_2	TiO_2	SnO_2	Al_2O_3	Cr_2O_3	Fe_2O_3	MgO	CaO	MnO	CoO	CuO	ZnO	BaO	PbO	Na_2O	K_2O	Ag_2O	Cl	Glass Types
VA-08	0.10	0.21	0.02	0.05	0.00	66.85	0.26	0.02	4.75	0.02	1.92	2.92	7.35	0.07	0.01	0.01	0.02	0.02	0.01	11.22	3.20	0.00	0.76	Low MgO-high Al_2O_3
VA-09	0.12	0.19	0.02	0.09	0.05	69.29	0.18	0.01	4.08	0.03	1.61	2.51	4.65	0.04	0.00	0.00	0.01	0.05	0.00	13.80	2.62	0.01	0.59	Low MgO-high Al_2O_3
VA-10	0.15	0.29	0.01	0.05	0.01	73.28	0.04	0.00	0.91	0.01	0.52	3.96	5.40	0.03	0.01	0.00	0.01	0.03	0.02	11.37	3.26	0.01	0.46	Type 6
VA-11	0.11	0.24	0.01	0.04	0.00	71.96	0.07	0.00	1.34	0.01	0.55	3.80	5.95	0.04	0.01	0.00	0.01	0.03	0.03	12.85	2.78	0.01	0.29	Type 6
VA-12	0.12	0.30	0.02	0.21	0.00	66.94	0.28	0.00	5.08	0.03	2.48	2.61	7.57	0.05	0.01	0.01	0.00	0.05	0.01	11.66	2.48	0.00	0.46	Low MgO-high Al_2O_3
VA-13	0.52	0.16	0.01	0.14	0.00	64.25	0.05	0.02	0.95	0.01	1.09	5.97	7.54	0.07	0.05	0.02	0.02	0.02	0.01	15.84	3.05	0.01	0.37	High MgO-low Al_2O_3

Appendix Table 6: EPMA results for glass from al-Qadisiyya in Samarra, Iraq. Results are presented in weight percent oxide/element.

Samples	SO_3	P_2O_5	V_2O_5	As_2O_5	Sb_2O_5	SiO_2	TiO_2	SnO_2	Al_2O_3	Cr_2O_3	Fe_2O_3	MgO	CaO	MnO	CoO	CuO	ZnO	BaO	PbO	Na_2O	K_2O	Ag_2O	Cl	Glass Types
VA-14	0.21	0.28	0.01	0.12	0.02	66.84	0.10	0.01	1.26	0.02	0.64	3.37	8.98	1.03	0.01	0.02	0.01	0.04	0.02	13.99	2.55	0.00	0.67	Al-Mina Group 1
VA-15	0.18	0.23	0.02	0.14	0.01	66.91	0.18	0.03	1.91	0.01	2.82	2.44	5.38	1.11	0.28	0.56	0.05	0.01	0.03	14.35	2.62	0.02	0.78	Type 2
VA-16	0.18	0.28	0.01	0.17	0.02	67.72	0.08	0.01	1.35	0.02	0.29	3.35	9.08	0.20	0.00	0.00	0.02	0.01	0.03	14.83	2.48	0.01	0.77	Al-Mina Group 1
VA-17	0.13	0.25	0.01	0.08	0.00	67.56	0.08	0.02	1.56	0.01	0.41	3.49	9.10	0.26	0.01	0.01	0.00	0.04	0.01	13.92	2.67	0.02	0.80	Al-Mina Group 1
VA-18	0.21	0.28	0.00	0.02	0.00	65.93	0.10	0.01	1.19	0.01	0.53	3.54	9.59	0.79	0.02	0.01	0.02	0.04	0.01	14.46	2.43	0.01	0.79	Al-Mina Group 1
VA-19	0.06	0.11	0.03	0.03	0.00	70.31	0.29	0.01	2.43	0.03	0.90	0.69	9.80	0.02	0.00	0.00	0.01	0.03	0.01	13.95	0.37	0.01	1.09	Egypt II
VA-20	0.24	0.34	0.03	0.16	0.01	66.51	0.09	0.01	1.80	0.01	0.58	3.04	10.16	1.59	0.01	0.01	0.01	0.02	0.05	12.49	2.48	0.02	0.66	Al-Mina Group 1
VA-21	0.24	0.31	0.00	0.20	0.01	65.84	0.09	0.01	1.15	0.00	0.58	3.39	9.54	0.79	0.01	0.01	0.01	0.01	0.04	15.00	2.38	0.00	0.77	Al-Mina Group 1
VA-22	0.26	0.34	0.01	0.19	0.00	66.00	0.10	0.00	1.17	0.02	0.49	3.56	9.55	0.74	0.01	0.00	0.01	0.03	0.01	14.91	2.30	0.00	0.78	Al-Mina Group 1
VA-23	0.22	0.36	0.01	0.02	0.00	66.32	0.07	0.03	1.22	0.01	0.50	3.45	9.44	0.73	0.01	0.01	0.02	0.03	0.03	14.87	2.33	0.01	0.78	Al-Mina Group 1
VA-24	0.22	0.27	0.01	0.23	0.02	67.79	0.10	0.02	1.46	0.01	0.51	3.19	9.44	0.78	0.01	0.02	0.01	0.05	0.04	13.88	2.03	0.01	0.74	Al-Mina Group 1
VA-25	0.20	0.34	0.01	0.14	0.00	64.73	0.09	0.11	1.16	0.01	0.62	3.39	9.03	0.78	0.01	1.75	0.04	0.03	0.21	14.38	2.31	0.01	0.72	Al-Mina Group 1
VA-26	0.19	0.16	0.00	0.23	0.01	66.48	0.09	0.01	1.34	0.02	0.65	5.36	6.53	1.16	0.00	0.01	0.01	0.02	0.02	15.29	2.39	0.01	0.56	High MgO-low Al_2O_3
VA-27	0.09	0.17	0.03	0.18	0.00	66.43	0.33	0.01	2.03	0.01	0.91	0.54	11.79	0.02	0.02	0.00	0.01	0.02	0.00	16.63	0.26	0.01	1.04	Egypt II
VA-28	0.23	0.29	0.02	0.18	0.00	67.68	0.08	0.02	1.34	0.01	0.52	3.35	9.52	0.76	0.01	0.02	0.02	0.02	0.06	13.55	2.21	0.01	0.70	Al-Mina Group 1

Appendix Table 7: EPMA results for glass from al-Mina in northern Syria. Results are presented in weight percent oxide/element.

Sample pictures:

Samples from al-Raqqa, Syria:



RAQ-01



RAQ-02



RAQ-03



RAQ-04



RAQ-05



RAQ-06



RAQ-07



RAQ-08



RAQ-09



RAQ-10



RAQ-11



RAQ-12



RAQ-13



RAQ-14



RAQ-15



RAQ-16



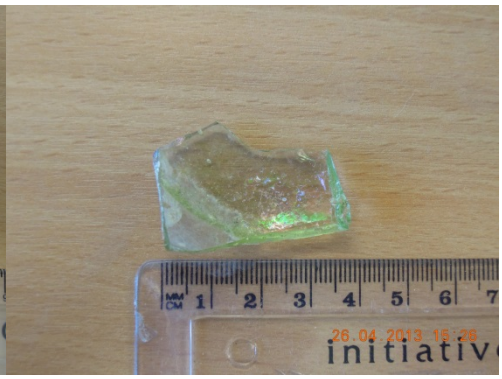
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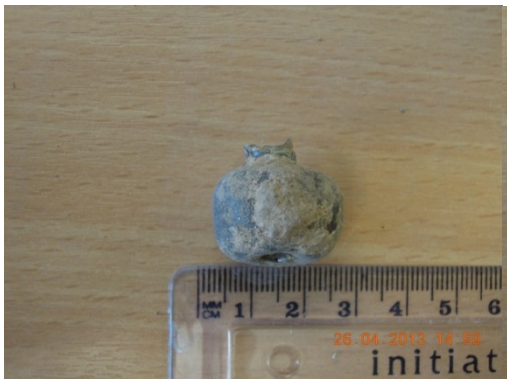
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RAQ-19



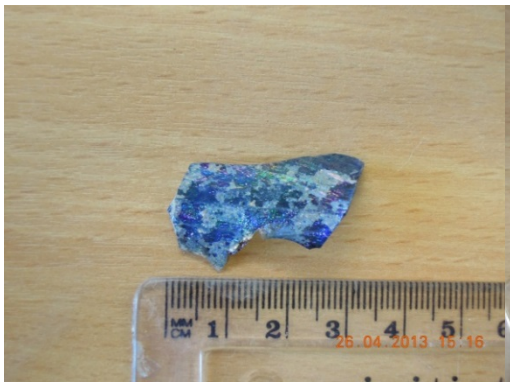
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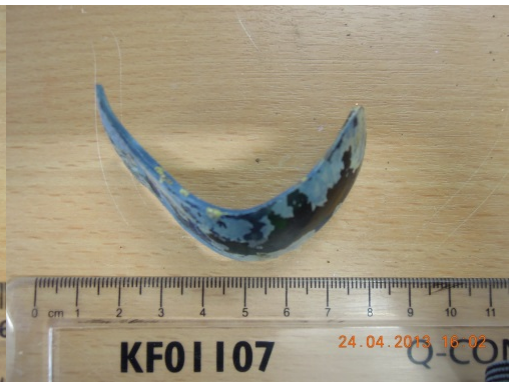
RAQ-21



RAQ-22



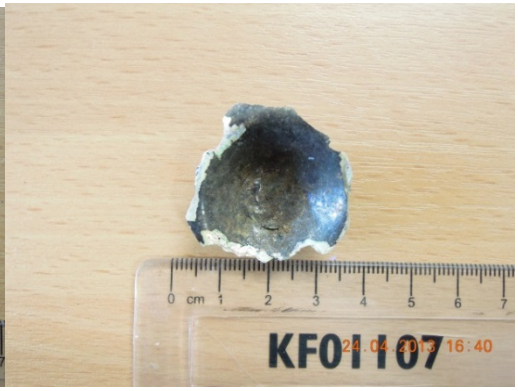
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RAQ-24



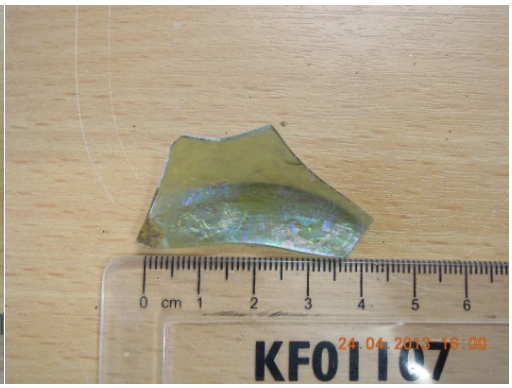
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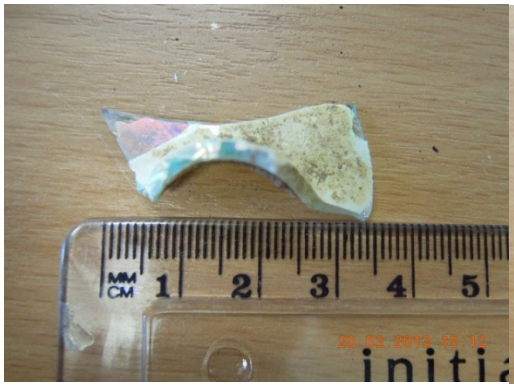
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RAQ-27



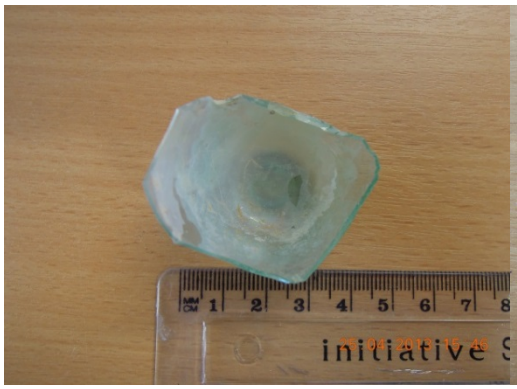
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RAQ-29



RAQ-30



RAQ-31



RAQ-32



RAQ-33



RAQ-34



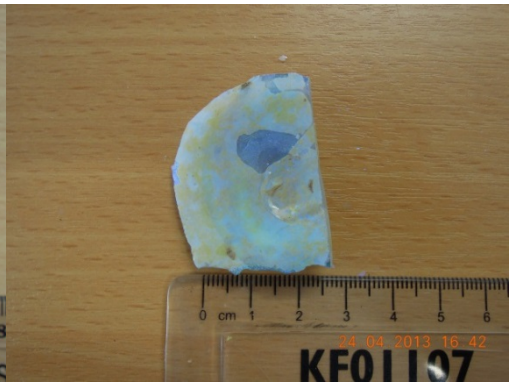
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RAQ-36



RAQ-37



RAQ-38



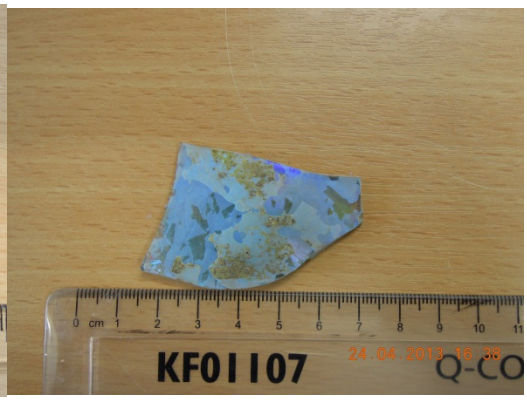
RAQ-39



RAQ-40



RAQ-41



RAQ-42



RAQ-43



RAQ-44



RAQ-45



RAQ-46



RAQ-47



RAQ-48



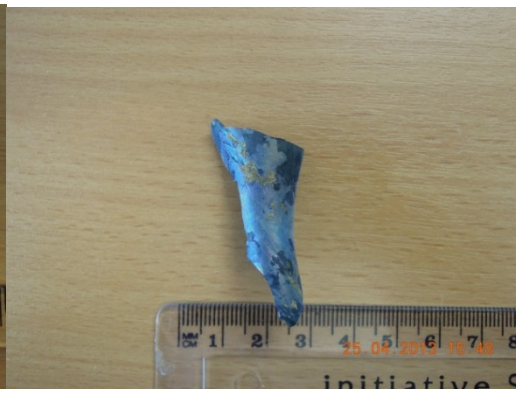
RAQ-49



RAQ-50



RAQ-51



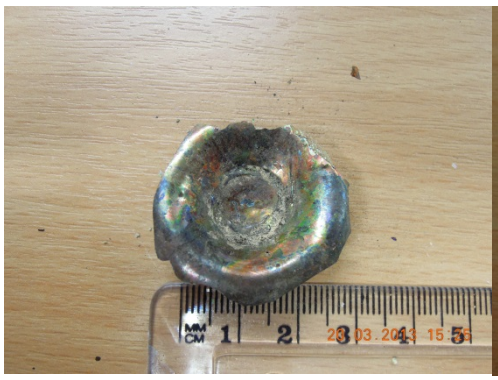
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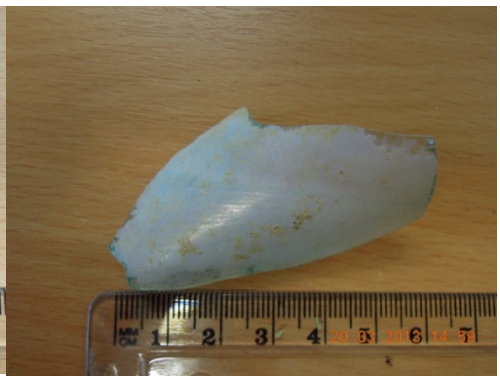
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RAQ-54



RAQ-55



RAQ-56



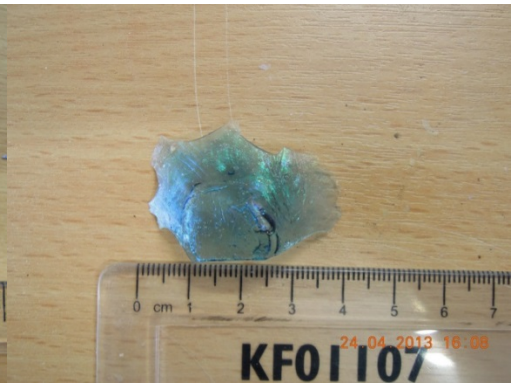
RAQ-57



RAQ-58



RAQ-59



RAQ-60



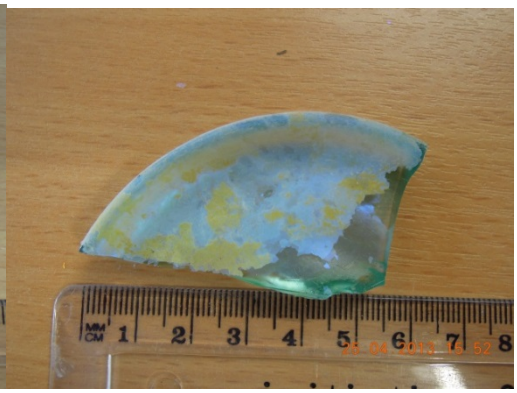
RAQ-61



RAQ-62



RAQ-63



RAQ-64



RAQ-65



RAQ-66



RAQ-67



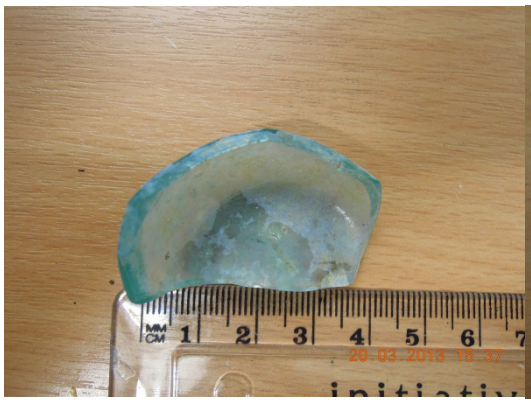
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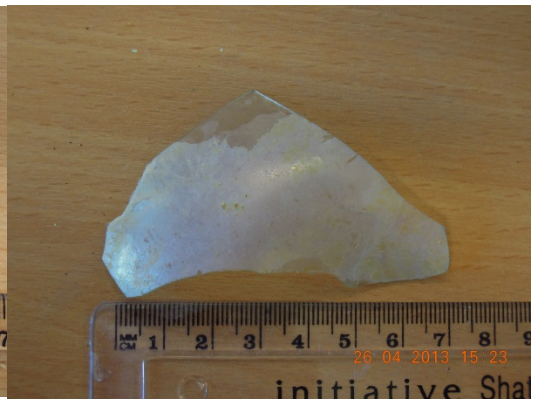
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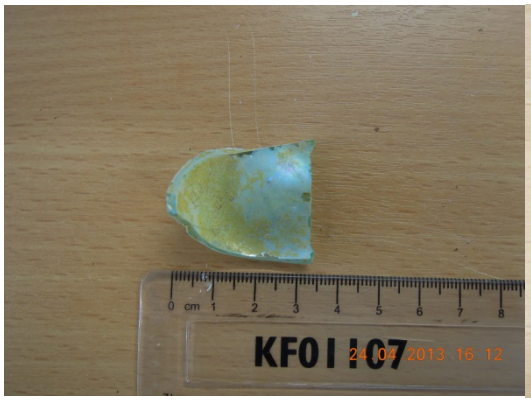
RAQ-70



RAQ-71



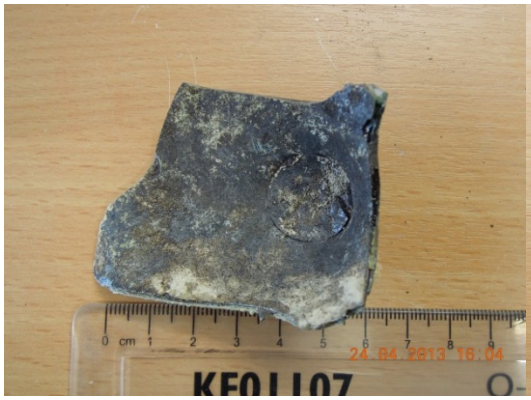
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RAQ-73



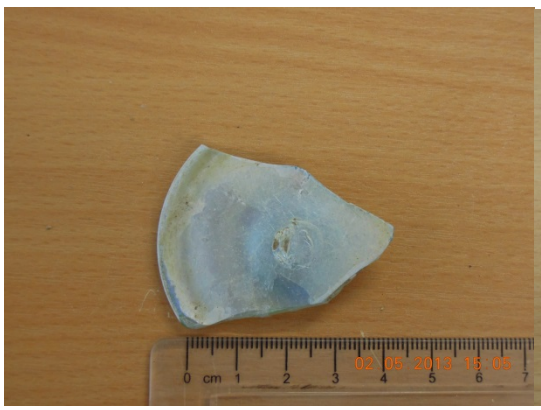
RAQ-74



RAQ-75



RAQ-76



RAQ-77



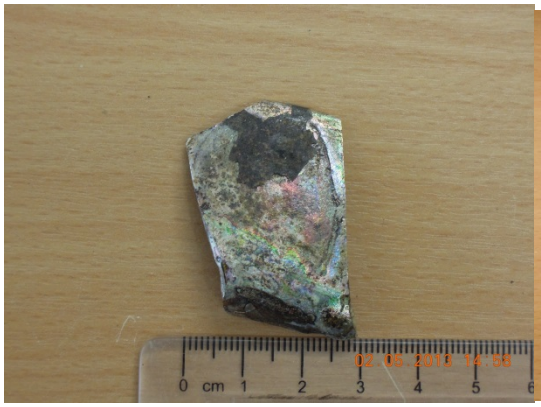
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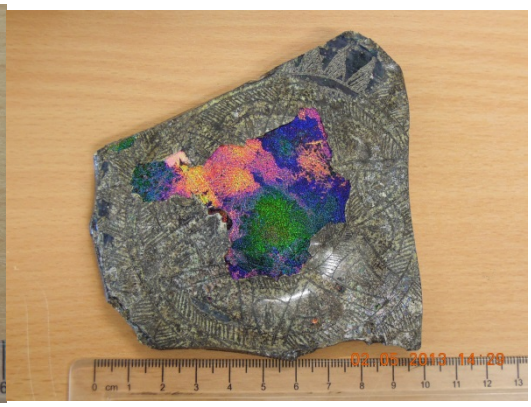
RAQ-79



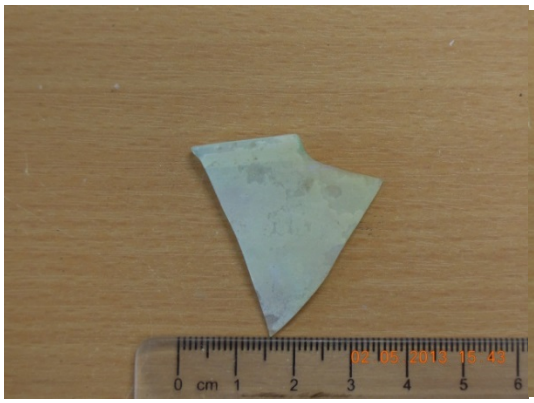
RAQ-80



RAQ-81



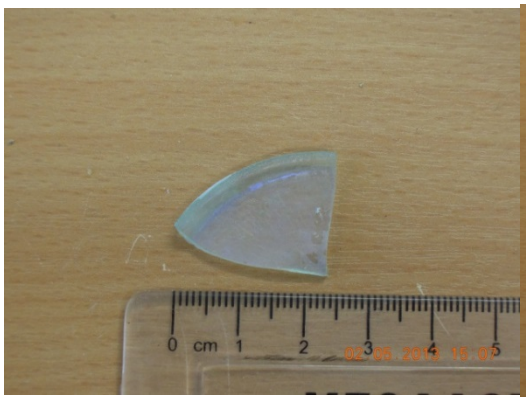
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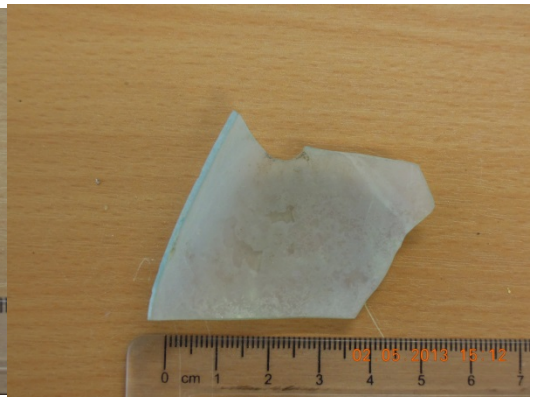
RAQ-83



RAQ-84



RAQ-85



RAQ-86



RAQ-87



RAQ-88



RAQ-89



RAQ-90



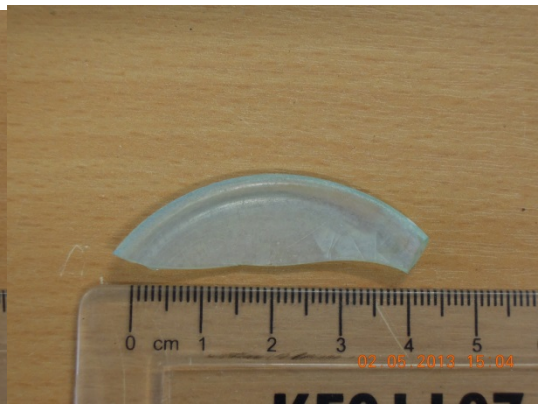
RAQ-91



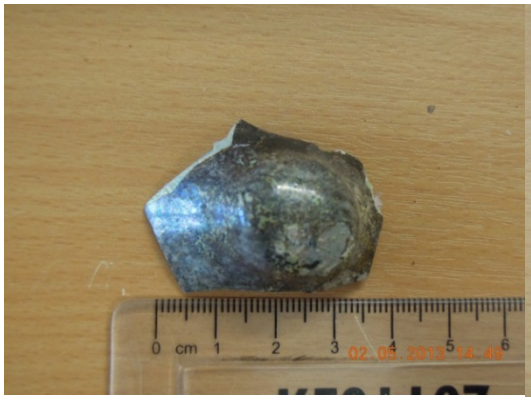
RAQ-92



RAQ-93



RAQ-94



RAQ-95



RAQ-96



RAQ-97



RAQ-98



RAQ-99



RAQ-100



RAQ-101



RAQ-102



RAQ-103



RAQ-104



RAQ-105



RAQ-106



RAQ-107



RAQ-108



RAQ-109



RAQ-110



RAQ-111



RAQ-112



RAQ-113

Samples from Tbilisi, Georgia:



Geo-01



Geo-02



Geo-03



Geo-04



Geo-05



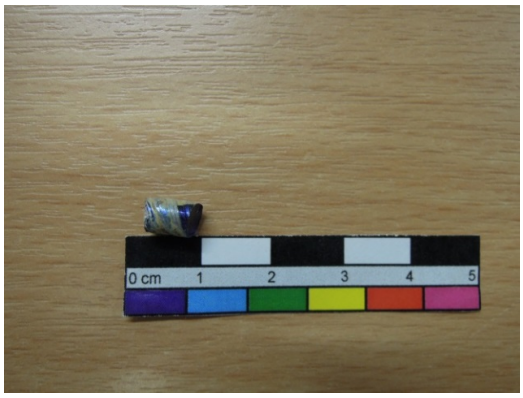
Geo-06



Geo-07



Geo-08



Geo-09

Samples from Zeyrek Camii in Istanbul, Turkey:



ZC-01



ZC-02



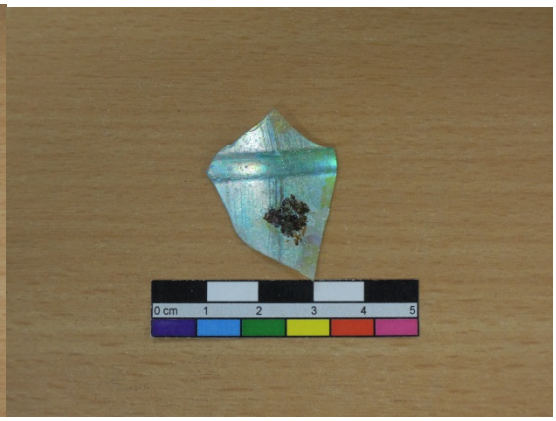
ZC-03



ZC-04



ZC-05



ZC-06



ZC-07



ZC-08



ZC-09



ZC-10



ZC-11



ZC-12



ZC-13



ZC-14

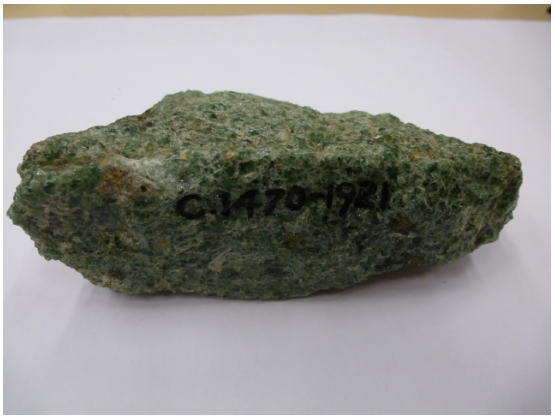


ZC-15

Samples from Fustat, Egypt:



VA-01

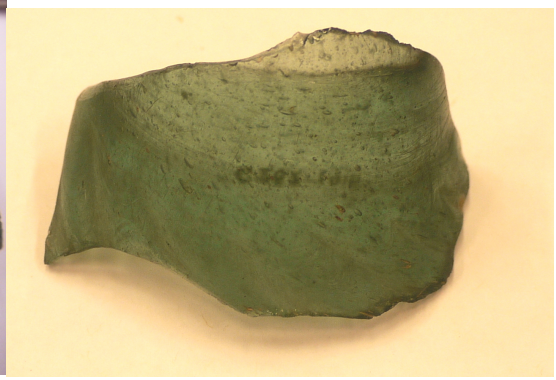


VA-02

Samples from Pemba, Island, Zanzibar:



VA-03



VA-04



VA-05



VA-06



VA-07

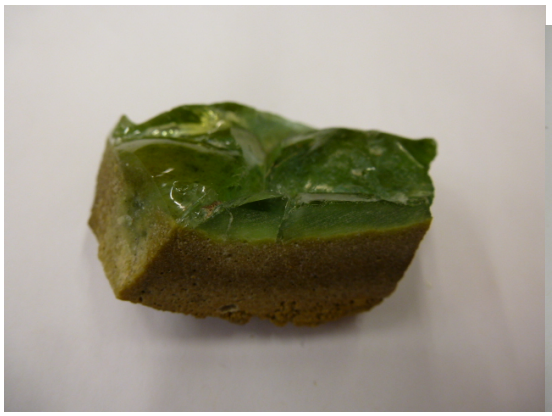
Samples from al-Qadisiyya in Samarra, Iraq:



VA-08



VA-09



VA-10



VA-11

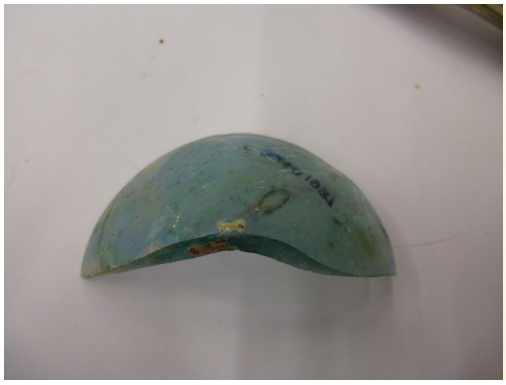


VA-12

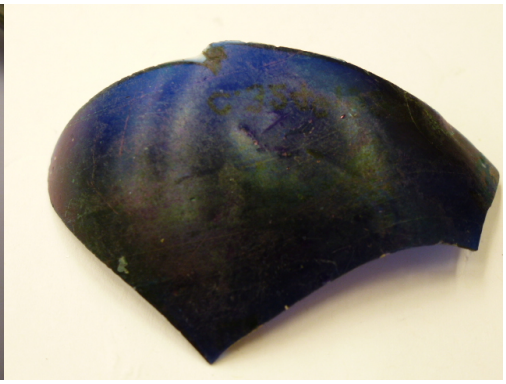


VA-13

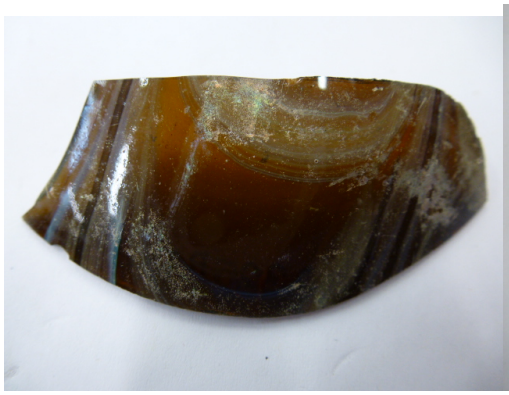
Samples from al-Mina, northern Syria



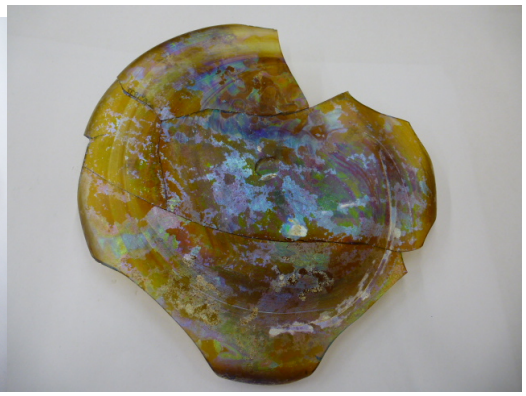
VA-14



VA-15



VA-16



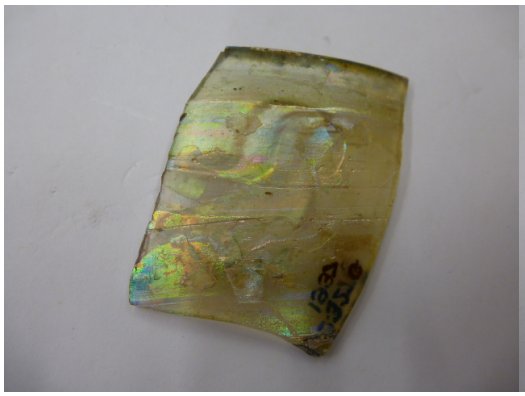
VA-17



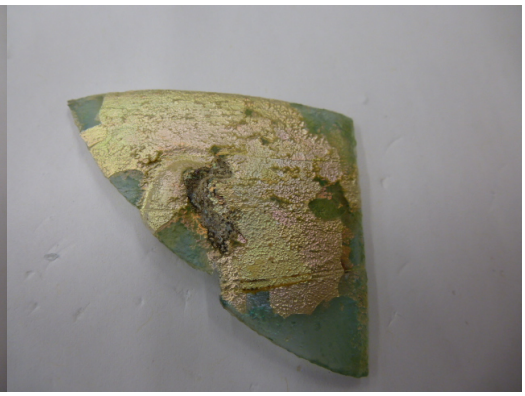
VA-18



VA-19



VA-20



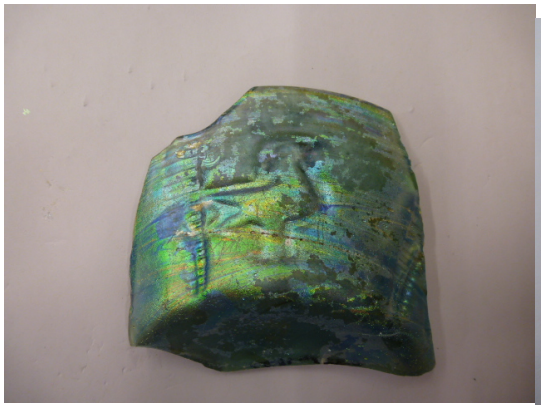
VA-21



VA-22



VA-23



VA-24



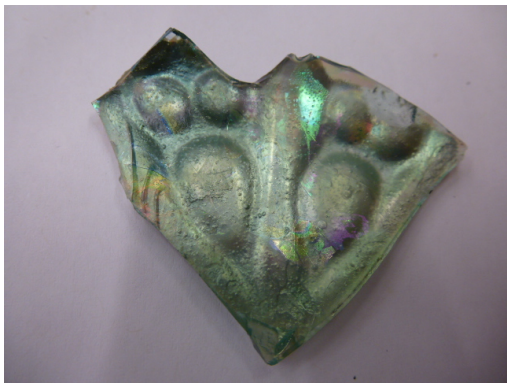
VA-25



VA-26



VA-27



VA-28